UNITED NATIONS UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME

LaGeo

Mar. 19, 2014 /IGH-LSG-ÁR-BS-PV-JLH-EdV

SHORT COURSE ON UTILIZATION OF LOW- AND MEDIUM-ENTHALPY GEOTHERMAL RESOURCES AND FINANCIAL ASPECTS OF UTILIZATION

Organized by UNU-GTP and LaGeo,
held in El Salvador during March 23rd – March 29th, 2014

SUNDAY, 23 March

Participants and trainers arrive in El Salvador and register into a hotel.

18:30-22:00 *Opening dinner at Mezzanine of Hilton Hotel*

MONDAY, 24 March

08:30-09:00 **Registration**
09:00-09:20 **Opening ceremony – Ing. Jorge Burgos, General Manager of LaGeo**
09:20-09:30 **Aim of the short course – organization and practical matters**
Ingimar G. Haraldsson, UNU-GTP and Evelyn de Velis, LaGeo

Geothermal energy overview – Chairman: Manuel Monterrosa, LaGeo

09:30-10:15 **Geothermal energy in the world and UNU-GTP capacity building activites** Paper
Lúdvík S. Georgsson, *Ingimar G. Haraldsson*, and Ingvar B. Fridleifsson, UNU-GTP
10:15-10:45 *Coffee break*
10:45-11:30 **Current status of geothermal resources development in Central America** Paper
Francisco Montalvo, LaGeo
11:30-12:00 **Geothermal activity and development in Mexico – Keeping the production going** Paper
Magaly Flores-Armenta, *Miguel Ramírez-Montes*, and Lilibeth Morales-Alcalá, CFE
12:00-12:30 **A Caribbean geothermal success story** Paper
Anelda Maynard-Date and Alexis George, NEVLEC
12:30-14:00 *Lunch*

Session continued – Chairman: Ingimar G. Haraldsson, UNU-GTP

14:00-14:20 **Geothermal development in Bolivia** Paper
Daniel Villarroel, *Danny Rivera and Pedro Ramos*, ENDE
14:20-14:40 **Geothermal development in Chile** Paper
Daniel Almarza, CER
14:40-15:00 **Geothermal development in Colombia** Paper
Eliana Mejía, Lorena Rayo, Javier Méndez, and Julian Echeverri, ISAGEN
15:00-15:20 **Geothermal development in Ecuador: History, current status and future** Paper
Andrés Lloret and Jerko Labus, INER
15:20-15.40 **Development of geothermal energy and factors that affect its utilization in Peru** Paper
Alcides Claros, MEM
15:40-16:10 *Coffee break*

Regional cooperation and capacity building – Chairman: Ingimar G. Haraldsson, UNU-GTP

16:10-16:40 **Regional Geothermal Training Programme at the University of El Salvador** Paper
Evelyn de Velis, LaGeo

16:40-17:00 **Regional Geothermal Office for Central America** Paper
Francisco Montalvo, LaGeo
17:00-17:30 **Discussion**
Francisco Montalvo, LaGeo and Ingimar G. Haraldsson, UNU-GTP

TUESDAY, 25 March

The principles of medium enthalpy geothermal power plants – Chairman: Miguel Ramírez-Montes, CFE

09:00-09:30 **Geothermal power plants** Paper
Einar T. Eliasson, Sverrir Thorhallsson, and *Benedikt Steingrímsson*, ÍSOR
09:30-10:00 **Thermodynamics of power production cycles** Paper
Páll Valdimarsson, Reykjavik University / Atlas Copco
10:00-10:30 **Binary power production cycles** Paper
Páll Valdimarsson, Reykjavik University / Atlas Copco
10:30-11:00 *Coffee break*

Binary power plants in Latin America – Chairman: Miguel Ramírez-Montes, CFE

11:00-11:30 **Geothermal binary cycle power plants – Principles, operation and maintenance: Case study from El Salvador** Paper
Angel Monroy and Godofredo López, LaGeo
11:30-12:00 **Geothermal energy: Current situation in Costa Rica** Paper
Jessica Arias, Dione Barahona, and *Lizeth Valverde*, ICE
12:00-12:30 **Experience with low enthalpy geothermal projects in Mexico** Paper
Ignacio Raygadas, CFE
12:30-14:00 *Lunch*

Design considerations for medium enthalpy geothermal power plants – Chairman: Thorleikur Jóhannesson, VERKÍS

14:00-14:30 **Piping design for geothermal projects** Paper
José Luis Henriquez and *Luis Aguirre*, LaGeo
14:30-15:00 **Design of binary plant components** Paper A Paper B
Páll Valdimarsson, Reykjavik University / Atlas Copco
15:00-15:30 **Exergy and thermoeconomics** Paper
Páll Valdimarsson, Reykjavik University / Atlas Copco
15:30-16:00 *Coffee break*
16:00-16:30 **Problems in geothermal operation – Scaling and corrosion** Paper
Einar Gunnlaugsson, Reykjavik Energy, Halldór Ármannsson, Sverrir Thorhallsson, and *Benedikt Steingrímsson*, ÍSOR
16:30-17:30 **Practical examples and discussion**
Páll Valdimarsson, Reykjavik University / Atlas Copco and José Luis Henriquez, LaGeo

WEDNESDAY, 26 March

Direct utilization of low- and medium-enthalpy geothermal resources – Chairman: Benedikt Steingrímsson, ÍSOR

09:00-09:20 **Direct use of geothermal resources** Paper
Thorleikur Jóhannesson and Carine Chatenay, VERKÍS
09:20-10:10 **Utilization of geothermal resources for space heating** Paper
Carine Chatenay, Halldóra Gudmundsdóttir, and *Thorleikur Jóhannesson*, VERKÍS
10:10-10:30 **Geothermal baths, swimming pools and spas: Examples from Ecuador and Iceland** Paper
Ingimar G. Haraldsson, UNU-GTP and *Andrés Lloret*, INER
10:30-11:00 *Coffee break*

11:00-11:30 **Geothermal energy in horticulture** **Paper A** **Paper B**
Árni Ragnarsson, ÍSOR, Magnús Ágústsson, Icelandic Agricultural Advisory Center, Martha Mburu and *Paul K. Ngugi*, GDC, *Thorleikur Jóhannesson*, VERKÍS

11:30-12:00 **Geothermal energy in aquaculture** **Paper**
Árni Ragnarsson, ÍSOR and *Thorleikur Jóhannesson*, VERKÍS

12:00-12:30 **Industrial applications of geothermal resources** **Paper**
Thorleikur Jóhannesson and Carine Chatenay, VERKÍS

12:30-14:00 *Lunch*

Session continued – Chairman: Paul K. Ngugi, GDC

14:00-14:30 **District heat distribution networks** **Paper**
Páll Valdimarsson, Reykjavik University / Atlas Copco

14:30-15:00 **Heat pumps and geothermal space cooling** **Paper**
Thorleikur Jóhannesson and Carine Chatenay, VERKÍS

15:00-15:30 **Hybrid power plant using three energy resources at the San Vicente geothermal field, El Salvador** **Paper**
Caleb Nájera, *Álvaro Flamenco*, and Salvador Handal, LaGeo

15:30-16:00 *Coffee break*

16:00-16:30 **Geothermal direct applications in Central America and Mexico** **Paper**
René Recinos, LaGEO

16:30-17:30 **Discussion**
Thorleikur Jóhannesson, VERKÍS

THURSDAY, 27 March

Field trip to Berlin binary cycle power plant and direct utilization sites.

FRIDAY, 28 March

Financial aspects of geothermal development – Chairman: José Luis Henríquez, LaGeo

09:00-09:45 **Phases of geothermal development in Iceland: From a hot spring to utilization** **Paper**
Benedikt Steingrímsson, ÍSOR

09:45-10:15 **Geothermal exploration and associated cost in Iceland** **Paper**
Bjarni Richter, *Benedikt Steingrímsson*, Magnús Ólafsson, and Ragna Karlsdóttir, ÍSOR

10:15-10:45 **EIA and permitting: Time and cost considerations** **Paper**
Ana Silvia de Arévalo, LaGeo

10:45-11:15 *Coffee break*

11:15-11:45 **Geothermal drilling: The price of reaching the resource** **Paper**
Miguel Ramírez-Montes and Magaly Flores-Armenta, CFE

11:45-12:15 **Geothermal power plants: Procurement and construction**
Páll Valdimarsson, Reykjavik University / Atlas Copco

12:15-12:45 **Operation, maintenance and monitoring: Manpower and material needs of Ahuachapan power plant, El Salvador** **Paper**
Godofredo López, LaGeo

12:45-14:00 *Lunch*

Session continued – Chairman: Páll Valdimarsson, Reykjavik University / Atlas Copco

14:00-14:20 **Electricity markets** **Paper**
Carlos Guzmán, LaGeo

14:20-14:40 **Government incentives and international support for geothermal project development** **Paper**
Ingimar G. Haraldsson, UNU-GTP

14:40-15:00 **From carbon financing in the context of geothermal development towards adaptation to climate change** **Paper**
Luis Franco, LaGeo

15:00-15:20 **Cost and revenues of direct use applications** Paper
Carine Chatenay and *Thorleikur Jóhannesson*, VERKÍS
15:20-15:50 *Coffee break*

Financial modelling of geothermal projects – Chairman: Páll Valdimarsson Reykjavik University / Atlas Copco

15:50-16:50 **Financial modelling of geothermal power projects** Paper
Paul K. Ngugi, GDC
16:50-17:30 **Discussion**
Paul K. Ngugi, GDC, José Luis Henríquez, LaGeo, and Benedikt Steingrímsson, ÍSOR

SATURDAY, 29 March

Financing geothermal projects – Chairman: Anelda Maynard-Date, NEVLEC

09:00-09:30 **Risks and risk mitigation in geothermal development** Paper
Paul K. Ngugi, GDC
09:30-10:00 **Feasibility study: Cost estimation for geothermal development** Paper
José Roberto Estévez, LaGeo
10:00-10:20 **Financing geothermal projects**
Migara Jayawardena, WB
10:20-10:40 **Bankable geothermal project documents** Paper
Paul K. Ngugi, GDC
10:40-11:10 *Coffee break*

Comparisons and large scale considerations – Chairman: Ana Silvia de Arévalo, LaGeo

11:10-11:30 **How do financial aspects of geothermal compare with other energy sources?** Paper
Carine Chatenay and *Thorleikur Jóhannesson*, VERKÍS
11:30-11:50 **Economic benefits of geothermal space heating from the perspective of Icelandic consumers** Paper
Ingimar G. Haraldsson, UNU-GTP
11:50-13:00 *Lunch*

Review and discussion – Chairman: Ana Silvia de Arévalo, LaGeo

13:00-13:30 **Review** (Instructors and Trainees)
13:30-14:00 **Discussion and recommendations**
14:00-14:30 *Coffee break*

Conclusions and closing remarks – Chairman: Ingimar G. Haraldsson, UNU-GTP

14:30-15:00 **Summary of the discussion, conclusions, and recommendations**
15:00-16:00 **Final closing ceremony**

16:00-16:30 ***Course assessment and next steps in training courses for Central America***
Meeting and review by instructors

19:00-21:00 *Closing cocktail hosted by LaGeo at Hilton Hotel.*

SUNDAY, 30 March

All guests depart from San Salvador for their home countries.

Presented at “Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization”, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS UNIVERSITY
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LaGeo S.A. de C.V.

GEOTHERMAL ENERGY IN THE WORLD AND UNU-GTP CAPACITY BUILDING ACTIVTIES

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ABSTRACT

The renewable energy sources are expected to provide at least 20% of the world primary energy in 2050. A key element in the mitigation of climate change is capacity building in renewable energy technologies in the developing countries, where the main energy use growth is expected. Based on the “World Energy Scenarios” report on the status in 2010 and predictions for 2050 (WEC, 2013), the primary energy consumption in the world was assessed to be 546 EJ in 2010, with about 80% coming from fossil fuels, but only 15% from renewable energy sources. The contribution of the renewables is discussed and their possibilities. Their current share in the energy production is mainly from biomass and hydro, followed by wind and geothermal energy. In a future envisioned with depleting resources of fossil fuels and environmentally acceptable energy sources, geothermal energy with its large technical potential is expected to play an important role.

Central America is one of the world´s richest regions in geothermal resources. Geothermal power stations provide about 12% of the total electricity generation of the four countries Costa Rica, El Salvador, Guatemala and Nicaragua, while hydro stations provide 46% of the electricity for the four countries, and wind energy 2%. The geothermal potential for electricity generation in Central America has been estimated some 4 GWe, and less than 500 MWe have been harnessed so far. With the large untapped geothermal resources and the existing significant experience, there are still ample opportunities to take geothermal to a higher level in the area. South America also hosts vast resources of geothermal energy that are largely unexploited, estimated to be in the range of 4-9 GWe. Exploration and development is now on-going in countries like Bolivia, Chile, Colombia, Ecuador, and Peru. Similarly, the 11 volcanic islands of the Eastern Caribbean have an estimated power potential of 16 GWe collectively, according to USDOE studies. Production is still limited to Guadeloupe, with 15.7 MWe, but exploration wells have been drilled in St. Lucia, Nevis, Dominica and Montserrat.

Finally, the activities of the UNU Geothermal Training Programme are described, including the 6 month training and postgraduate academic studies in Iceland with reference to Latin America. Special attention is given to the “UN Millennium Development Goals Short Courses” given almost annually in El Salvador since 2006, at first for the benefit of Central America, but more recently reaching to a large part of Latin America, and some of the volcanically active Caribbean Islands. Further development of geothermal capacity building in the region is discussed and the current Diploma Course given at the University of El Salvador.

1. INTRODUCTION

Geothermal energy is one of the renewable energy sources that can be expected to play an important role in an energy future where the emphasis is no longer on fossil fuels, but on energy resources that are at least semi-renewable and environmentally acceptable for the long term, especially with regard to emission of greenhouse gases and other pollutants. For developing countries which are endowed with good geothermal resources, it is a reliable local energy source that can at least to some extent be used to replace energy production based on imported (usually) fossil fuels. The technology is proven and cost-effective. For developing countries that have good resources and have acquired the necessary local expertise it has become very important. Kenya is a good example of this, as well as the Philippines, El Salvador and Costa Rica where geothermal energy is providing for 10-20% of the electricity production. Iceland should also be mentioned as the only country where geothermal energy supplies more than 60% of the primary energy used. This is done through direct use for space heating, bathing, etc., and through production of electricity (Ragnarsson, 2010).

Geothermal systems can be classified into a few different types but with reference to variable geological conditions each one is in principle unique, so that good knowledge is needed through exploration. Furthermore, development of a geothermal system for electrical production is a capital intensive undertaking, and thus requires financial strength, or at least access to good financing. Therefore, for developing geothermal resources, good training and expertise are needed for the exploration and development work, and furthermore strong financial backup for the project is necessary.

Here, the role of geothermal energy in the world's energy mix is presented with some emphasis on its utilization in Latin America and the Caribbean region. Then capacity building activities will be discussed. The operations of the United Nations University Geothermal Training Programme (UNU-GTP) will be introduced and the need for further geothermal capacity building in the region discussed.

2. THE NEED FOR MORE ENERGY

Amongst the top priorities for the majority of the world´s population is access to sufficient affordable energy. There is a very limited equity in the energy use in the different parts of the world. Some two billion people, a third of the world´s population, have no access to modern energy services. A key issue to improve the standard of living of the poor is to make clean energy available to them at prices they can cope with. The world population, now at 7 billion people, is expected to continue to increase to the end of the 21st century, and possibly double through the century. To provide sufficient commercial energy (not to mention clean energy) to the people of all continents during this century is thus an enormous task.

The renewable energy sources are expected to provide 20-30% of the primary energy in 2050 (WEC, 2010). The technical potential of renewable energy sources is estimated 7600 EJ/year, and thus certainly sufficiently large to meet future world energy requirements (WEA, 2000). The question is how large a part of the technical potential can be harnessed in an economical, environmentally and socially acceptable way.

The main growth in energy use will certainly be in the developing countries. It is thus very important to support developing and transitional countries with fast expanding energy markets, such as China and India, to try as possible to meet their growing energy demands by developing their renewable energy resources. In some countries, e.g. in Central America and the East African Rift Valley, the majority of the grid connected electricity is already provided by hydro and geothermal energy. It is necessary to assist them in developing their renewable energy resources further so they are not compelled to meet the fast growing energy demands by fossil fuels.

3. WORLD ENERGY SOURCES

With technological and economic development, estimates of the ultimately available energy resource base continue to increase. Economic development over the next century will apparently not be constrained by geological resources. Environmental concerns, financing, and technological constraints appear more likely sources of future limits (Fridleifsson, 2002). In all scenarios of the World Energy Council (WEC), the peak of the fossil fuel era has already passed (Nakicenovic et al., 1998). Oil and gas will continue to be important sources of energy in all cases, but the role of renewable energy sources and nuclear energy vary highly in different scenarios and the proposed level to which these energy sources can be expected to replace coal. In all the scenarios, the renewables are however expected to become significant contributors to the world primary energy consumption. They are expected to cover a large part of the increase in the general energy consumption and the energy needed to replace coal.

But are these scenarios realistic? Table 1 (WEA, 2000) shows that there is no question that the technical potential of renewable energy resources is sufficiently large to meet future world energy requirements. The question is, however, how large a part of it can be harnessed in an economical, environmentally and socially acceptable way. This will probably vary between the energy sources. It is worth noting, that the present annual consumption of primary energy in the world is close to 550 EJ (Table 2).

TABLE 1: Technical potential of renewable energy sources
Source: World Energy Assessment (WEA, 2000)

	EJ / year
Hydropower	50
Biomass	276
Solar energy	1,575
Wind energy	640
Geothermal energy	5,000
TOTAL	**7,600**

TABLE 2: World primary energy consumption in 2010
Source: World Energy Assessment (WEC, 2013)

Energy source	**Percentage %**
Fossil fuels	**79.6**
Oil	31.5
Natural gas	20.9
Coal	27.2
Renewables	**14.8**
Hydropower	2.3
Biomass	12.1
Other renewables (wind, geothermal, solar, tidal)	0.4
Nuclear	**5.5**
Total – absolute value 546 EJ	**100**

Table 2 shows the world primary energy consumption mix in 2010 (WEC, 2013). Fossil fuels provide 80% of the total, with oil (32%) in first place, followed by coal (27%) and natural gas (21%). The renewables collectively provide 15% of the primary energy, mostly in the form of biomass (12%) and much less by hydropower stations (2.3%) and the other renewables (0.4%). Nuclear energy provides 6% of the world primary energy.

The total supply in 2010 is estimated to be 546 EJ (WEC, 2013). WEC's latest future predictions are based on two very different scenarios, the consumer driven, *Jazz* where the total energy supply is expected to increase to 879 EJ in 2050, while in the voter/control driven *Symphony,* it is only expected to increase to 696 EJ. The role of the renewables varies a lot depending on the scenario, in Jazz the share of the fossil fuels is expected to continue to be very high, about 77%, while in Symphony it has lowered to 59%. The share of the renewables is expected to rise, but only to about 20% in Jazz, while in Symphony it is assumed to reach almost 30%. The expected significant increase in energy efficiency is notable.

If we only look at the electricity production, the role of hydropower becomes much more significant. The world electricity production was about 22,126 TWh in 2011 as compared with 6,115 TWh in 1973 (IEA, 2013). Most of the electricity was produced by coal (41%), followed by natural gas (22%), hydro (16%), nuclear (12%), and oil (5%). Only 2% of the electricity was provided by the "other renewables" (geothermal, solar, wind, biofuels, and waste).

Table 3 shows the installed capacity and electricity production in 2005 for the renewable energy sources, namely hydro, biomass, wind, geothermal, and solar energy (from Fridleifsson et al., 2008). The data for the table is compiled from "Tables" in the 2007 Survey of Energy Resources (WEC, 2007). It should be noted that the installed capacity for biomass is not given in the "Tables", but reported as "in excess of 40 GW" in the text. The capacity factor for biomass is thus uncertain. No figures are given for the installed capacity and electricity production of tidal energy in the survey. The table clearly reflects the variable capacity factors of the power stations using the renewable sources. The capacity factor of 73% for geothermal is by far the highest. Geothermal energy is independent of weather conditions contrary to solar, wind, or hydro applications. It has an inherent storage capability and can be used both for base load and peak power. The relatively high share of geothermal energy in electricity production compared to the installed capacity (1.8% of the electricity with only 1% of the installed capacity) reflects the reliability of geothermal plants which are commonly operated at capacity factors in excess of 90%.

TABLE 3: Electricity from renewable energy resources in 2005

	Installed capacity		**Production per year**		**Capacity factor**
	GWe	**%**	**TWh/yr**	**%**	**%**
Hydro	778	87.5	2,837	89	42
Biomass	40*	4.5	183	5.7	52*
Wind	59	6.6	106	3.3	21
Geothermal	8.9	1.0	57	1.8	73
Solar	4	0.4	5	0.2	14
Total	**890**	**100**	**3,188**	**100**	**41****

* Capacity factor is uncertain; **Weighted average.

Table 3 also serves to demonstrate that renewable energy sources can contribute significantly more to the mitigation of climate change by cooperating than by competing. It underlines that geothermal energy is available day and night every day of the year and can thus serve as a supplement to energy sources which are only available intermittently. It is most economical for geothermal power stations to serve as a base load throughout the year, but they can also, at a cost, be operated to meet seasonal variations and as peak power.

In 2009, electricity was produced from geothermal energy in 24 countries, increasing by 20% in the 5-year period from 2004 to 2009 (Bertani, 2010). Table 4 lists the top sixteen countries producing geothermal electricity in the world in 2009, and those employing direct use of geothermal energy (in GWh/year). Figure 1 shows the top fourteen countries in the world with the highest percentage share of geothermal in their national electricity production. Special attention is drawn to the fact that El Salvador, Costa Rica and Nicaragua are among the seven top countries, and that Guatemala is in tenth place.

TABLE 4: Top sixteen countries utilising geothermal energy in 2009;
data on electricity from Bertani (2010) and on direct use from Lund et al. (2010)

Geothermal electricity production		**Geothermal direct use**	
	GWh/yr		**GWh/yr**
USA	14,974	China	20,932
Philippines	10,311	USA	15,710
Indonesia	9,600	Sweden	12,585
Mexico	7,047	Turkey	10,247
Italy	5,520	Japan	7,139
Iceland	4,597	Norway	7,001
New Zealand	4,055	Iceland	6,768
Japan	3,064	France	3,592
Kenya	1,430	Germany	3,546
El Salvador	1,422	Netherlands	2,972
Costa Rica	1,131	Italy	2,762
Turkey	490	Hungary	2,713
Papua – New Guinea	450	New Zealand	2,654
Russia	441	Canada	2,465
Nicaragua	310	Finland	2,325
Guatemala	289	Switzerland	2,143

The largest geothermal electricity producer is the USA, with almost 15,000 GWh/yr, but amounting to only 0.5% of their total electricity production. It is different for most of the other countries listed in Table 4, with geothermal playing an important role in their electricity production. That certainly applies to the second country on the list, the Philippines, where the production of 10,300 GWh/yr means that geothermal supplies 17% of the total produced electricity. The same applies to Kenya, the total production of 1,430 GWh/yr puts the country in 9th place with regard to world production but constitutes 17% of the total electricity production in Kenya. For direct use (Lund et al., 2010), China heads the list followed by the USA, Sweden and Turkey. No Central American country is on the list of the 16 countries highest in direct use of geothermal energy.

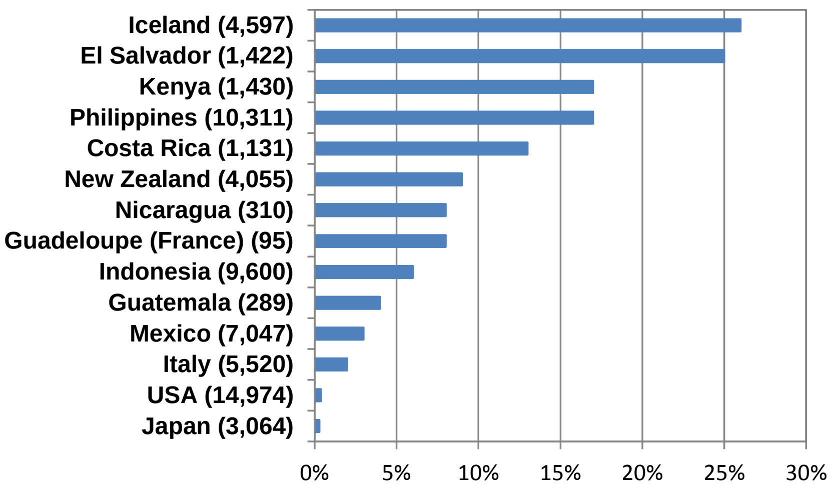

FIGURE 1: The fourteen countries with the highest % share of geothermal energy in their national electricity production. Numbers in parenthesis give the annual geothermal electricity production in GWh in 2009 (based on Bertani, 2010)

4. GEOTHERMAL ELECTRICITY IN LATIN AMERICA AND EASTERN CARIBBEAN

Central America is one of the world´s richest regions in geothermal resources. Geothermal power stations provide about 12% of the total electricity generation of the four countries Costa Rica, El Salvador, Guatemala and Nicaragua, according to data provided from the countries (CEPAL, 2010; see also Table 4). In each of the 4 countries there are geothermal power plants in operation in two geothermal areas. The photo in Figure 2 is taken at the Ahuachapán geothermal power plant in El Salvador, while Figure 3 shows the Las Pailas binary power plant in Costa Rica. The electricity generated in the geothermal areas is in all cases replacing electricity generated by imported oil. The geothermal potential for electricity generation in Central America has been estimated some 4 GWe (Lippmann 2002), but less than 0.5 GWe have been harnessed so far. Exploration and production drilling has been ongoing in several new fields in the region with positive results, most recently in the San Vicente field in El Salvador.

FIGURE 2: Some lecturers and participants in Short Course IV in 2012 visiting the Ahuachapán geothermal power plant in El Salvador

FIGURE 3: The Las Pailas binary geothermal power plant in Costa Rica

South America also hosts vast sources of geothermal energy that are largely unexploited. In 1999, the Geothermal Energy Association estimated the continent´s potential for electricity generation from geothermal resources to be in the range of 4-9 GWe based on available information and assuming technology available at the time (Gawell et al., 1999). These resources are largely the product of the convergence of the South American tectonic plate and the Nazca plate that has given rise to the Andes mountain chain, with its countless volcanoes. High-temperature geothermal resources in Bolivia, Chile, Colombia, Ecuador and Peru are mainly associated with the volcanically active regions, although low-temperature resources are also found outside them. Despite this, the only geothermal power plant which has been operated on the continent is the 0.7 MW binary demonstration unit in the Copahue field in Argentina, which was decommissioned in 1996 (Bertani, 2010). However, all of these countries have some history of geothermal exploration, and the interest has recently been reinvigorated with the changes in global energy prices and the increased emphasis on renewables to combat global warming (Haraldsson, 2013).

The 11 volcanic islands of the Eastern Caribbean lying on the inner arc have an estimated power potential of 16,310 MWe collectively, according to USDOE studies. Guadeloupe, as of 2004, has an operating facility of 15.7 MWe and is the only island in the region harnessing power from its geothermal resources. St. Lucia, Nevis and most recently Dominica have drilled exploration wells to analyse the resource for commercial exploitation. The most significant recent progress was the drilling of 3 deep vertical exploration wells in Dominica in 2012 (Maynard-Date, 2012; George, 2012), with two more exploration wells drilled in 2013-2014, while the first deep exploration well was drilled in Montserrat in 2013.

4. THE UNU GEOTHERMAL TRAINING PROGRAMME IN ICELAND

4.1 Introduction

The UNU Geothermal Training Programme (UNU-GTP) was established in Iceland in 1978. Its mandate is to assist developing countries with significant geothermal potential to establish groups of specialists in geothermal exploration and development by offering six month specialized training for professionals employed in geothermal research and/or development. More recently, the UNU-GTP also offers successful candidates the possibility of extending their studies to MSc or PhD degrees in geothermal sciences or engineering in cooperation with the University of Iceland. A similar agreement has now been signed with Reykjavik University. The UNU-GTP also organizes Workshops and Short Courses on geothermal development in Africa (started in 2005), Central America (started in 2006), and China (in 2008) (Fridleifsson, 2010).

During 1979-2013, 554 scientists and engineers from 53 countries have completed the annual six month courses. They have come from countries in Asia (39%), Africa (34%), Latin America (15%), Central and Eastern Europe (11%) and Oceania (1%). Since 2000, 35 have graduated with an MSc degree (end of 2013), and the first UNU PhD Fellow graduated in February 2013 from the University of Iceland. In January 2014, ten were pursuing their MSc studies, and two their PhD studies at the University of Iceland.

The UNU-GTP Short Courses are a special contribution of the Government of Iceland to the Millennium Development Goals of the United Nations. A part of the objective is to increase the cooperation between specialists in neighbouring countries in the field of sustainable use of geothermal resources. About 200 scientists/engineers and decision makers have participated in the 3 workshops that have each been a week, and more than 650 scientists/engineers have now been trained at the Short Courses, which have extended over 1-3½ weeks. Many former UNU Fellows are lecturers and co-organizers of the UNU-GTP Workshops and Short Courses. An offspring of the Millennium Short Courses has been the possibility of UNU-GTP to offer customer-designed geothermal short courses, which has now become an important part of the UNU-GTP operations (Georgsson, 2010; 2012a; 2012b).

Since the start of the Workshops/Short Courses in 2005/6, the long term aim has been that the courses would develop into sustainable regional geothermal training centres. This is foreseen to happen in Kenya for the benefit of the African countries. And now, the Inter-American Development Bank (IDB) with the support of the Nordic Development Fund (NDF) is supporting a post-graduate diploma programme at the University of El Salvador for the benefits of the Latin American countries, run under Consejo Nacional de Energía – CNE, in El Salvador, with the cooperation of LaGeo and under the guidance of UNU-GTP.

4.2 The 6 month geothermal training in Iceland

The main emphasis of the 6 month training is to provide the participants with sufficient understanding and practical experience to permit the independent execution of projects within a selected discipline in their home countries. Nine specialized lines of training are offered, *Geological Exploration*, *Borehole Geology*, *Geophysical Exploration*, *Borehole Geophysics*, *Reservoir Engineering*, *Environmental Studies*, *Chemistry of Thermal Fluids*, *Geothermal Utilization* and *Drilling Technology*. Each participant is meant to follow only one line of training, but within each line there is a considerable flexibility to allow for the needs of the individual.

The basic set-up of the 6 month training includes a 6 week introductory lecture course which aims to provide the individual with background knowledge on most aspects of geothermal energy resources and technology. It is followed by lectures and practical training in the field that the individual is specializing in (6 weeks), Excursions are arranged to some of the main geothermal fields under exploration and utilization in Iceland, with seminars held and case histories presented on each field (2 weeks). The final phase is the execution of an extensive research project (10-12 weeks), under the guidance of an expert supervisor, which is concluded with a research project report. The trainees are encouraged to work on geothermal data from their home country if available. The reports are published in the annual yearbook "Geothermal Training in Iceland" (edited by Lúdvík S. Georgsson, international publishing code ISBN 978-9979-68). All research reports are also available on the home page of the UNU-GTP (*www.unugtp.is*). Figure 4 shows the recently revised time schedule and contents of the six month specialized courses at UNU-GTP in Iceland.

Week	Geological Exploration	Borehole Geology	Geophysical Exploration	Borehole Geophysics	Reservoir Engineering	Chemistry of Thermal Fluids	Environmental Science	Geothermal Utilization	Drilling Technology
1 2 3 4 5 6	Introductory Lecture Course Main aspects of geothermal energy exploration and utilization Practicals and short field excursions								
7 8 9 10	Field geology Lithological, tectonic & hydrothermal mapping Temperature surveying	Sample preparation Cutting analysis Petrography - Lithological & alteration logs	Thermal methods - Magnetics Gravity - Seismic methods Resistivity of rocks - Resistivity methods: DC, TEM & MT	Well logging & testing - theory & practises Logging and testing demonstrations Reservoir physics & well/reservor modelling Monitoring response to exploitation		Sampling of fluid & gas - Wet steam wells - Analytical methods Thermodynamics - Data processing and interpret.	EIA project planning Chemistry - Physics Biology - Monitoring Revegetation - Safety	Thermal design of power plants & source systems - Direct use of geothermal heat - Scientific modelling of utilization systems	Drilling equipment & procedures - Well design Rig operations - Safety Management - Cementing
11 12	Excursion to some of the main geothermal fields of Iceland, geothermal power plants and direct use facilities								
13 14	Gradient wells Remote sensing - GIS	XRD - Fluid inclusions Logging software	Processing & modelling resistivity data - GPS	Resource management & reinjection Data processing & software applications		Water-rock interaction Corrosion & scaling	Gas dispersion & abatem. Corrosion & scaling	Power plant components - Control systems - Corrosion & scaling	Completion - Testing Problems - Drilling software
15 16 17 18 19 20 21 22 23 24 25 26	**Project and report writing**	**Project and report writing**	**Project and report writing**	**Project and report writing**	**Project and report writing**	**Project and report writing**	**Project and report writing**	**Project and report writing**	**Project and report writing**

FIGURE 4: Approximate time schedule and contents of the 6 month specialized courses at UNU-GTP

The largest groups of UNU Fellows have come from Kenya (89), China (82), El Salvador (36) and the Philippines (36). Figure 5 shows the UNU Fellows who completed the 6 months training in 2013.

For the past several years, regular funding of the UNU-GTP has allowed financing of six months training of about 20 UNU Fellows per year, with extra 1-3 Fellowships per year being financed through other sources, at least partially, until recently. The last four years have seen a dramatic increase in the latter. Improved set-up and new facilities in Iceland have made it possible for UNU-GTP to accept additional Fellows if financed through external sources. This is reflected in the large groups in 2010-2013, with the largest group to date trained in 2013, consisting of 34 UNU Fellows, 13 of whom were mainly financed through other agencies. Especially Kenya has utilized this opportunity as possible. Figure 6 shows the development of the training capacity of the UNU Geothermal Training Programme in Iceland from the beginning in 1979 to 2013. It should be noted that the numbers for 2013, include 5 additional Kenyan borehole geologists, who got a similar training through a 3 month course and 6 month training in Kenya in 2012-2013, and have thus been given a similar status as conventional UNU Fellows.

For a more detailed description of the general operations of the UNU-GTP see Fridleifsson (2010) or the UNU-GTP webpage, *www.unugtp.is*.

FIGURE 5: UNU Fellows in Iceland for the 6 month training in 2013

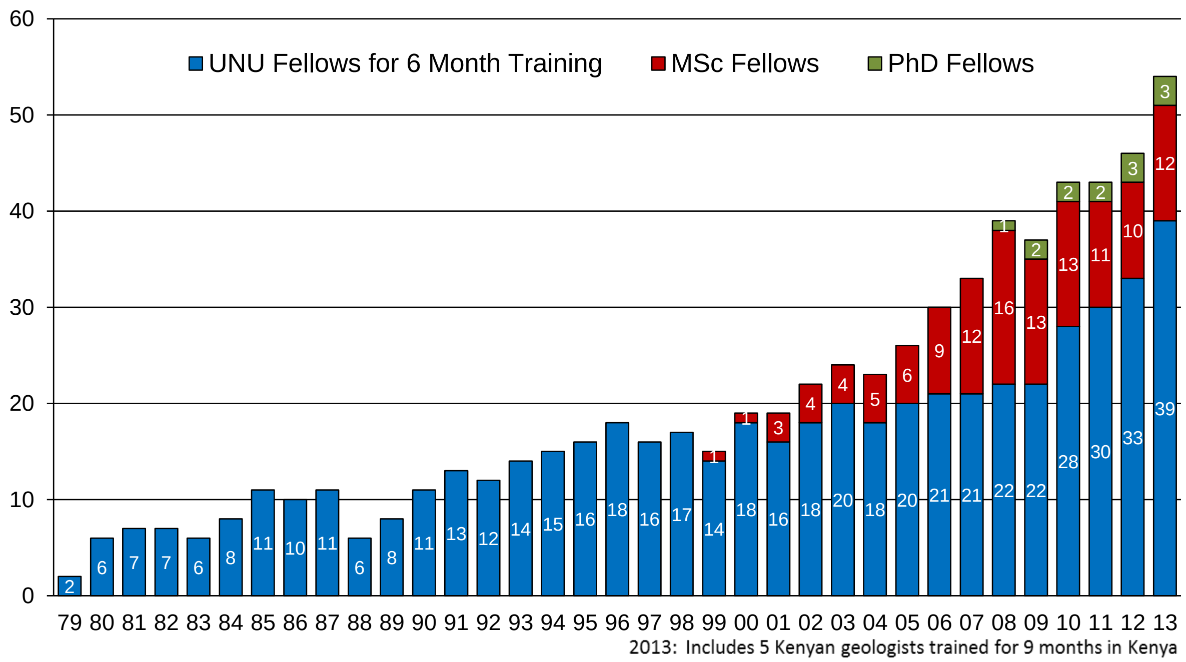

FIGURE 6: The gradual development of the training capacity of the UNU Geothermal Training Programme in Iceland from 1979 to 2013

4.3 The MSc and PhD programme

The aim of establishing an MSc programme in cooperation with the University of Iceland (UI) was to go a step further in assisting selected countries to strengthen their specialist groups even further and increase their geothermal research capacity, through admittance and support for postgraduate academic studies. The six months training at the UNU-GTP fulfils 25% of the MSc programme credit requirements (30 of 120 ECTs). Since 2001, 35 former UNU Fellows (China 2, Costa Rica 1, Djibouti 1, El Salvador 5, Eritrea 2, Ethiopia 2, Indonesia 4, Iran 3, Jordan 1, Kenya 9, Mongolia 1, Philippines 2, Rwanda 1 and Uganda 1) have completed an MSc degree in geothermal science and engineering

(December 2012) through the UNU-GTP MSc programme, with 6, or 17%, from Latin America. At the beginning of 2014, 10 are doing their MSc studies in Iceland, 1 of whom comes from El Salvador, and 1 from Nicaragua. The MSc theses have been published in the UNU-GTP publication series, and can also be obtained from the UNU-GTP webpage (*www.unugtp.is*). All of the MSc Fellows have been on UNU-GTP Fellowships funded by the Government of Iceland.

Finally, three former UNU Fellows, all coming from Africa, have been admitted to PhD studies at the University of Iceland on UNU-GTP Fellowships, with the first ones starting in the academic year 2008-2009. On February 15, 2013 a new milestone was reached in the operations of the UNU-GTP with the first one of these defending her PhD thesis. Dr. Pacifica F. Achieng Ogola from Kenya was in fact the first person from Africa to graduate with a doctoral degree from UI.

4.4 Workshops and Short Courses

The Short Courses/Workshops are set up in a selected country in the target region through cooperation with local energy agencies/utilities and/or earth science institutions, responsible for exploration, development and operation of geothermal facilities in the respective countries. In implementation, the first phase has been a week long workshop during which decision makers in energy and environmental matters in the target region have met with the leading local geothermal experts and specially invited international experts. The status of geothermal exploration and development has been introduced and the possible role of geothermal energy in the future energy mix of the region discussed. The purpose has, on one hand, been to educate key decision makers in the energy market of the respective region about the possibilities of geothermal energy, and increase their awareness of the necessity for more effort in the education of geothermal scientists in the region, and, on the other hand, to further the cooperation between specialists and decision makers in the different countries.

The workshop is followed by "annual" specialized Short Courses for earth scientists and engineers in surface exploration, deep exploration, production exploration, environmental studies and production monitoring etc., in line with the type of geothermal activity found in the respective region, and the needs of the region. Material presented and written for these events has been published on CDs and is also available on the website of the UNU-GTP (*www.unugtp.is*).

4.4.1 The African Series of Millennium Short Courses

During the planning of the first Workshop, the priority region was East Africa with its huge and to a large extent unused potential for geothermal power development, and urgent need for electric power. Cooperation was sought with Kenya, which has been the leading African country in geothermal development. The cooperation has generally meant that the costs of all invited foreign participants (travels and accommodation) and non-local lecturers (salaries, travels and accommodation) are covered by the UNU-GTP and the Icelandic Government, while the costs of the local Kenyan participation and some of the local arrangements are born by the Kenyan geothermal companies.

The first event in Africa, "*Workshop for Decision Makers on Geothermal Projects and their Management*", was held in Kenya in November 2005. At the Workshop, high-level decision makers from five countries met to learn about and discuss the main phases of geothermal development and what kind of manpower, equipment, and financing was needed for each phase, and analyse what was available in the region (Fridleifsson et al., 2005).

The result of the Workshop was that the Short Courses in East Africa should begin with a focus on surface exploration which was the field acutely needed for most countries in the region. The first Short Course was the ten day "*Short Course on Surface Exploration for Geothermal Resources*" held in November, 2006. The purpose was to give "a state of the art" overview of the methods used in surface geothermal exploration, and discuss the status and possibilities of geothermal development in East Africa. During the last 6 years, the annual Short Course in Kenya gradually developed into a more general course on geothermal exploration: "*Short Course on Exploration for Geothermal Resources*", which is now 3½ week long.

Participation in the Short Courses in Kenya has increased every year, not least due to the big pressure on capacity building in Kenya itself, which is needed for its intended fast-tracking of geothermal development in the next two decades. New countries have also been added to those invited most years, and in many cases, they have been participating for the first time in geothermal meetings in the UNU-GTP events. In total, 19 countries of Africa have now participated, the majority of them on a fairly regular basis. The highest number of participants in a single event is 69 in the 2013 Short Course, and the total number of participants in the Workshop/Short Courses is now over 420 persons. The Short Courses in East Africa have certainly proven to be a valuable addition to the capacity building activities of the UNU-GTP in Africa. They are now established as a good first training opportunity for young African scientists and engineers engaged in or being groomed for geothermal work, who are given an introduction to state-of-the-art exploration techniques for geothermal resources and the possible development of this valuable renewable energy source.

The UNU-GTP foresees a further development of the Short Courses in Africa, and expects that in the near future they will develop into a permanent regional school for geothermal training. The Kenyan cooperation partners are now preparing building of facilities which can make this possible, and if current plans hold, this should turn into a reality soon. For a further description of the UNU-GTP Workshops and Short Courses in Africa see Georgsson (2010; 2011; 2012a) or the UNU-GTP webpage (*www.unugtp.is*).

4.4.2 The Central-American Series of Millennium Short Courses

Similar to East Africa, in Central America geothermal resources are now playing an ever increasing role in the power production of countries like El Salvador, Costa Rica, Nicaragua and Guatemala, with considerable untapped potential. And Mexico has certainly been one of the world's largest producers of geothermal electricity for many years. The UNU-GTP has since its early years supported this region through training of many staff members of geothermal institutions, especially in El Salvador and Costa Rica. Hence, Central America was selected as the region for the second Series of Millennium Short Courses, with LaGeo S.A de C.V. in El Salvador chosen as a cooperation partner for this task. LaGeo (with its predecessors) has been responsible for geothermal development in El Salvador since the 1970s, and has all the know-how necessary to be an active and strong partner in hosting this series of courses, as it has certainly proven to be.

The "*Workshop for Decision Makers on Geothermal Projects in Central America*" was held in San Salvador in late November 2006 (Fridleifsson and Henriquez, 2006). The fifty participants in the 6 day event were mainly from the four countries in Central America most active in geothermal development, i.e. Costa Rica, El Salvador, Guatemala, and Nicaragua, and some of them were from the highest level. The Workshop was a sound success. In its conclusions, it said "*the importance of local geothermal energy resources and their possible potential in increased power production in the region is emphasized, along with the minimal environmental impact of geothermal, and the need for increased training and regional technical cooperation in this field."* Figure 7 shows most of the participants of the workshop.

With geothermal development in Central America at a more advanced stage compared to East Africa, it has not been necessary to put the same emphasis on surface exploration in the Short Courses. So the topics have differed from one event to another. The first one was titled "*Short Course on Geothermal Development in Central America: Resource Assessment and Environmental Management*", a week-long event held in El Salvador in late November 2007 (Fridleifsson et al., 2007). Regional participants were 45 + 17 lecturers, with additional international lecturers coming from Iceland, Kenya and the Philippines (Tables 5 and 6).

FIGURE 7: Participants in the first UNU-GTP Workshop in Central America in 2006

TABLE 5: Participants in the Millennium Short Courses in Central America 2007-2013

Country	2007	2009	2011	2012	2013	Total
Bolivia				1		**1**
Chile				5	5	**10**
Colombia			5	2	4	**11**
Costa Rica	6	7	6	1	2	**22**
Dominica		2	2	2	1	**7**
El Salvador	22	9	23	28	18	**100**
Ecuador			1	2	3	**6**
Guatemala	1	1	2	1	2	**7**
Honduras	2	2	5	2	4	**15**
Mexico	1		3	6	6	**15**
Nevis		2	2	1	2	**9**
Nicaragua	13	7	13	11	11	**55**
Peru					3	**3**
Others		2		3		**5**
Total	**45**	**32**	**62**	**65**	**61**	**264**

TABLE 6: Lecturers in the Millennium Workshops and Short Courses in El Salvador in 2006-2013

Short course / Workshop	Total	Home country	Neighb. countries	Intern.	Iceland	UNU-Fellows
El Salvador 2006	25	8	9	5	3	9
El Salvador 2007	16	3	5	3	5	7
El Salvador 2009	19	12	4	0	5	11
El Salvador 2011	25	12	6	1	6	14
El Salvador 2012	26	10	8	3	5	11
El Salvador 2013	22	10	6	1	5	14

The third event in Central America was delayed to 2009. The two week long "*Short Course on Surface Exploration for Geothermal Resources*" was held in October 2009 in El Salvador. It was a shorter version of the courses that had been held in East Africa in 2007-2009, with the main emphasis on geophysics and chemistry of thermal fluids, and aimed at young earth scientists in the region (Georgsson et al., 2009). The last day consisted of participation in the "Central American Geothermal Workshop", a cooperative event between LaGeo, the International Geothermal Association (IGA) and UNU-GTP, intended to highlight geothermal development in Central America. The Short Course reached a broader audience than the first two with participation from the East Caribbean Region. The third Short Course was the "*Short Course on Geothermal Drilling, Resource Development, and Power Plants*", a week long course given in January 2011. Here, the UNU-GTP reached for the first time to countries in South America (Georgsson et al., 2011). The topic also proved to be very interesting to many private companies in the geothermal business in the region, reflected in their increased participation, even at their own cost. This is a trend which continued in the last two events, the one week long *Short Course IV on Geothermal Development and Geothermal Wells*" in March 2012 (Georgsson et al., 2012), and "*Short Course V on Conceptual Modelling of Geothermal Systems*" in February 2013. Tables 5 and 6 show the number of participants and lecturers. Figure 8 shows the participants of the Short Course in 2013.

FIGURE 8: Participants and lecturers in the El Salvador Short Course in 2013

The Short Courses in El Salvador have brought new and important components to geothermal development in Central America. They have not only increased the available training capacity for the region, but also furthered cooperation between the countries of the region in geothermal development. The geothermal development in Central America is on average at a higher level than in East Africa, which means that the future need in capacity building is more varied. We foresee the need for Short Courses covering topics ranging from surface exploration to development, field management, production monitoring, environmental aspects, and even techniques for direct use. However, participation can also be expected to cover a wider geographical area where geothermal resources have not been developed to the same extent. Many of the small nations of the Eastern Caribbean region have important geothermal resources to be developed. Participants from this region can be expected to become a significant factor in the Short Courses in the near future. Similarly, participation from South America is also expected to increase, as interest in the development of both high- and low-temperature resources in this part of the world grows.

From a more general perspective, the Short Courses have become a new channel to the more advanced training in Iceland with the strongest participants showing their ability and strength, and thus opening the possibility to be selected for training in Iceland. There are now many examples of good participants in the Short Courses being selected for the 6 month training in Iceland. And in a few cases it has even led to MSc studies in Iceland, with the first graduation in April 2010. The Short Courses have also been an important element towards increased cooperation between the countries within the region.

4.5 Customer-designed Short Courses

The latest capacity building service of the UNU-GTP are the customer-designed Short Courses in developing countries, given for the first time in 2010. This new service of the UNU-GTP was triggered by an urgent need for training in countries planning fast-tracking of geothermal development, while it has also been an offspring of the regular training and Short Courses and the material prepared there. This has proven a good opportunity for some countries/ institutions in need of a rapid capacity building process, beyond what UNU-GTP can service under its conventional operations, and which have themselves the strength or the support of external sources (e.g. multilateral or bilateral aid agencies) to finance such events. The paying customer defines the outline of the Short Course, while UNU-GTP is a guarantee of the quality of the contents.

In 2010-2013, 13 such Short Courses or Advanced Training have been held for six different customers in three continents. The contents have varied from general geoscientific courses to more specialized ones, such as on geothermal drilling, as well as scaling and corrosion in geothermal installations. Similarly, the length has varied from one week to 6 months, based on the need and target group. An example is the week long “Short Course on Geothermal Exploration and Development” held in El Salvador in November 2011. The Short Course was sponsored by the Organization of American States (OAS) for the benefit of three South-American countries, Ecuador, Colombia and Peru, all of which have consequently been invited to send participants to the UNU-GTP Millennium Short Courses.

5. DISCUSSION

One of the major concerns of mankind today is the ever increasing emission of greenhouse gases into the atmosphere and the threat of global warming. It is internationally accepted that a continuation of the present way of producing most of our energy by burning fossil fuels will bring on significant climate changes, global warming, rises in sea level, floods, draughts, deforestation, and extreme weather conditions. One of the key solutions to avoid these difficulties is to reduce the use of fossil fuels and increase the sustainable use of renewable energy sources. Geothermal energy can play an important role in this aspect in many parts of the world.

Using indigenous renewable energy resources is an important issue and a possible solution for many countries, not least from the third world. This applies very much to Latin America and the eastern Caribbean Islands. The volcanic systems of Central America and along the Andes mountain chain, as well as the volcanoes of the eastern Caribbean Islands, are a powerful heat source for the numerous high-temperature geothermal systems found in the region. These renewable energy resources have the potential to supply clean and sustainable energy to countries in dire need for energy and at the same time reduce their dependence on fossil fuels. When considering the wealth of these resources, it can be argued that it is surprising, how slow the development has been in S-America and the Caribbean region.

Capacity building and transfer of technology are key issues in the sustainable development of geothermal resources. Many industrialised and developing countries have significant experience in the development and operations of geothermal installations for direct use and/or electricity production. It is important that they open their doors to newcomers in the field. We need strong international cooperation in the transfer of technology and the financing of geothermal development in order to meet the Millennium Development Goals and the threats of global warming.

The UNU-GTP is intent on assisting the Latin American and Caribbean countries in geothermal capacity building as best it can, so geothermal power can play a bigger role in the energy future of the region. This we will continue to do both through offering UNU Fellowships for 6 month training and postgraduate academic studies in Iceland, and through Short Courses in the region itself. Here, we especially hope to be able to intensify our effort with regard to countries in the early stages of development.

A *Geothermal Diploma Course* in Spanish and open for all the CentralAmerican countries was given twice in El Salvador in 2010-2012, with both financial and educational support from Italy (Caprai et al., 2012). Through the funding of the Nordic Development Fund (NDF) with supplementary funding, administration and management by the Inter-American Development Bank (IDB) this was continued in 2013, with 26 participants, 10 of whom came from outside El Salvador, from all over Latin America. This course will continue for at least the next two years. The long-term aim is however to work towards establishing a model for a sustainable post-graduate university programme, which could even progress to an MSc programme, to be established in El Salvador for the benefit of the Latin American countries, with the cooperation of UNU-GTP, LaGeo and Salvadorian universities, amongst others. This can prove an important basis for taking geothermal development in the region to a new level. The annual UNU-GTP Short Course could be foreseen to become an integral part of this diploma course.

REFERENCES

Bertani, R., 2010: Geothermal power generation in the world. 2005-2010 update report. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 41 pp.

Caprai, A., Flores Díaz, J.A., Montalvo, F., Alegría, R., Giunta, G., Campos, S.E., de Flamenco, C., Ramírez, T., de León Torres, F., Guidos, J., Monterrosa, M., de Arévalo, A.S., 2012 : *Proyecto creación de una actividad de formación en geotermia en el sistema academic Salvadoreño – En el marco del Diplomado de Especialización en Geotermia.* CNR-IGG, UES, Ministerio degli Affari Esteri – Cooperzione Italiana allo Sviluppo, LaGeo S.A. de C.V., Consejo Nacional de Ciencia y Tecnologia, Universitá di Palermo, 109 pp.

CEPAL, 2010: *Centro América: Estadísticas del subsector electric, 2009*. United Nations, Comisión Económica para América Latina y el Caribe, Sede Subregional en México, 79 pp.

Fridleifsson, I.B., 2002: Energy requirements for the new millennium. In: *Human development and the environment: Challenges for the United Nations in the new millennium*. United Nations University Press, Tokyo, 220-233.

Fridleifsson, I.B., 2010: Thirty one years of geothermal training in Iceland. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 10 pp.

Fridleifsson, I.B., Bertani, R., Huenges, E., Lund, J.W., Ragnarsson, A., and Rybach, L., 2008: The possible role and contribution of geothermal energy to the mitigationof climate change. In: Hohmeyer, O., and Trittin, T. (eds.), *IPCC Scoping Meeting on Renewable Energy Sources, Proceedings*. Luebeck, Germany, 59-80.

Fridleifsson, I.B., Georgsson, L.S., and Mwangi, M.M. (eds.), 2005: Papers presented at *„Workshop for Decision Makers on Geothermal Projects and their Management“*. UNU-GTP and KenGen, Naivasha, Kenya, November 14-18, 2005. UNU-GTP, CD SC-01.

Fridleifsson, and Henriquez, J.L. (eds.), 2006: Papers presented at *„Workshop for Decision Makers on Geothermal Projects in Central America“*. UNU-GTP and LaGeo, San Salvador, El Salvador, November 26 – December 2, 2006. UNU-GTP, CD SC-02.

Fridleifsson, I.B., Holm, D.H., Henriquez, J.L., and Torio, E.C. (eds.), 2007: Papers presented at *„Short Course on Geothermal Development in Central America: Resource Assessment and Environmental Management"*. UNU-GTP and LaGeo, San Salvador, El Salvador, November 25 – December 1, 2007. UNU-GTP, CD SC-04.

Gawell, K., Reed, M., and Wright, P.M., 1999: *Preliminary report: Geothermal energy, the potential for clean power from the Earth*. Geothermal Energy Association, Washington D.C., 15 pp.

George, A., 2012: Geothermal energy in Dominica. *Presented at the 3rd Caribbean Sustainable Energy Forum, St. Kitts, September 2012.*

Georgsson, L.S., 2010. UNU Geothermal Training Programme – Taking the training to the developing countries. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 9 pp.

Georgsson, L.S., 2011: Importance of capacity building in geothermal: UNU-GTP contribution in Kenya and Africa. *Proceedings of the Kenya Geothermal Conference 2011,* 10 pp.

Georgsson, L.S., 2012a: Geothermal training for Africans – The operations of the UNU-GTP in Iceland and Africa and possible future development. *Proceedings of the ARGeo C-4, 4th East African Geothermal Conference, Nairobi, Kenya,* 9 pp.

Georgsson, L.S., 2012b: UNU-GTP and capacity building for geothermal development in the Caribbean islands. *Presented at the 3rd Caribbean Sustainable Energy Forum, St. Kitts, September 2012.*

Georgsson, L.S., de Velis, E., Haraldsson, I.G., Holm, D.H., and de Henriquez, E. (eds.), 2011: Papers presented at *"Short Course on Geothermal Drilling, Resource Development and Power Plants"*. UNU-GTP and LaGeo, San Salvador, El Salvador, January16-22, 2011. UNU-GTP, CD SC-12.

Georgsson, L.S., de Velis, E., Wilde, M.A.G., de Henriquez, E., (eds.), 2009: Papers presented at *„Short Course on Surface Exploration for Geothermal Resources".* UNU-GTP and LaGeo, San Salvador, El Salvador, October 17-30, 2009. UNU-GTP, CD SC-09.

Georgsson, L.S., Haraldsson, I.G., de Velis, E., Wilde, M.A.G., and de Henriquez, E. (eds.), 2012: Papers presented at *"Short Course on Geothermal Development and Geothermal Wells".* UNU-GTP and LaGeo, San Salvador, El Salvador, March 11-17, 2012. UNU-GTP, CD SC-14.

Haraldsson, I.G., 2013: Geothermal activity in South America: Bolivia, Chile, Colombia, Ecuador, and Peru. Papers presented at *"Short Course on Conceptual modelling of Geothermal Systems", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador, Feb. 24 – March 2,* 18 pp.

IEA, 2013: Key world energy statistics 2013. International Energy Agency, Paris, 82 pp. Web: http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf

Lippmann, M.J., 2002: Geothermal and the electricity market in Central America. *Geothermal Resources Council, Transactions*, *26,* 37-42.

Lund, J.W., Freeston, D.H., and Boyd, T.L., 2010: Direct utilization of geothermal energy 2010 worldwide review. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 23 pp.

Maynard-Date, A., 2012: Geothermal development progress in Eastern Caribbean Islands. Papers presented at *"Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador, March 11-17,* 8 pp.

Nakicenovic, N., Grübler, A., and McDonald, A. (editors), 1998: *Global energy perspectives*. Cambridge Univ. Press, 299 pp.

Ngugi, P.K., 2012: Kenya's plans for geothermal development – a giant step forward for geothermal. *Proceedings of "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo 11-17 March, 2012, El Salvador,* 8 pp.

Ragnarsson, Á., 2010: Geothermal development in Iceland 2005-2009. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 12 pp.

WEA, 2000: *World energy assessment: energy and the challenge of sustainability*. Prepared by UNDP, UN-DESA and the World Energy Council**.** United Nations Development Programme, New York, 508 pp.

WEA, 2004: *World energy assessment: overview 2004 update*. Prepared by UNDP, UN-DESA and the World Energy Council**.** United Nations Development Programme, New York, 85 pp.

WEC, 2007: *2007 Survey of energy resources*. World Energy Council 2007, 427-437. (Available on *www.worldenergy.org*).

WEC, 2013: *World energy scenarios. Composing energy futures to 2050.* World Energy Council, UK, 281 pp.

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

CURRENT STATUS OF GEOTHERMAL RESOURCES DEVELOPMENT IN CENTRAL AMERICA

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ABSTRACT

Central America is rich in geothermal resources, however only a small portion has been developed and is currently used for electricity generation. In countries like El Salvador, Nicaragua, Costa Rica and Guatemala, the geothermal exploration led to the first resource evaluation and the beginning of commercial exploitation of some areas such as Ahuachapán in 1975, Momotombo in 1983, Berlin in 1992, Miravalles in 1994, Zunil in 1998, San Jacinto Tizate in 2005, Amatitlán in 2006 and recently Las Pailas in 2011. Currently, the region has a gross installed capacity of 624.1 MWe, generating an annual average of 410.2 MWe. From the existing geothermal potential in Central America, the electricity generated provides an average of 12% of the total produced, and more significant in countries like El Salvador, Costa Rica and Nicaragua where it contributes 24%, 14% and 13% respectively of the total electricity consumption in each country for the year 2012. Geothermal generation capacity in Central America in 2012 was 3542 GWh which is equivalent to 7.9% of the total electricity generated by different sources. The potential resource in Central America has been estimated very close to the total amount currently used in electric power, that is, about 5057 MWe.

1. INTRODUCTION

Central America belongs to the so-called Pacific Ring of Fire and has been affected throughout its history by intense seismic and volcanic activity, resulting in catastrophic events that have impacted negatively on the economic, social and cultural development of the region.

The geodynamic situation of the isthmus and the occurrence of these natural phenomena can be attributed mainly to the subduction of the Cocos plate beneath the Caribbean plate (whose boundaries are known as the Middle America Trench, which are within the Pacific Ocean), and the presence of faults (fractures of the crust) that are active in the Motagua-Chamalecón Polochic fault system, thus separating the Caribbean plate from the North American plate.

In Figure 1, the Cocos and the Caribbean tectonic plates collide, about 100 km parallel to the Pacific coast of Central America. The black arrows indicate the direction of movement. Volcanoes are formed in a narrow strip parallel to the shock zone. The process of subduction occurs when the Cocos plate disappears beneath the continental crust producing a fusion of mass and extensional faulting. Along the trench, the subduction of the Cocos oceanic plate beneath the Caribbean plate is given at a rate of 73-84 mm/year (De Mets, 2001). The convergence movement of the Cocos plate is to the northeast. Some of the material of the Cocos plate melted by the high temperatures of the Earth's mantle, rises almost vertically and enters the Caribbean plate along a nearly straight line, forming the Central American volcanic chain that runs northwest -southeast.

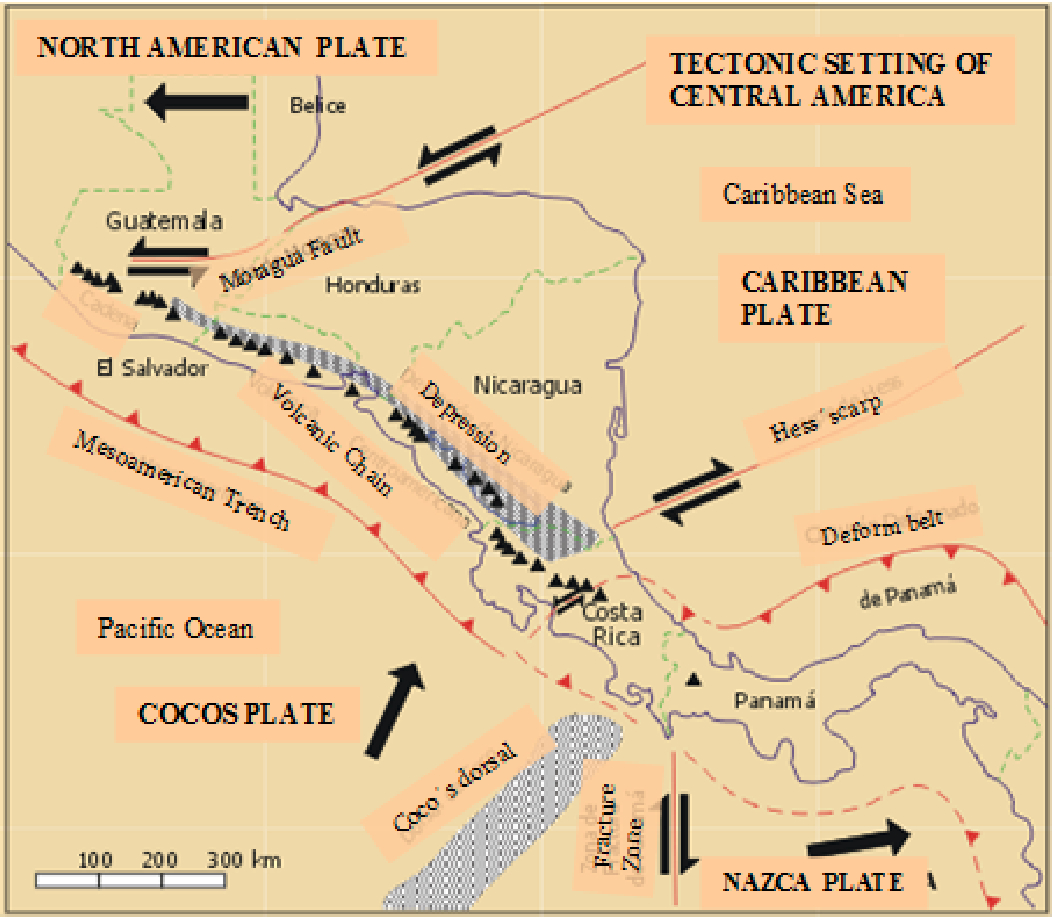

FIGURE 1: Subduction of the Cocos plate over the Caribbean plate and the volcanic chain (modified from CEPREDENAC)

2. GEOTHERMAL RESOURCES IN CENTRAL AMERICA

Central America is rich in geothermal resources, however only a small portion has been developed and is currently used for electricity generation. The subduction process as mentioned above is responsible for the creation of the volcanic chain in the region which provides a potential source of energy because the exploited geothermal fields, are located in areas of anomalous heat flow in the vicinity of shallow magma chambers associated with volcanoes, producing temperatures between 200-300°C at depths between 500 and 3,000 m, where the heat is transported by conduction in the rocks and convection in the geothermal fluids.

In countries like El Salvador, Nicaragua, Costa Rica and Guatemala, the geothermal exploration began in the late fifties and early sixties, resulting in the identification of several promising areas for the start of drilling that led to the first resource evaluation and the beginning of commercial exploitation of some areas such as Ahuachapán in 1975, Momotombo in 1983, Berlin in 1992, Miravalles in 1994, Zunil in 1998, San Jacinto Tizate in 2005, Amatitlán in 2006 and recently Las Pailas in July 2011 and San Jacinto Tizate in January (U3) and December 2012 (U4).

Figure 2, shows the location of the geothermal fields currently in operation and main geothermal areas that have been subject to exploration in Central America. Those with high temperature (> 200°C) have been utilized for generating electricity and very low application of low temperature resources have been done.

FIGURE 2: Location of the geothermal fields in operation and main geothermal areas in Central America (modified from Google)

Currently, governments in the region show more interest in developing renewable energy resources in their countries, especially in geothermal energy. This change is probably the result of high oil prices, instability in this market, uncertainties in future climate conditions (which could affect the output of hydroelectric projects), and the need of reducing CO_2 emissions by overriding the environmental impacts associated with burning wood and fossil fuels to generate electricity.

3. GEOTHERMAL RESOURCES AND CURRENT ESTIMATED POTENTIAL

Geothermal resource development in Central America should contribute significantly to achieving the Millennium Development Goals, generating electricity based on geothermal fluids that are clean, renewable, sustainable and an indigenous source of energy.

Their use can provide several advantages:

- offset the price of electricity;
- protect the Central American countries against future rises in the oil market;
- contribute to reduced environmental pollution; and
- create more job opportunities especially in rural areas where the development of the geothermal projects are carried out.

Lippmann (2002) reports the total electricity generation capacity that can be achieved in Central America from geothermal resources, could be in the range of 2000 to 16000 MW, giving a most likely value around 4000 MW. Table 1 shows the estimated geothermal potential of different sources including the geothermal potential to be developed given the current installed capacity. It can be seen that the total estimated potential for the region by the various energy sources is up to 4594 MWe and an average of 3510 MWe (various sources for TE in Table 1).

TABLE 1: Estimated geothermal Potential (MWe) for electricity generation

Geot. Pot. (MWe)	**TE**	**FD**	**TE**	**FD**	**TE**	**FD**	**TE**	**FD**	**TE**	**FD**
Nicaragua	1750	1586	1200	1036	992	828	1000	836	1519	1355
Costa Rica	1000	796	235	31	750	546	235	31	865	659
Guatemala	1000	951	1000	951	480	431	1000	951	1000	951
El Salvador	500	296	333	129	362	158	450	246	644	440
Honduras	130	130	120	120	122	122	126	126	116	116
Panama	50	50	40	40	42	42	40	40	450	450
Total	4430	3808	2928	2306	2748	2126	2851	2230	4594	3971
Source:	**Lippman 2002**		**CEPAL 2004**		**JICA 2005**		**SICA 2006**		**Essen 2013, mod. IILA 2009**	

Note: Geot. Pot. = Geothermal potential; TE = Total Estimated; FD = Future Development

4. GEOTHERMAL RESOURCES AND CURRENT ELECTRICAL GENERATION

Currently, from the existing geothermal potential in Central America, only a relatively small amount has been used to generate electricity providing an average of 13%, but seems to have significant savings in fossil fuels, especially in countries like El Salvador, Costa Rica, Nicaragua and Guatemala contributing 23.97, 13.92, 12.7 and 2.82% respectively of total electricity consumption in each country (Table 2).

The data in Table 2, includes information regarding the installed capacity for the new power plants in Costa Rica and Nicaragua (Las Pailas and San Jacinto Tizate, respectively).

TABLE 2: Geothermal Power Generation in 2012 (CEPAL)

Country	Installed Capacity (MWe)	Available Capacity (MWe)	Annual Energy produced (GWh/y)	National participation rate (%)
El Salvador	204.4	168.0	1420.4	24.29
Costa Rica	206.0	160.1	1402.6	13.92
Nicaragua	164.5	54.1	473.8	12.70
Guatemala	49.2	28.0	245.6	2.82
Total	624.1	410.2	3542.4	

Note: CEPAL 2012 reports a geothermal installed capacity for Costa Rica of 217.5 MW.

By the year 2009, the region has an installed capacity of 506.6 MW, generating an annual average of 417.5 MWe. In 2010, the installed capacity remained the same and the annual generation was a little bit lower at 357.4 MWe. Currently, the installed capacity has increased in 2012 up to 624 MW, generating annually 410 MWe and 3542 GWh which is equivalent to 7.9% of the total electricity generated by different sources. Figure 3 shows the evolution of installed capacity and annual average generation in the last 5 years in C.A.. Even though the installed capacity has increased, the generation does not show the same trend. This is an important point of discussion, as there may be several influencing factors such as technical, economic and regulatory aspects.

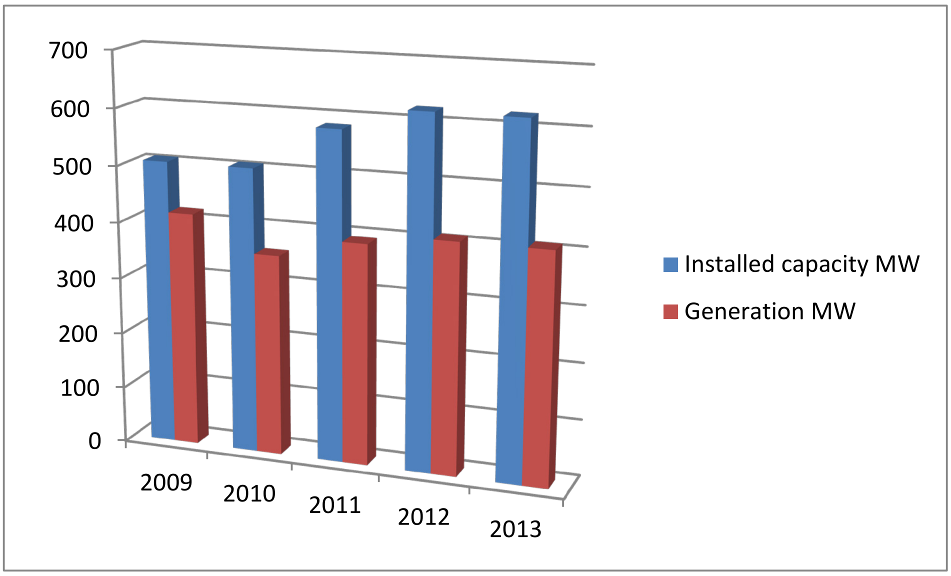

FIGURE 3: Evolution of installed capacity and annual average generation since 2009

On the other hand, as shown in Figure 4, the geothermal generation is the third in importance as a percentage compared to other types of energy used in Central America.

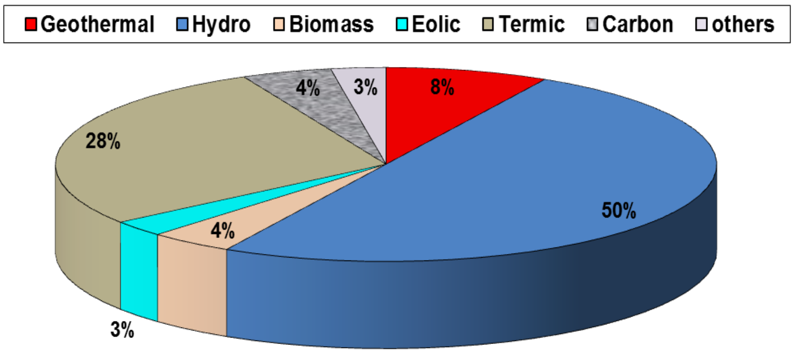

FIGURE 4: Electrical generation by energy source in Central America 2012

Figure 5 shows the percentage for each country of the total generated electricity from geothermal resources in 2012.

Figure 6 shows the percentage of the different geothermal fields on the total generated electricity from geothermal resources in 2012.

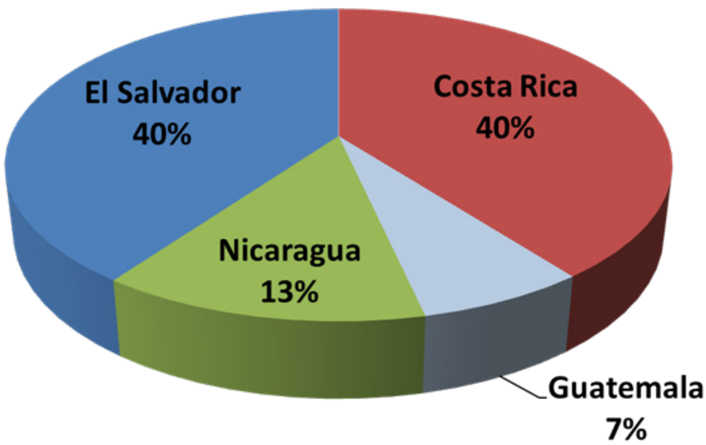

FIGURE 5: Electrical generation by geothermal resources in Central America 2012

The contribution of geothermal power to the national grid of each country in Central America contains the updated data for 2012 both in geothermal generation (GWh) and percentage (Figure 7 and Figure 8).

It should be noted that El Salvador, Costa Rica, Nicaragua and Guatemala are considered among the top 10 countries in the world producing a good percentage of the total electricity consumption in each country (Figure 9).

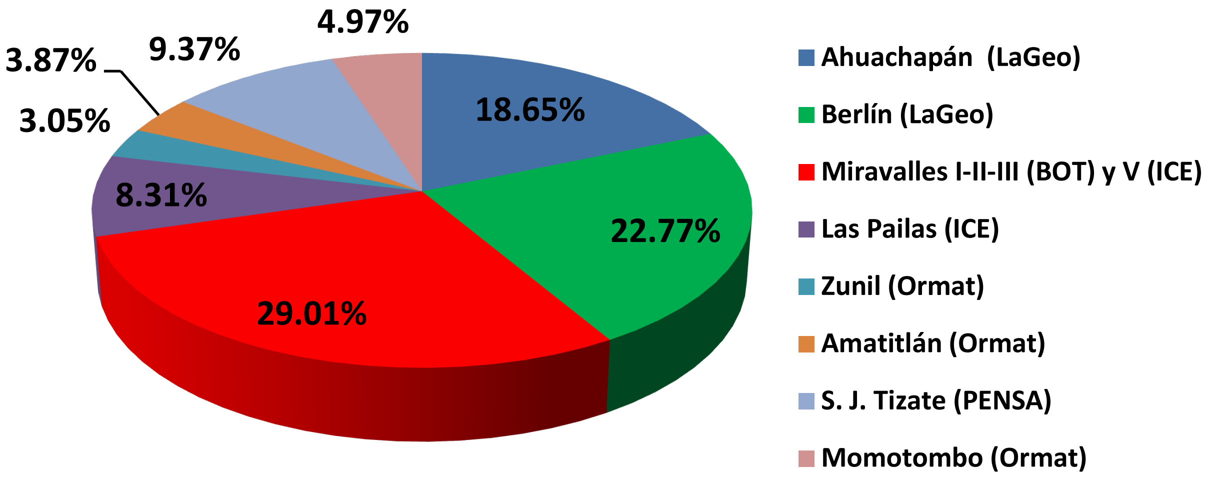

FIGURE 6: Percentage of geothermal production for each field in Central America by 2012

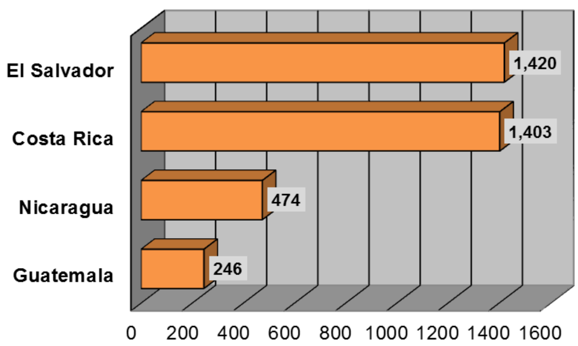

FIGURE 7: Geothermal energy production for electrical uses in 2012 (GWh)

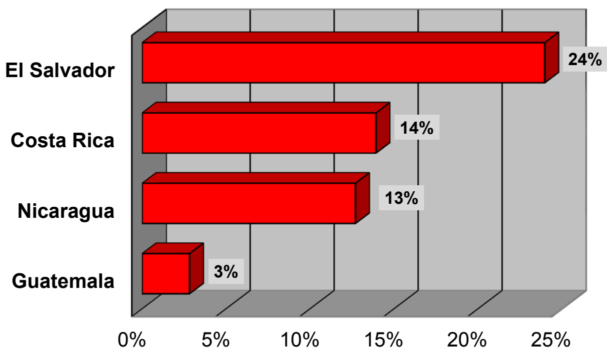

FIGURE 8: Percentage of contribution and electrical generation for 2012

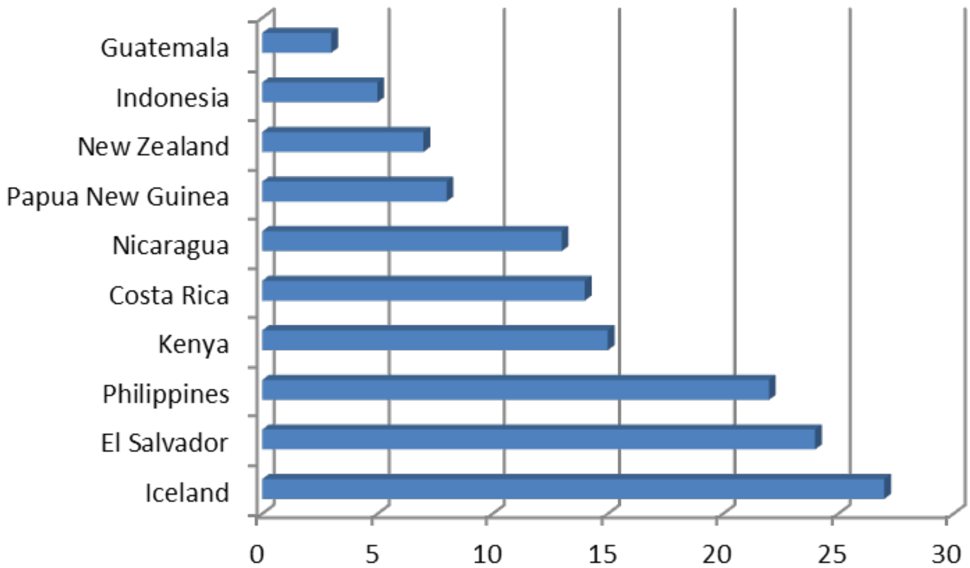

FIGURE 9: Top 10 countries with the highest percentage contribution of geothermal power to the national grid (modified from Bertani, 2007)

5. GEOTHERMAL DEVELOPMENT HISTORY

The geothermal development in Central America since 1975 is shown in Figure 10. The increase in installed capacity was faster in the first twenty five years, with an increment of around 400 MWe, after that, developing projects seemed to be of minor importance. Similar behavior was reported for the geothermal generation increasing from 72 to 3542 GWh in 37 years.

Worldwide, only 25 countries use geothermal power for electricity production (IGA). In 2010, total global capacity was 10,717 megawatts (Figure 11).

Even if Larderello (Italy) started the first commercial geothermal plant in the first part of twentieth century, within the last 50 years of commercial electricity generation, several plants installed in different countries have established and proven the geothermal industry as a cost-competitive renewable power generation technology.

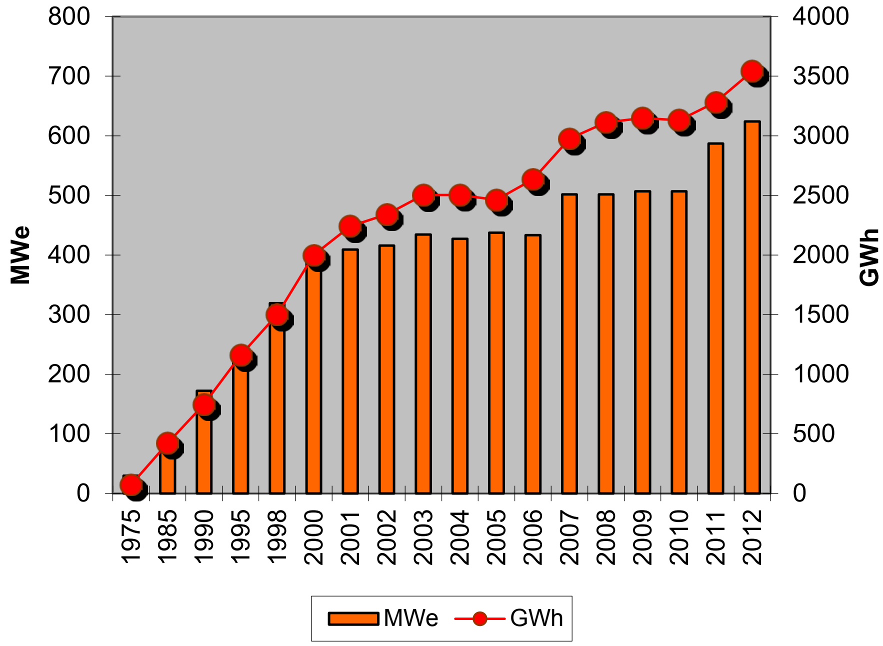

FIGURE 10: Geothermal development history and generation in Central America

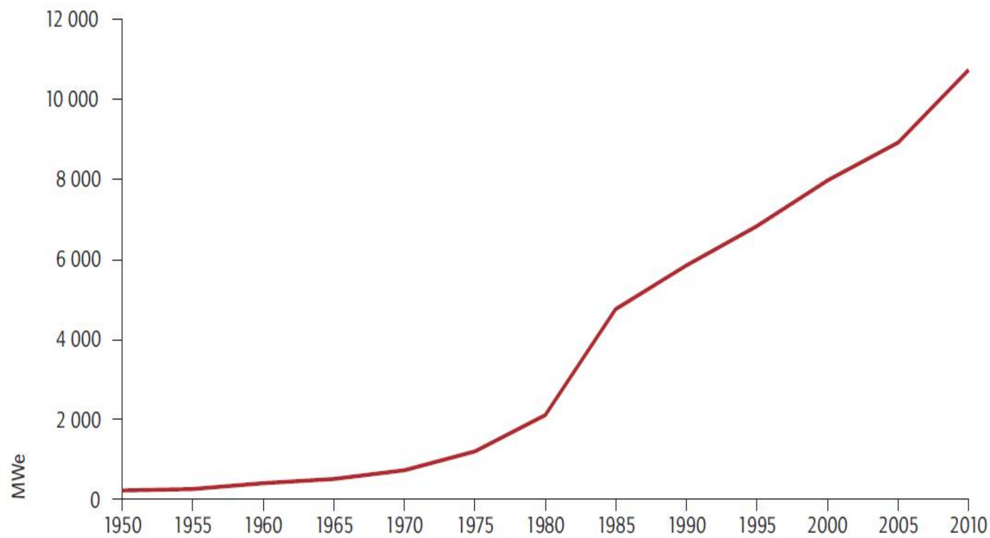

FIGURE 11: World geothermal development – Installed capacity

The majority of generation capacity is concentrated in a few countries: the U.S., the Philippines, Indonesia, Italy, Mexico, Iceland, Japan and New Zealand (Figure 12). After the first experiment of geothermal exploitation was carried out at Larderello in 1904, the first industrial power plant (250 kW) was put into operation in 1913, and geothermal power production has since increased continuously up to the present value of 810 MW installed capacity (711 MW running capacity). The first geothermal power plants in the U.S. were built in 1962 at The Geysers dry steam field, in northern California. It is still the largest producing geothermal field in the world, with a peak capability of nearly 1,100 MW, enough electricity to supply a city of over a million inhabitants. The largest field that generates the most electricity in Latin America is Cerro Prieto, Baja California, Mexico (720 MW).

While these established markets will continue to account for the geothermal growth in the short term, several regions, including Central America, the Caribbean and East Africa, and others countries like Chile, Argentina, Turkey, Russia and Canada are looking to exploit robust. geothermal resource potential as power generation demand and global fuel price increases (Stephure, T., 2009; Figure 12).

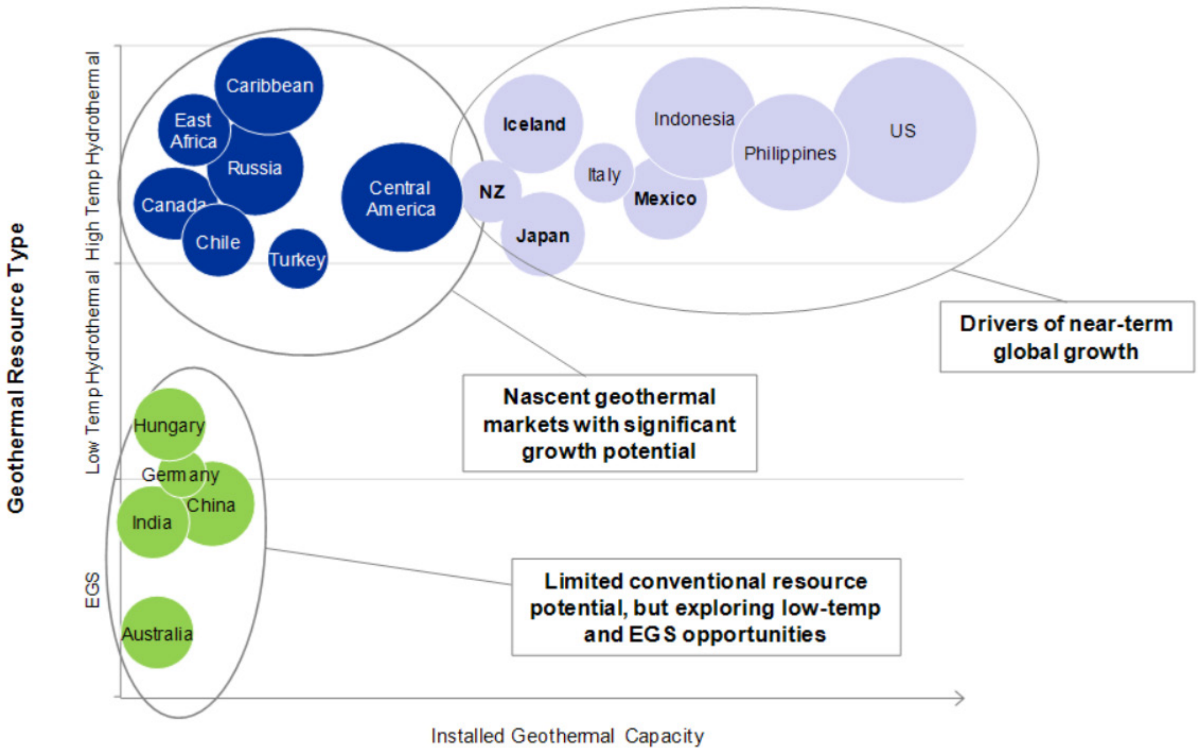

FIGURE 12: Global Geothermal Country Rankings by Installed Capacity and Pipeline.
Note: Bubble size reflects MW resource potential (Stephure, 2009)

The Figure 12, also shows other countries like Hungary, Germany, India, China and Australia exploring low enthalpy resources technology or with Enhance Geothermal system (EGS). Geothermal exploration is increasing, mostly due to improved technology and techniques. Several projects are underway around the world, but face financing, drilling risk, skilled labor shortages and other factors like environmental regulations mainly related to the location of geothermal resources in national parks that could limit the development over the next decade.

Figure 13 shows the world geothermal-electric installed capacity by 2012. The countries of Costa Rica, El Salvador and Nicaragua are currently placed in position ten, eleven and twelve in the geothermal world, respectively.

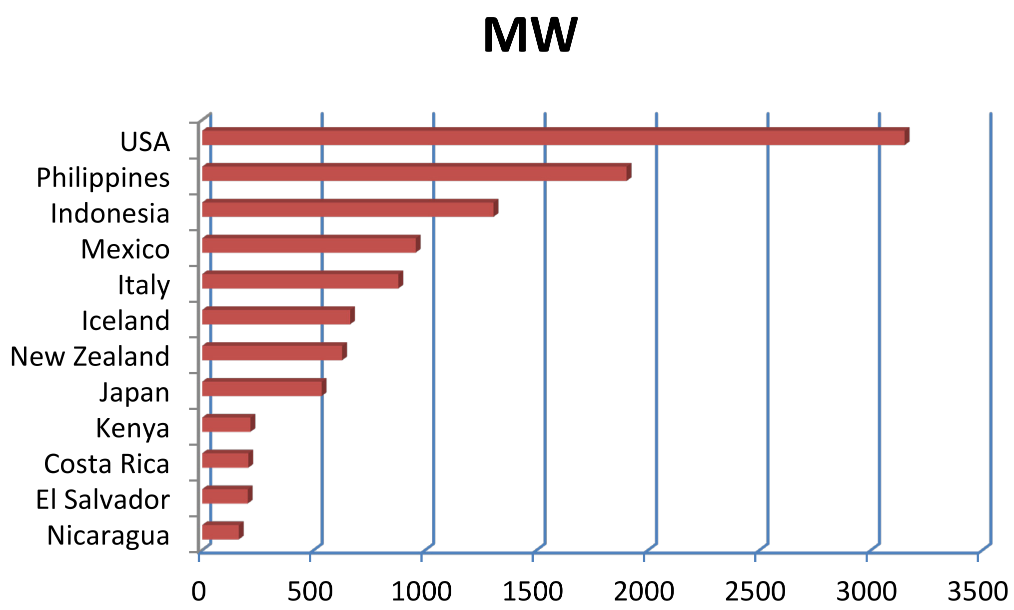

FIGURE 13: World geothermal installed capacity (modified from IGA, 2012)

6. FUTURE DEVELOPMENT IN CENTRAL AMERICA

According to Earth Policy Institute (EPI) estimates 2007 (www.earthpolicy.org), the MW required to meet the total demand for electricity in each country for 2010 are shown in Figure 14. The importance for the governments and private companies to accelerate research and development of geothermal resources in the region should be noted. As mentioned earlier, the potential resources in Central America has been estimated very close to the total amount currently used in electric power that was reported for EPI, about 4317 MWe (5057 MWe for the year 2012).

Figure 14, shows the MWe required from geothermal resources in the Central American countries to achieve the annual current total demand of electricity by 2010 (according to EPI 2007). See Table 1.

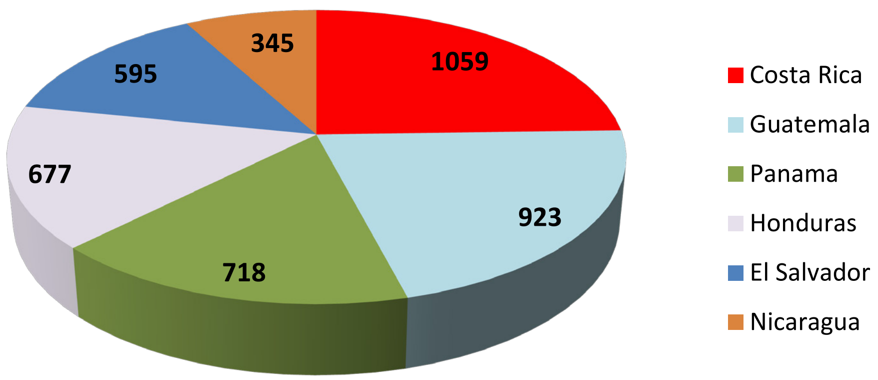

FIGURE 14: MWe required from geothermal resources in the Central American countries to achieve the annual current total demand of electricity by 2010 (EPI, 2007)

Bertani (2010) presents a forecasting for the geothermal installed capacity in Central American countries by the year 2015 as shown in Table 3. These estimations gave an increase in installed capacity of 261 MWe over the coming years (considering the total installed capacity by 2012 of 624 MWe).

Some new projects that are underway and will be developed in the near future are described in Table 4, which would imply an increase in geothermal capacity in the region of about 352 up to 649 MWe over the coming years.

TABLE 3: Geothermal installed capacity forecasting by the year 2015 (Bertani, 2010)

Country	MWe
Costa Rica	200
El Salvador	290
Guatemala	120
Nicaragua	240
Honduras	35
Total	885

Currently, in Costa Rica there are two operating geothermal fields, Miravalles in which five power plant units are operated with a total installed capacity of 163.5 MWe. In the second half of 2011 (25th July) the first plant in the Las Pailas geothermal field was commissioned, located on the Pacific side on the slopes of the Rincón de la Vieja Volcano in the Guanacaste province, with a gross capacity of 42.5 MWe and 35 MWe net power (Sánchez, ICE, 2013). The power plant is formed by two ORMAT binary units with a net generation of 150.6 Gw/h in 2011 and 285 GWh in 2012 (Mainieri, ICE 2012; Castro ICE, 2013). Instituto Costarricense de Electricidad (ICE) is also exploring two steam fields in the country's west, financed by the Japanese government, under an agreement of understanding between the Costa Rican Electricity Institute (ICE) and the International Cooperation Agency of Japan (JICA) in order to install two new geothermal plants, called Las Pailas II and Borinquen.

TABLE 4: Future development projects in Central America

Country	New Geothermal Development
Costa Rica	Las Pailas II 35-55 MW; Borinquen 55-110 MW; Tenorio; Arenal
El Salvador	Chinameca 50 MWe, San Vicente 30 MWe; Berlin U5, 28 MWe + Binary Cycle 2, 5.7 MWe; Optimization Ahuachapán Phase III 5 MWe
Guatemala	Amatitlán 20-50 MWe; Tecuamburro; Moyuta; San Marcos; La China; La Gloria; Joaquina; Atitlán
Nicaragua	San Jacinto Tizate Binary Cycle 10 MWe; Casitas-San Cristóbal 33-225 MWe; El Hoyo-Monte Galán; Managua-Chiltepe; Mombacho; Caldera de Apoyo
Honduras	GeoPlatanares 35 MWe; Azacualpa 20 MWe; Pavana 20 MWe
Panamá	Barú Colorado 5 MWe

El Salvador has increased its total geothermal power capacity since 2007 from 151.2 MWe to 204.4 MWe, building two new units in the Berlin area and the optimization project in Ahuachapán which has reached levels of up to 85% of total capacity installed. El Salvador is continuing to develop geothermal energy projects in the areas of San Vicente and Chinameca, where drilling to confirm the resource and exploitation is scheduled to continue in 2012-2014, where temperatures of about 250 ° C and 230 ° C respectively have been recorded in the recently drilled wells in both fields.

For Guatemala, the potential of geothermal energy has been estimated at 400 MWe, has been successfully utilized so far in the Zunil and Amatitlan fields. Feasibility studies are conducted in the Tecuamburro, San Marcos and Moyuta geothermal fields. In addition, the 30 MWe expansion of Amatitlán is planned. The government of Guatemala has granted four concessions in 2011-2012, which will focus on analyzing the potential for possible development. The concessions are the Atitlan, Joaquina, La Chinita, El Ceibillo and La Gloria projects.

In Nicaragua, in addition of Momotombo, the exploitation of the geothermal field of San Jacinto-Tizate property of Polaris Energy Nicaragua (PENSA) has begun, with the installation of two wellhead units with a total installed capacity of 10 MWe. Actually, two more units have started operation by 2012, expanding the gross installed capacity to 87 MWe. Concessions have recently been given to the Mombacho volcano, Caldera de Apoyo and San Cristóbal-Casitas.

Honduras will develop its first geothermal power plant in the Platanares geothermal field, located in a different geological structure of the typical features of high-temperature fields associated with volcanic structures. Geoplatanares, the company that holds the concession will in the future start to drill exploration wells to confirm the feasibility and proceed to commercial development. Exploration activities are on the way in the Azacualpa and Pavana geothermal areas. In the future, the completion of feasibility studies, environmental and financial, exploration drilling, production drilling, infrastructure adequacy of access, connection to the national transmission system, supply of equipment, plant construction and commercial operations are programmed.

In Panamá, the Government is structuring Terms of Reference for the assessment of geothermal potential in the country and a pre-feasibility study for electricity production of a Barú-Colorado geothermal field by Centram Geothermal INC. (5 MW) near the Barú Volcano. Preliminary studies suggest a country potential from 100 MW to 450 MW.

In Central America, geothermal constitutes the second most important renewable energy source in the region. To date, there has been progress such as the exploration, development and exploitation potential of this resource estimated in the order of 3000-4000 MW distributed among Costa Rica, Guatemala, El Salvador and Nicaragua; in the case of Panama and Honduras, there are only preliminary estimates, but the geological-tectonic point of view, indicates that there are also potential resources for electricity generation, but probably at a limited scale compared with the others due to the volcanic activity.

The Figure 15 shows the total estimated geothermal potential (from Table 1, Essen 2013) and the geothermal potential that could be developed in the future. If we can assume an average of the total estimated geothermal potential of 3510 MWe and taking into account the installed capacity by 2012, the geothermal potential to be developed in the future could reach about 2886 MWe (82% of the total estimated). Although currently the geothermal energy in Central America has been successfully developed in several countries, there is still much work to do according to estimates of existing geothermal potential in the region.

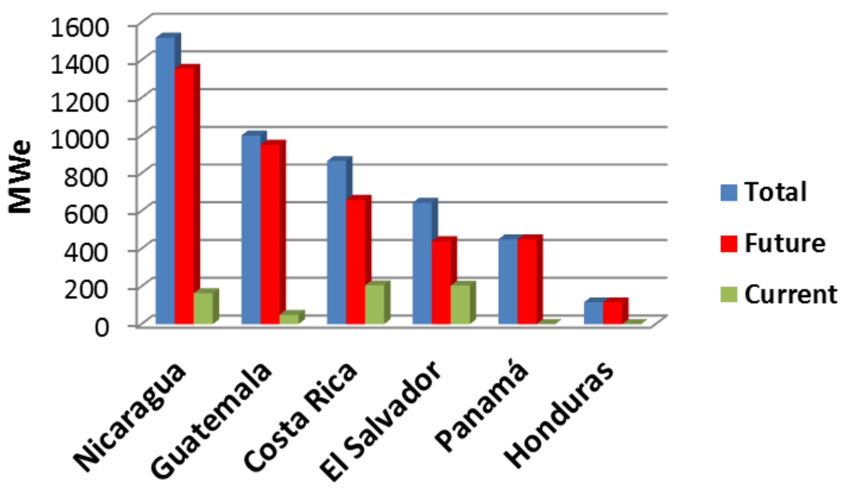

FIGURE 15: Total estimated geothermal potential and to be developed in MWe (modified from IILA, 2010)

The potential resource in Central America, has been estimated very close to the total amount currently used in electricity power generation, which is about 5057 MWe (CEPAL, 2012).

7. DIRECT USE OF GEOTHERMAL ENERGY IN CENTRAL AMERICA

Direct use of geothermal energy is well known in ancient times, in Central America pre-Columbian cultures used the hot springs for medicinal, culinary, religious or social purposes. Some of the sites are currently geothermal areas in El Salvador, and were known to the Indians who inhabited these areas as "ausoles". The word according to some historians, comes from the Nahuatl "atl" (water) and "Soloni" (loud boiling sound) as the Dictionary of the Royal Academy of Spanish Language (RAE) which considers salvadoreñismo to mean loud boiling water, because the soil water boiling springs form impressive fumaroles (Jose Perez Bouza: Spanish Influences on the Nahuatl of El Salvador 1994).

In general, direct use of geothermal energy currently used in Central America include mostly the drying of fruits, cement blocks and pools or hot springs.

Due to the warm temperate climate of Central America there is no current application of heating systems for buildings and greenhouses, but a few research studies for cooling spaces have been made.

More specifically, some studies have been performed and are using the resource for moderate to low temperature use as follows:

- Costa Rica, practically limited to the use of thermal pools, although there are technical studies for drying fruits and grains in the geothermal field of Miravalles;
- El Salvador has thermal baths and some tests in domestic application in the drying of fruits in the Berlin geothermal field in a natural dehydration process;
- Guatemala has thermal baths at different sites also applies to industrial drying of fruits and concrete blocks in the geothermal field of Amatitlán;
- Honduras has several places with hot springs in Copan and Gracias; and
- In Panamá, thermal water has been used in the touristic industry. Natural thermal baths are very famous in El Valle de Antón.

Lund et al (2010) has estimated that in Central America there is currently a total installed capacity of 7.2 MW thermal, with a total amount of energy use of 162.5 TJ / year equivalent to 45.1 GWh per year (Table 6).

TABLE 5: Direct uses in Central American countries (Lund et al, 2010)

Country	**Capacity MWt**	**Annual TJ/año**	**Annual GWh/año**	**Capacity factor**
Costa Rica	1.0	21.0	5.8	0.67
El Salvador	2.0	40.0	11.1	0.63
Guatemala	2.3	56.5	15.7	0.78
Honduras	1.9	45.0	12.5	0.74
Total	7.2	162.5	45.1	0.71

REFERENCES

Bertani, R., 2007: *Long term projections of geothermal-electric development in the world*. Enel Green Power, Italy 2007.

Bertani, R., 2010: Geothermal power generation in the world 2005–2010 Update Report. *Proceedings World Geothermal Congress 2010 Bali, Indonesia*, 41 pp. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0008.pdf

Castro, S., 2013: *Personal communication*. Instituto Costarricense de Electricidad (ICE), February 2013.

CEPAL, 2007: *Estrategia energética sustentable Centroamericana 2020*. Naciones Unidas - Comisión Económica para América Latina y El Caribe (CEPAL) and Secretaría General Sistema de Integración Centroamericano (SICA), report LC/MEX/L.828, 115 pp. Website: http://www.enee.hn/PDFS/EstrategiaCentroamericana2020.pdf

CEPAL, 2012: *Centroamérica: Estadísticas del subsector eléctrico, 2012*. Naciones Unidas - Comisión Económica para América Latina y El Caribe (CEPAL), report LC/MEX/L.1039, 89 pp. Website: http://www.eclac.org/publicaciones/xml/3/49833/Centroamerica-EstadisticasdeProduccion.pdf

DeMets, C., 2001: A new estimate for present-day Cocos-Caribbean plate motion: Implications for slip along the Central American volcanic arc. *Geophysical Research Letters, 28*, 4043–4046.

IGA, 2012: *IGA News*. International Geothermal Association, Quarterly No. 90, 15 pp. Web: http://www.geothermal-energy.org/publications_and_services/iga_newsletter.html

IILA, 2010: *Estado actual y desarrollo de los recursos geotérmicos en Centro América*. Instituto Italo Latino Americano (IILA). Cuadernos IILA Nueva Serie Técnico-Científica n°5.

Lippmann, M.J., 2006: United Nations Millennium Development Goals and geothermal development in Central America. *Presented at "Workshop for decision Makers on Geothermal Projects in Central America", organized by UNU-GTP and LaGeo in San Salvador, El Salvador*, 7 pp. Website: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-02-02.pdf

Lund, J.W., Freeston, D.H., Boyd, T.L., 2010: Direct Utilization of Geothermal Energy 2010 Worldwide Review. *Proceedings World Geothermal Congress 2010 Bali, Indonesia*, 23 pp. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0007.pdf

Mainieri, A., 2011: *Personal communication*. Instituto Costarricense de Electricidad (ICE), February 2011.

Montalvo, F., 2011: Current status of geothermal resources development in Central America. *Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador*, 10 pp. Website: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-12-03.pdf

Montalvo, F., 2012: Current status of geothermal resources development in Central America. *Presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, El Salvador*, 13 pp. Website: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-14-04.pdf

Montalvo, F., 2013: Current status of geothermal resources development in Central America. *Presented at "Short Course on Conceptual Modeling of Geothermal Systems", organized by UNU-GTP and LaGeo, El Salvador*, 14 pp. Website: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-16-03.pdf

Quintanilla, A., 2013: *Personal communication.* Polaris Geothermal Inc., February 2013.

Sánchez, E., 2013: *Personal communication*. Instituto Costarricense de Electricidad (ICE), November 2013.

SICA, 2007: *Alianza en energía y ambiente con Centroamérica. Guía Centroamericana de financiamiento de carbono*. Secretaría General Sistema de Integración Centroamericano (SICA), 2da edición, 153 pp.

Stephure, T., 2009: *Geothermal development expands globally*. Website: http://www.renewablesbiz.com/article/09/05/geothermal-development-expands-globally

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

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GEOTHERMAL ACTIVITY AND DEVELOPMENT IN MEXICO – KEEPING THE PRODUCTION GOING

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ABSTRACT

Geothermal energy in Mexico is almost entirely used to produce electricity, since its direct uses are still under development and currently remain restricted to bathing and swimming. The net installed geothermal-electric capacity in Mexico as of 2013 is 823.4 megawatts (MW). This capacity is currently operating in four geothermal fields: Cerro Prieto (570 MW), Los Azufres (191.6 MW), Los Humeros (51.8 MW) and Las Tres Vírgenes (10 MW). However, the running capacity is less than that, because of production decline mainly at Cerro Prieto geothermal field, one of the largest geothermal fields in the world. All of the geothermal fields and power plants are owned and operated by the governmental agency CFE (Comisión Federal de Electricidad). During 2013, thirty eight power plants of condensing, back-pressure and binary cycle types were in operation in those fields. The annual geothermal production (2013) was 55.6 million metric tons of steam at an annual average rate of 6,353 tons per hour (t/h). Steam was delivered by an average of 225 production wells, and was accompanied by 67.4 million metric tons of brine that was disposed of through 26 injection wells and a solar-evaporation pond operating in Cerro Prieto. Geothermal power plants in the fields produced 5,769 gigawatts-hour (GWh) of electric energy in 2013, which represented 2.3% of the whole electric generation in Mexico in that year. Exploration of the Acoculco, Baja California Norte, El Chichonal, and Cuitzeo Lake geothermal areas is in the execution stage.

1. INTRODUCTION

In Mexico, geothermal resources remain to be mainly utilized to produce electricity. The public service of electricity in Mexico is provided by the Federal Government. Until October 10, 2009, two public facilities, the Comisión Federal de Electricidad (CFE) and Luz y Fuerza del Centro (LFC), owned and operated by the government, were in charge of generation, transmission, distribution and commercialization of electric energy. Since that date, only CFE has this responsibility. Electric uses of geothermal are planned, developed and operated by the Gerencia de Proyectos Geotermoeléctricos – the geothermal division of the CFE (Gutiérrez-Negrín et al., 2010).

2. THE ELECTRIC INDUSTRY

The Federal Electricity Commission (CFE) is a company created and owned by the Mexican government. It generates, distributes and markets electric power for almost 36, 4 million customers.

This figure represents almost 100 million people. The CFE incorporates more than a million new customers every year. The infrastructure to generate electric power is made up of 224 generating plants, having an installed capacity of 51,780 megawatts (MW). 22.67% of its installed capacity stems from around 22 plants which were built using private capital and are currently operated by independent power producers (IPP).

The CFE generates power using various technologies and primary energy sources. It has thermoelectric, hydroelectric, coal-fired, geothermal and wind powered plants and facilities, as well as one nuclear power plant, (Gutiérrez-Negrín, 2007). In order to take the power from its generating plants to the household of each one of its customers, the CFE has more than 817,458 km of power lines that transmit and distribute electric power. Electricity reaches almost 190,000 communities (of these, 190,732 are small villages). Also, 97.9% of the population has access to electric service.

As of December 2013 the total installed electric capacity in Mexico was 52,695 MW (Table 1). This total includes 22 independent power producers (IPP) amounting 12,850 MW, whose power plants were constructed and are operated and owned by private companies (CFE, 2013). By law, the IPPs sell all their electric generation to the CFE through long-term power purchasing contracts, since they are not allowed to negotiate and contract with private costumers.

TABLE 1: Mexico development of installed capacity and generation

		2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Capacity (MW)	CFE	36,855	36,971	38,422	37,325	37,470	38,397	38,474	38,927	39,704	39,270	39,362	39,845
	IPP	3,495	6,756	7,265	8,251	10,387	11,457	11,457	11,457	11,907	11,907	12,418	12,850
	Total	40,350	43,727	45,687	45,576	47,857	49,854	49,931	50,384	51,611	51,177	51,780	52,695
Generation (TWh)	CFE	177.05	169.32	159.53	170.07	162.47	157.51	157.16	154.14	160.37	170.42	175.8	161.59
	IPP	21.83	31.62	45.85	45.56	59.43	70.98	74.23	76.5	78.44	84.26	81.73	83.99
	Total	198.88	200.94	205.39	215.63	221.9	228.49	231.4	230.64	238.81	254.68	257.53	245.58

As indicated in Table 2, almost three quarters of the installed capacity for public service in Mexico (74%) is based on fossil-fuel power plants (hydrocarbons and coal), and more than one fifth (21%) on hydroelectric plants. Geothermal electric capacity represents 1.6% and wind only 0.2%. The rest (2.7%) is represented by nuclear power plants and photovoltaic (Figure 1).

TABLE 2: Gross installed capacity by generation type (December 2013)

Generation Type	Effective capacity MW	Percentage
Oil and Gas	26,263.02	45%
Hydroelectric	11,266	21.4%
Coal	2,600	4.9%
Geothermal	823.4	1.6%
Wind	86.75	0.2%
Nuclear	1,400	2.7%
Photovoltaic	7,68	0.011
Oil and Gas (private)	12,852.4	24.4%
Total	**52,695.75**	**100%**

The electric generation for public service in Mexico in 2013 was 245,588 GWh, as reported in the same Table 1. More than three quarters (82%) of the electric energy for public service in Mexico in 2013 was generated by power plants fuelled by hydrocarbons and coal, only 10% was produced by hydroelectric plants, 4% by nuclear power plants, 2.3% by geothermal-electric plants and 0.1% by wind power plants, as implicated in Table 3 (Figure 2).

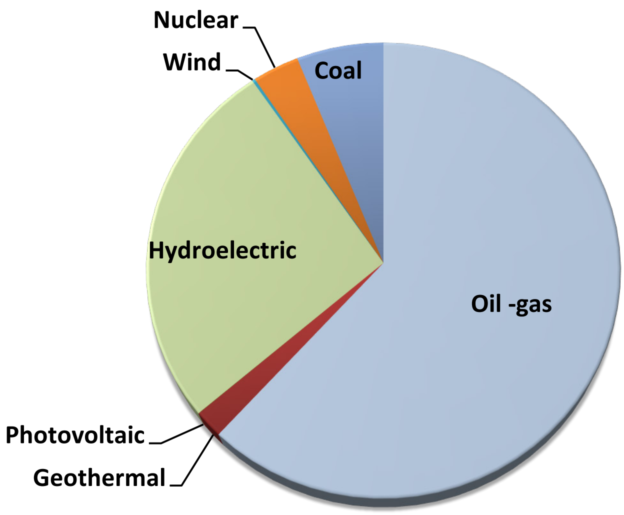

FIGURE 1: Breakdown of the total CFE electric installed capacity in Mexico as of December 2013

TABLE 3: Generation of electricity by source

Generation type	Percentage
Geothermal	2.3%
Coal	6%
Nuclear	4.6%
Wind	0.1%
Photovoltaic	0.01%
Hydraulic	10.7%
Oil and Gas	42%
Oil and Gas (Private Producers)	34.2%

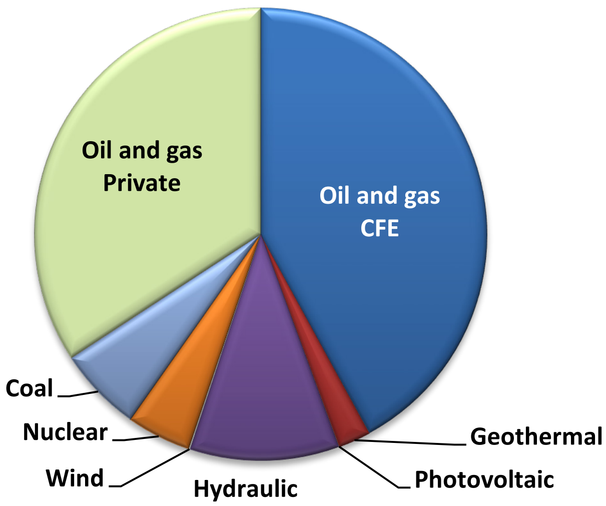

FIGURE 2: Total generation of electricity in Mexico in 2013, by type of power plant and fuel used

3. GEOTHERMAL ELECTRICITY

The net geothermal-electric capacity in Mexico is 833.4 MW as shown in Figure 3, installed into four geothermal fields (Cerro Prieto, Los Azufres, Los Humeros and Las Tres Vírgenes). Table 4 shows the running capacity for each field, the projects under construction and future increases on capacity. The fifth field, La Primavera (Cerritos Colorados project), remains on stand-by, even though a potential of 75 MW was assessed long time ago, (CFE, 2011). Installation of the first units in this field is expected to start soon, since the Environmental Impact Assessment has been approved for a 25 MW power station. However some social opposition is still in the surrounding cities and has to be solved in order to be able to construct the power station there.

FIGURE 3: Locations of Mexican geothermal fields under exploitation (Cerritos Colorados, formerly known as La Primavera, remains in stand-by). The national capacity factor in 2013 was 80.6% or 0.8 on average. All the fields and power units are managed and operated by personnel of the CFE.

That present geothermal-electric capacity represents 2.3% of the total electric capacity for public service in the country. Thirty eigth power plants of several types (condensing, back pressure and binary cycle), between 1.5 and 110 MW, operate in those fields, fed by 225 geothermal wells with a combined production of 6,355 metric tons of steam per hour (t/h). The production wells have depths between 600 and 4,400 meters. Steam comes with almost 7,700 t/h of brine that is injected through 26 injection wells, or treated in a solar evaporation pond of 14 km^2 in Cerro Prieto. During 2013, steam produced in those fields amounted 55.6 million of metric tons, and the power plants generated 5,768 gigawatts-hour (GWh), which represented 2.3% of the electric energy produced in Mexico.

TABLE 4: Geothermal capacity in Mexico

Geothermal Field	Start up year	Running Capacity MW	Under Construction MW	New Projects MW
Cerro Prieto, BC	1973	570		
Los Azufres, Mich	1982	191.6	1 x 50	1 x 25
Los Humeros, Pue	1990	51.8		2 x 25
Las Tres Vírgenes, BCS	2001	10		2
Cerritos Colorados, Jal				25

4. KEEPING THE PRODUCTION GOING

4.1 Cerro Prieto Geothermal Field

Cerro Prieto is the oldest and largest Mexican geothermal field in operation. It is located in the northern part of Mexico (Figure 3), and its first power units were commissioned in 1973. Commercial exploitation started in 1973, so this reservoir has been under extraction conditions for 40 years. There are currently installed 11 units of condensing type: four 110 MW double-flash, four single-flash of 25 MW each and one 30 MW single-flash, low pressure, amounting 570 MWe (Table 5). These power units produced 3,996 GWh in 2013 at an annual capacity factor of 78% (0.78). The decrease in annual capacity factor is due to the production decline of steam in the wells. This geothermal field lies in a pull-apart basin produced between two active strike-slip faults (the Cerro Prieto and Imperial faults) belonging to the San Andreas Fault System. Thinning of the continental crust in the basin has produced a thermal anomaly that is the ultimate cause of the heat source of the geothermal system. The geothermal fluids are contained in sedimentary rocks (lenticular sandstones intercalated in series of shales) with a mean thickness of 2,400 meters. More than 400 geothermal wells have been drilled in 40 years in Cerro Prieto, with depths up to 4,400 m. 159 production wells were in operation during 2013 producing 34.54 million tons of separated steam at an annual average rate of 3,942 tons per hour (t/h). The annual average production rate per well was 24.7 t/h. There were also 17 injection wells in operation that returned to the reservoir around 59.82 million tons of total separated brine. The rest was disposed in the solar evaporation pond of 14.3 km^2 in surface. Taking into account the steam produced in 2013 in Cerro Prieto, the gross steam specific consumption results in an annual average of 8.5 tons per MWh.

TABLE 5: Source: Cerro Prieto Geothermal Field, December 2013

Current situation	**CPI**					**CPII**		**CPIII**		**CPIV**				**Total**
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	
Installed capacity MW	37.5	37.5	37.5	37.5	30	110	110	110	110	26.95	26.95	26.95	26.95	570
Specific consumption t/MWh	10.6	10.6	10.6	10.6		8.09	8.09	8.18	8.18	6.81	6.81	6.81	6.81	
Steam required t/h	398	398	398	398		890	890	900	900	184	184	184	184	4,316
Year of commissioning operation	Apr-73	Oct-73	Feb-79	Apr-79	Jan-82	Jan-86	Apr-84	Jan-86	Agu-86	Apr-00	May-00	Jun-00	Jul-00	
Years in operation	37	37	32	32	29	25	27	25	25	11	11	11	11	

Figure 4 shows the historic production in this geothermal field, including the annual number of wells repaired and drilled annually. As it is shown in this figure, production is no longer sustainable under the actual injection and extraction conditions. Therefore, there is an exploration campaign going on and projects to make more efficient use of the steam in order to compensate the production decline and being able to reach a sustainable level of production and generation in the field. According to numerical models, the sustainable level of Cerro Prieto will be of around 3000 t/h of steam. Several studies are under execution in order to review and change production and extraction strategies to reduce annual production decline.

4.2 Los Azufres Geothermal Field

Los Azufres is the second geothermal field operating in Mexico. It is located in the central part of the country, 250 km away from Mexico City, and lies within the physiographic province of the Mexican

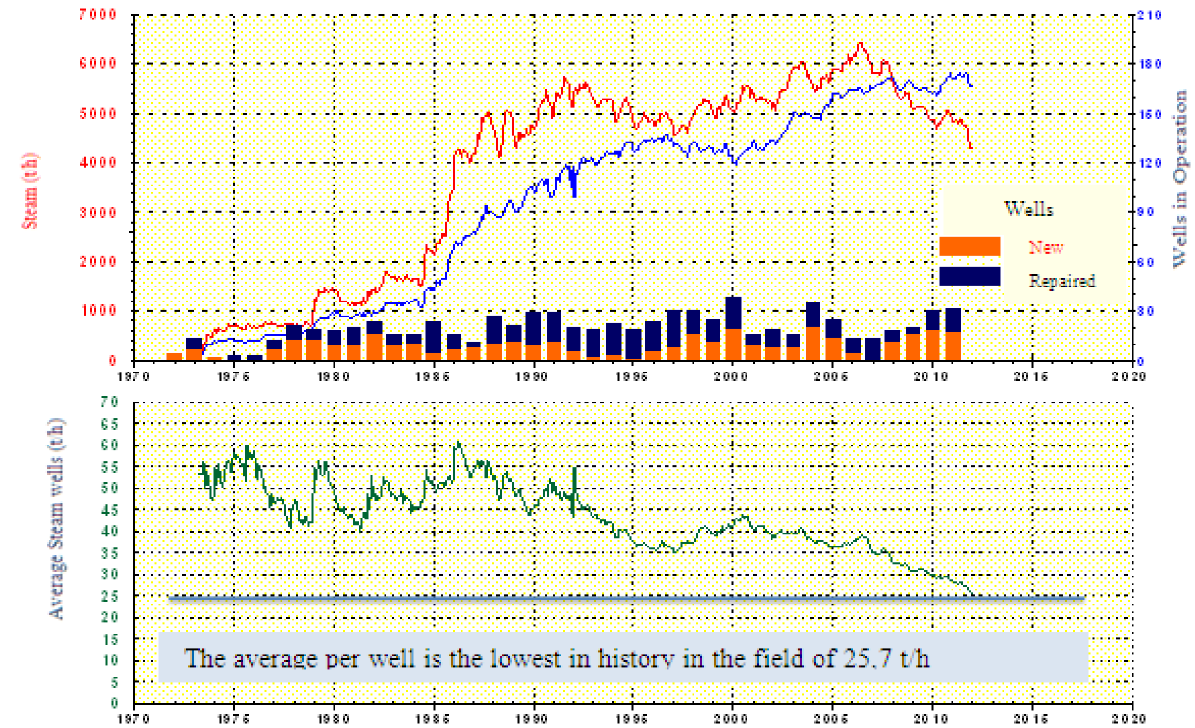

FIGURE 4: Historic production of Cerro Prieto Geothermal Field

Volcanic Belt in a pine-forest at 2,800 m a.s.l. The first power units were commissioned in 1982, and presently there are 12 power units in operation: one condensing of 50 MW, four condensing of 25 MW each and seven 5 MW back-pressure. The total installed capacity is 191.6 MW (Table 4). Generation of electricity in 2013 was 1,503GWh, at an annual capacity factor of 95% (0.95). Los Azufres is a volcanic field whose geothermal fluids are hosted by andesites affected by three fault systems produced by local and regional tectonic activity. The most important of such systems presents an E-W trend and controls the movement of the subsurface fluids. The heat source of the system seems to be related to the magma chamber of the nearby San Andrés volcano that is the highest peak in the area. Along 2013, 40 production wells were in operation in Los Azufres, which produced 14.8 million tons of steam, at an annual average rate of 1689 t/h. The annual mean production per well was 42 t/h. The produced steam was accompanied by 4.4 million tons of brine that was fully injected into the reservoir through 6 injection wells. The gross specific consumption in Los Azufres in 2013 was 9.33 tons of steam per MWh, which is one of the historically lowest in this field yet still higher than in Cerro Prieto.

Figure 5 shows the historical annual production of steam at Los Azufres. As it can be seen, production has been maintained and the geothermal power plant ranks in the first 15 places of best operational conditions in the country competing with 144 power plants in Mexico (CFE, 2014).

Late 2013, an international bid has been sent in order to install a new project in the north part of the field. This project is named Azufres III (Phase A) and consists of 50 MW and Azufres III (Phase B) consist of 25 MW net capacity project.

4.3 Los Humeros Geothermal Field

The geothermal field of Los Humeros is also of volcanic type. It is located in the eastern-central part of Mexico, at the eastern end of the Mexican Volcanic Belt. Its power units number 1 and 2 started to commercially operate in 1990, and currently there are five back-pressure units of 5 MWe each and one

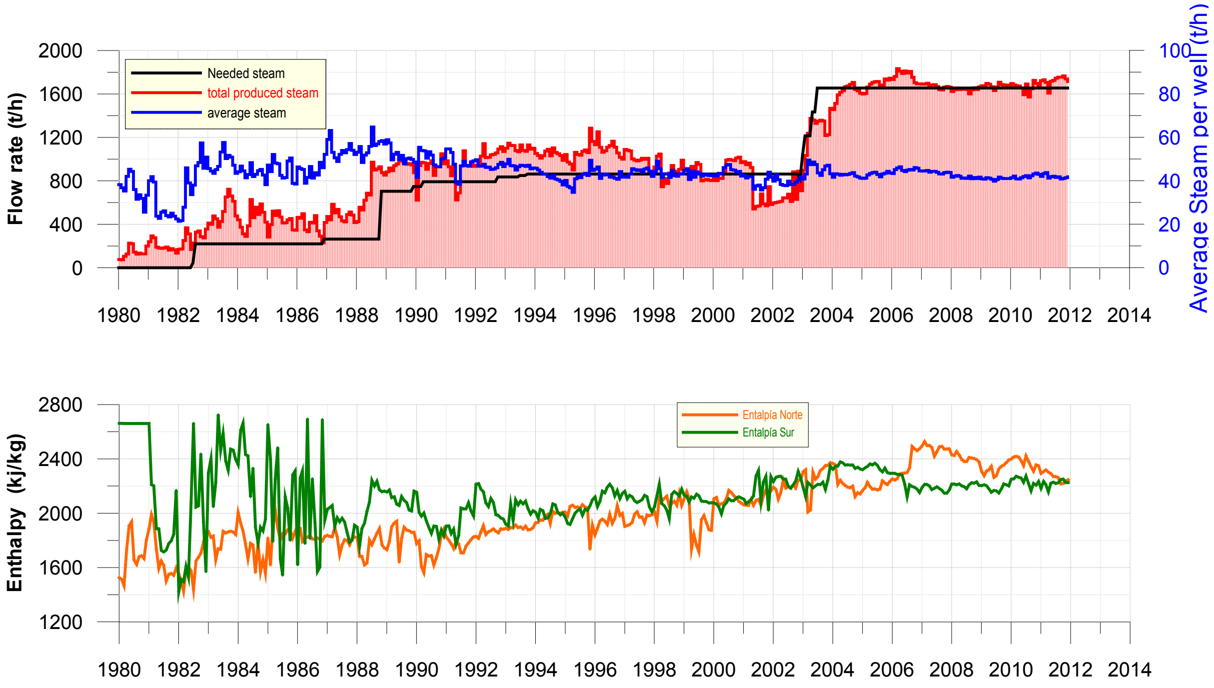

FIGURE 5: Historic production of Los Azufres Geothermal Field

unit of 26.8 MWe, with a total operating capacity of 51.8 MWe. Los Humeros lies inside a Quaternary caldera (Caldera de Los Humeros) at 2,600 m a.s.l. The geothermal fluids are also contained in andesites overlying a complex basement composed of metamorphic, sedimentary and intrusive rocks. The heat source is the magma chamber that produced two collapses and formed the Los Humeros and Los Potreros calderas, being the latter nested in the first one. Los Potreros collapse occurred 100,000 years ago, and the last volcanic activity has been dated in 20,000 years. There were 23 production wells operating in Los Humeros during 2013. They produced 5.47 million tons of steam at an annual mean rate of 624 t/h, resulting in an average production per well of 27 t/h. The wells in Los Humeros produce usually low brine, and so occurred in 2013 when 0.73 million tons of brine was obtained. The brine was returned to the reservoir by three injection wells. Generation of electricity in Los Humeros was 335.76 GWh. The capacity factor in 2013 was 61% (0.61), but the gross specific consumption was 15.16 tons of steam per MWh.

Figure 6 shows the historical annual production of steam at Los Humeros. As it can be seen, production has been maintained and this geothermal power plants together with Los Azufres ranks in the first 15 places of best operational conditions in the country competing with 144 power plants in Mexico.

As part of the development of this geothermal field, there is right now under construction Los Humeros III this project consisting of substitution of 4 units of 5 MW each in order to installed two new 25MW each one. After commissioning these power stations total install capacity in the field will be 100 MW, meaning a 50% of increment. Additional plans are discussed in section 5 of this paper.

4.4 Las Tres Virgenes Geothermal Field

Las Tres Vírgenes is the most recent field in operation in Mexico. It is located in the middle of the Baja California peninsula, at the north of the state of Baja California Sur and inside the buffer zone of the El Vizcaíno Biosphere Reserve. There are only two condensing 5 MW power units in operation that were officially commissioned in 2002. Generation of electricity in 2013 was 54.58 GWh, at an annual mean capacity factor of 56% (0.56). Las Tres Vírgenes is inside a Quaternary volcanic

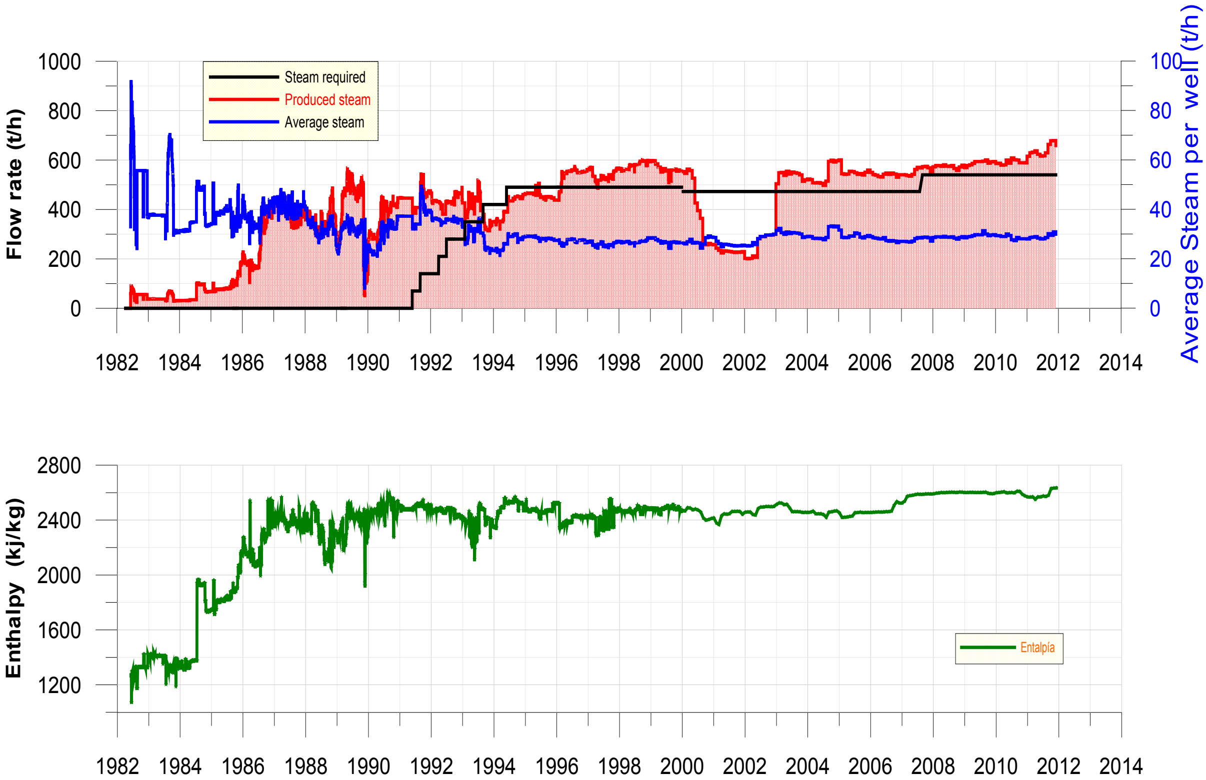

FIGURE 6: Historic production of Los Humeros Geothermal Field

complex composed of three N-S aligned volcanoes, from which the name of the field becomes. The geothermal fluids are hosted by intrusive rocks (chiefly granodiorite) and the heat source of the system is related to the magma chamber of the La Virgen volcano, the youngest and most southern of the volcanic complex. During 2011 there were four production wells in operation that produced 0.788 million tons of steam at an annual mean rate of 90 t/h (Figure 7). The annual average production per well was 22t/h. Unlike Los Humeros, wells of Las Tres Virgenes produce much brine: in 2013 the associated brine was 2.42 million tons. All this brine was fully injected through one injection well. In this moment the option of installing a binary cycle power plant is under economic analysis. The gross specific consumption in Las Tres Virgenes was 13.39 tons of steam per MWh in 2013, which is considerably higher than reported five years ago (Gutiérrez-Negrín and Quijano-León, 2005), and yet is lower than obtained in Los Humeros. The steam produced and the electricity generated in Las Tres Vírgenes in 2013 represents the highest ones since the field started to be exploited, even though they are still far away from the optimum.

Because of that during 2013, the mean capacity factor has been increased compared with 2012, thus contributing with almost 65% of the total isolated generation system in that part of the country. In 2014 it is expected to increase the capacity factor in this field to be comparable to Los Azufres and Los Humeros.

5. NEW GEOTHERMAL DEVELOPMENTS

The National Development Plan 2015-2018 states that environmental sustainability is a central public policy of Mexico. This implies the country should take into consideration the environment as one of the elements of competitiveness and economic and social development. Using renewable sources of energy can simultaneously reduce the dependence on fossil fuels, reduce the emissions of greenhouse

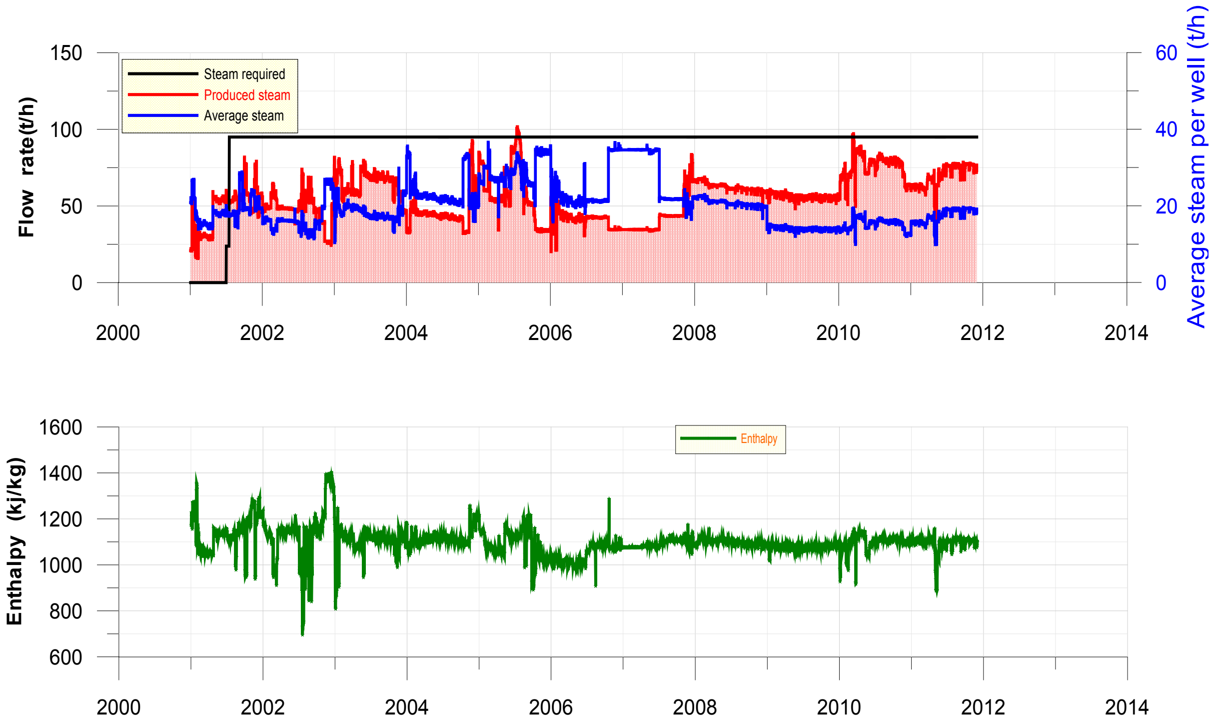

FIGURE 7: Historic production of Las Tres Virgenes Geothermal Field

gases and increase the added value of economic activities. Mexico has great potential in renewable energy, especially geothermal and provides ample opportunities to be exploited, and meet the challenges of global warming. According to this public policy, geothermal projects for the near term are shown in Table 6.

The project Los Humeros III phases A and B is composed of two condensing units of 25 MW each to be commissioned in 2015 (phase A) and 2018 (phase B). Phase A includes the replacement of 3 x 5 MW backpressure units, using the same amount of steam to generate 10 MW of additional power and in the phase B, 2 backpressure units 5MW each one will be replace for one of 25MW of to generate another 15 MW of additional power.

TABLE 6: Mexican geothermal projects in the near term

Projects	**2015**	**2018**
Los Humeros III Phase A	25	
Los Humeros III Phase B		25
Los Azufres III Phase B		25
La Tres Virgenes	2	
	Total = 77	

Los Azufres III (phase B) project is scheduled for late 2015. This project consists of one 25 MW unit, which considers dismantling four 3 MW backpressure units currently in operation. Therefore, the net additional capacity in this field will be 10 MWe.

6. EXPLORATION

Exploratory studies of geology, geochemistry and geophysics have made it possible to identify areas of high, medium and low enthalpy geothermal potential interest of approximately 500 MW. The most likely areas are showed in Figure 8 and Table 7.

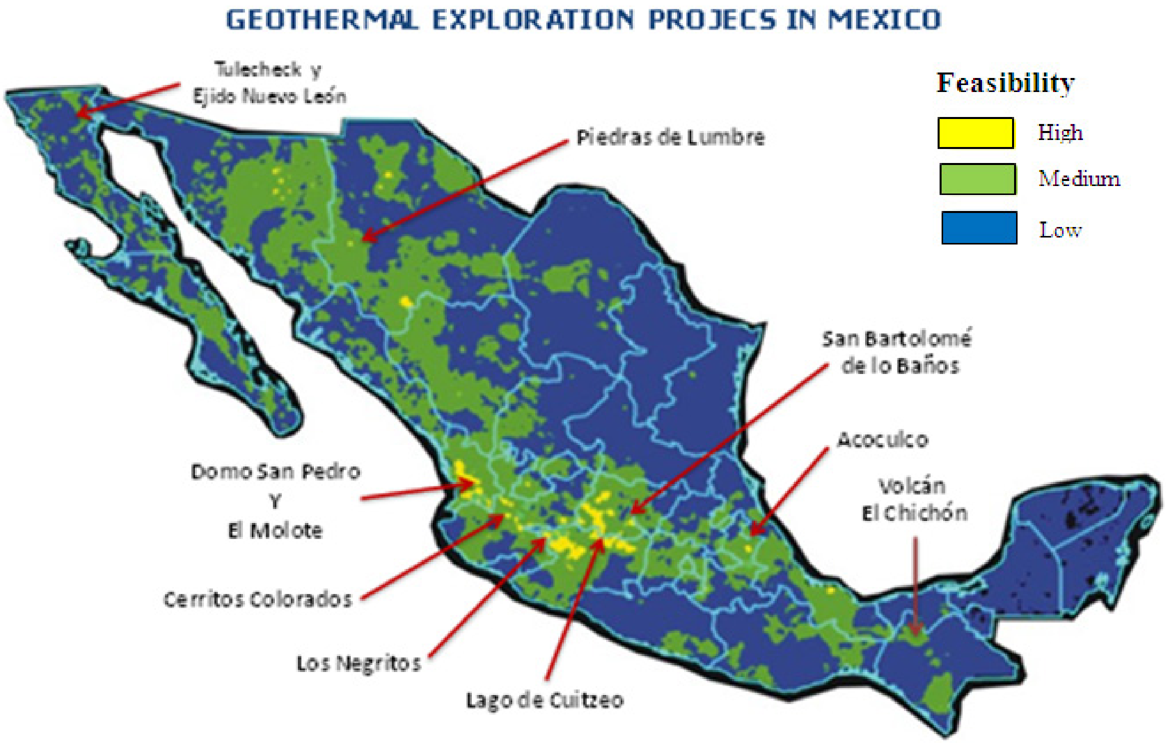

FIGURE 8: Main geothermal areas in the exploration stage

TABLE 7: Geothermal exploration projects

Project	Objective	Current Status
Cerritos Colorados, Jal.	Install 25 MW, condensing type unit	EIA approved, but social issues still in progress
Nuevo Leon y Saltillo	Evaluate potential and install 100 MW	Exploration drilling 2013-2015.
Acoculco, Puebla.	Assessment as a EGS project.	2 depth wells drilled with high temperature but negligible permeability.
Tulecheck, BC.	Binary Cycle project	2 exploration wells drilled in 2010.
El Chichonal, Chis.	Exploration for high temperature resources	Exploration studies in progress 3 exploration wells to be drilled 2013-2014
Tacaná, Chis.	Exploration for high temperature resources	Exploration studies in progress
Cuitzeo Lake	Binary Cycle project	Exploration studies in progress 3 exploration wells to be drilled 2013-2014

6.1 El Chichonal Volcano

Studies to evaluate the geothermal potential of the Chichonal Volcano area started since the 80's with geological surveys, identification of thermal manifestations and geochemical evaluation, concluding that this area presents the best conditions for the existence of high enthalpy resource in the state of Chiapas.

In 1982 Chichonal Volcano erupted causing a disaster in the region. After the eruption, the volcano has been studied by numerous scholars and academic institutions, from the point of view of volcanic hazards; recently CFE has started exploration studies to locate exploration wells. Geothermometry estimates temperatures around 220°C.

6.2 Piedras de Lumbre, Chich

The geothermal area of Piedras de Lumbre is located 220 km in a straight line southwest of Chihuahua City and 60 km southwest of San Juanito, Chihuahua railroad station-Pacific, within the municipality of Maguarichi.

In the past, this geothermal area had a 300 kW binary cycle power plant, fed by a shallow low-enthalpy reservoir. This unit supplied energy to a nearby, small village then isolated from the grid. The unit was dismantled when the grid reached the village, but recently the CFE reassumed exploration surveys looking for a high temperature, deeper reservoir.

6.3 Tulecheck

This geothermal area is located in the Mexicali Valley around 15 km south of the city of Mexicali, about 20 km northwest of Cerro Prieto, and between 6 and 8 km east of the Sierra Cucapa. A low enthalpy resource is expected to be developed there, since geothermometry studies indicate temperatures of 180-200°C.

6.4 Acoculco

The Acoculco geothermal zone, Pue., is a volcanic complex located in the eastern Mexican Volcanic Belt and the Sierra Madre Oriental provinces. Currently two exploratory wells have been drilled by the CFE in the area, with temperatures above 300°C and low permeability. With the known information is not still possible determine the feasibility of a geothermal-electric project, and further studies are required. However, given the most recent results this project is a candidate to be developed as an enhanced (or engineered) geothermal system in the future.

6.5 Cuitzeo Lake

Some geothermal manifestations occur at the shores of this lake, located in the state of Michoacán, presenting geothermometry temperatures of around 200°C. A low enthalpy resource is expected to be developed here. Geophysical, geological and geochemical exploration surveys were finished in 2010, and exploration wells are to be sited in order to continue with the assessment of the project.

6.6 Nuevo Leon Ejido

Geological and thermal information was obtained from eight exploratory wells drilled in the 80's. Temperatures above 250°C in a deep reservoir were identified. Therefore the east of Cerro Prieto has been selected for new power stations in order to compensate the production and generation reduction in the actual geothermal field. This project will be called Ejido Nuevo León and development wells will be drilled in order to extract the enough steam for the new projects. A geothermal capacity of around 100 MW is calculated.

7. CONCLUSIONS

Mexico is a very rich country in renewable sources of energy, and then it is possible reduce simultaneously the dependence on fossil fuels, reduce GHG emissions and increase the added value of economic activities. Mexico has great potential in renewable energy, especially geothermal, and provides ample opportunities to be exploited, to meet the challenges of global warming.

There are four geothermal fields in commercial operation. Cerro Prieto has been in operation for 40 years and currently presents a large production decline requiring changes in the exploitation and injection strategy.

Mexico occupies the fourth geothermal installed capacity place worldwide. However its growing has been slow compared with other countries such as the US and Indonesia. For 2015 it is expected the installed capacity to grow to ~1050 MW, with projects Los Humeros II and III and Los Azufres III

Besides that, large exploration campaigns are running in order to find new geothermal areas that can be commercially exploited using both high and medium enthalpy systems. The most important places are El Chichonal volcano, Cuitzeo Lake, Acoculco and Cerritos Colorados.

REFERENCES

CFE, 2011: *Programa de obras e inversiones del sector eléctrico 2009-2018*. CFE, Subdirección de Programación, Coordinación de Planeación, 262 pp.

CFE, 2014: *SGD-index*. Internal statistics of CFE generation.

Gutiérrez-Negrín, L.C.A., 2007: 1997-2006: A decade of geothermal power generation in Mexico. *Geothermal Resources Council Transactions, 31*, 167-171. Web: http://pubs.geothermal-library.org/lib/grc/1025212.pdf

Gutiérrez-Negrín, L.C.A., and Quijano-León, J.L., 2005: Update of geothermics in Mexico. *Proceedings World Geothermal Congress 2005, Antalya, Turkey*, 10 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0102.pdf

Gutiérrez-Negrín, L.C.A., Maya-González R., and Quijano-León, J.L, 2010: Current status of geothermics in Mexico. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 11 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0101.pdf

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A CARIBBEAN GEOTHERMAL SUCCESS STORY

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ABSTRACT

The archipelago of islands that are washed on the East by the Atlantic Ocean and the West by the Caribbean Sea are commonly known as the Caribbean and are closely knit, economically, politically, socially, culturally, spiritually and geographically. Some of these islands show great potential for geothermal development and have been utilising low temperature geothermal applications such as bathing since the early 1600s. According to a series of studies done in the Caribbean Region (Huttrer, 1996; 1998a; 1998b; 2000), collectively these islands have the potential to produce geothermal energy in excess of 16 GWe. Additionally, according to the peak demand forecast from Nexant (2010) these islands would only be using approximately half of this value by 2028.

The recent success story of the Commonwealth of Dominica in its geothermal development has positioned this country to be the next country in 30 years to build a commercial geothermal plant in the Region. Based on the overall objective of this project, the Commonwealth of Dominica would also by 2020 start a Regional Electrical Power Interconnection Grid by supplying the French territories of Guadeloupe and Martinique with 100 MWe via submarine cables.

Following the path laid out by the Commonwealth of Dominica, countries in the Region with similar resources can seek to develop and sell power to the neighbouring countries, hence creating a Caribbean Regional Power Grid. This direction set out by the Commonwealth of Dominica would drastically aid in the economic and social development of the Caribbean Region and contribute positively to Climate Change.

1. BACKGROUND

The Commonwealth of Dominica is a small island nation in the Lesser Antilles Region of the Caribbean. It has a population of 71,293 (2011 Census) and measures 290 square miles. Its economy is primarily based on Agriculture and Tourism. Having no petroleum resources, the energy and transport sectors are susceptible to the fluctuating cost of oil on the international market. However, with the potential that exists in terms of clean renewable energy production with the natural resources available, Dominica can seek to address those problems and to maintain or improve its status as the Nature Isle of the Caribbean and improve the quality of life of its people.

In 2005, great strives was made with the initiation of an exploration survey which was carried out in the Wotten Waven area in Dominica, in the frame of the Eastern Caribbean Geothermal Development Programme "Geo-Caraïbes" funded by the Organization of American States (OAS). Subsequent to the OAS programme another programme called "Geothermal Energy in Caribbean Islands" or "Géothermie Caraïbes" was initiated by the European Union (E.U), the Commonwealth of Dominica and France under the European INTERREG IIIB Programme "Espaces Caraïbes". The partners include the Government of the Commonwealth of Dominica (GoCD), the Regional Councils of Guadeloupe and Martinique, Agence de l'Environnement et de la Maitrise de l'Energie (ADEME) and the Bureau de Recherches Géologiques et Minières (BRGM) and CFG Services.

The programme was focused on the Roseau Valley Geothermal Field located about 8km ENE of the Capital of Roseau, which exhibits many surface manifestations including hot springs, fumaroles, phreatic craters etc. The geo-scientific surveys that were conducted by the BRGM group in 2008, identified a potential geothermal reservoir to be investigated and tested by deep exploratory wells.

2. PROJECT DEVELOPMENT

Being guided by the previous studies, the exploratory phase of the project which involved the drilling of three exploratory geothermal wells in the Roseau Valley Geothermal field commenced. The wells were drilled utilizing the 'Wire-line Coring' mining technique. A level area of approximately 3000m^2 was prepared for the drilling rig and related equipment to carry out the drilling and testing activities. The three drilling sites are located in the communities of Wotten Waven (Well site WW-1) and Laudat (Well sites WW-2 and WW-3) respectively (Figure 1).

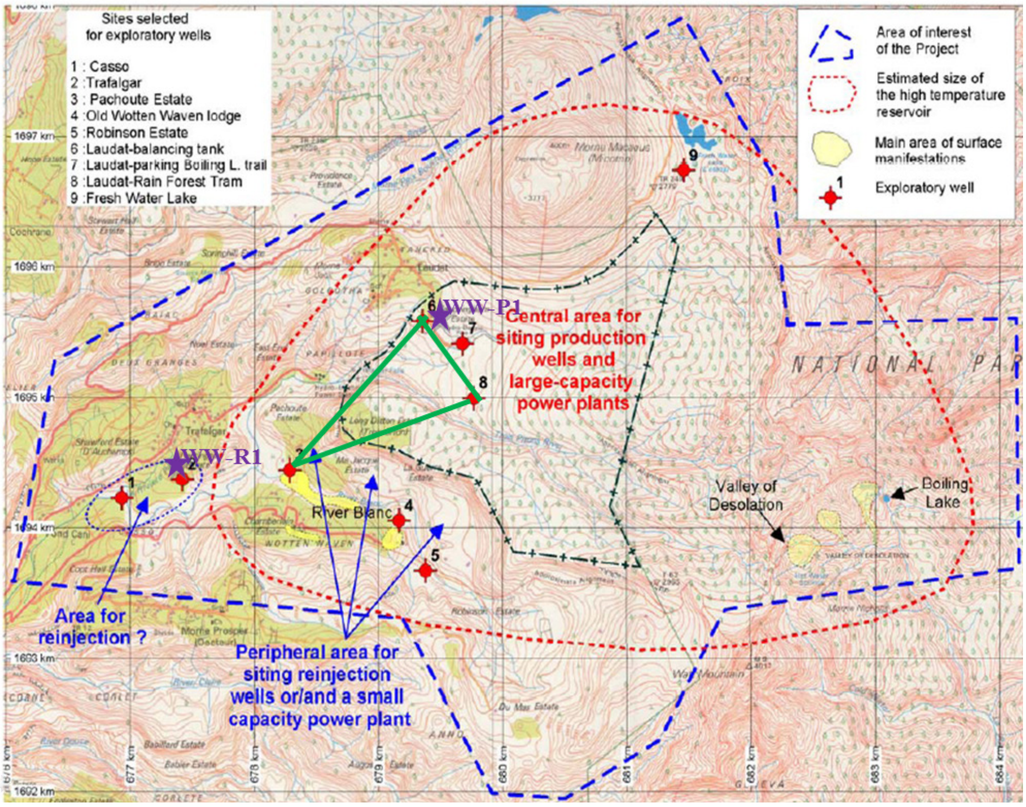


FIGURE 1: Drilling sites

The objective of the exploratory works was to determine the quantity and quality of the geothermal resource in the Roseau Valley, how this resource reacts to economic and technical exploitation and the level of electricity which could be generated to provide a cheaper source of energy for Dominica. Once successful, the overall long term objective would be the construction of a geothermal power plant to meet local demand and to sell surplus electricity to the neighbouring islands of Guadeloupe and Martinique via submarine cable.

Preliminary assessments carried out using the available data from the exploration wells drilled and the pre-feasibility studies, confirm that there was in fact sufficient geothermal resources to develop the proposed Small Geothermal Power Plant (SGPP) of up to 15 MW for the local market. The completed flow tests and collected data (Tables 1 and 2) confirm a geothermal resource base of 65 MW at a 90 percent (P90) probability of confidence which is considered to be a usual threshold for commercial developers and financiers (Figure 2) to determine the bankability of an investment.

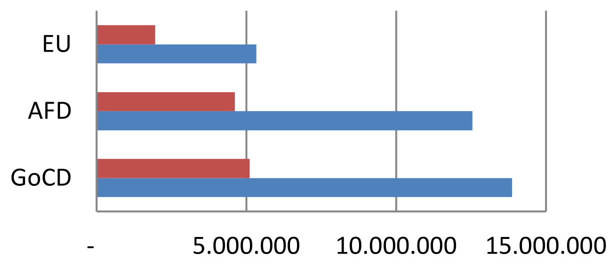
TABLE 1: Summary of drilling operations for exploratory wells

Activity	WW-2	WW-3	WW-1
Commencement date	16-Dec-2011	15-Feb-2012	28-Mar-2012
Completion date	28-Jan-2012	14-Mar. 2012	27-Apr-2012
Final depth	1469 m	1613 m	1200 m
Depth of 4 ½" slotted liner	1337 m	1605 m	1200 m
Number of days drilling	41	29	31
Total number of work days	65	40	42

TABLE 2: Flow test results of exploratory wells

	WW-2	WW-3	WW-1
Date of flow test	Mar. 9-10 2012	17-Apr-2012	27-Jun-2012
Highest temperature logged	241°C	245°C	238°C
Highest pressure logged	82 bars	98 bars	100 bars
Enthalpy	940 kJ/kg	980 kJ/kg	1028 kJ/kg
Potential generation rate	0.5 MW	2.9 MW	3.9 MW

Having successfully completed the phase of drilling and testing of three exploratory wells and proven the existence of a viable geothermal resource, GoCD has progressed to the next stage of seeking to develop a 10 – 15 MWe Small Geothermal Power Plant (SGPP) within the Roseau Valley Geothermal field. The GoCD has received funding from the AFD by way of a €6.5M concessionary loan agreement for the implementation of the drilling and testing program that basically consists in the drilling and testing of 2 full size wells (a production well [WW-P1] and an injection well [WW-R1]). The sites for drilling are



	GoCD	AFD	EU
US$	5.105.557	4.619.010	1.961.655
XCD$	13.871.288	12.549.389	5.329.620

FIGURE 2: Overall cost of exploratory drilling

located in Laudat (Well Pad WW-3) and Trafalgar, approximately six (6) and four (4) miles respectively, from the capital Roseau (Figure 1).

The drilling of the reinjection well WW-R1 started on November 6, 2013 and was completed by December 20, 2013. This well achieved a depth of 1915m and its completion saw the commencement of the directional production well WW-P1 in January 14, 2014 and was completed on March 1, 2014 with a depth of 1505m. The flow test of the production well WW-P1 is planned for the end of May 2014. Preliminary injection tests indicate that the well is highly permeable with temperatures above 230 degrees Celsius, with an expected generation capacity of 5-7 MW.

Being the Nature Isle of the Caribbean, the GoCD seeks to consider all the relevant impact such a project will have on key aspects of the country such as the Environment. Therefore, the Environmental Impact Assessment (EIA) for the drilling of two production wells commenced at the end of August 2013 prior to the disturbance of any flora or fauna in the desired area. The EIA was funded by the Regional Council of Guadeloupe and was carried out by a number of consulting firms to include:

- Caraïbes Environnement is a consulting firm based in Guadeloupe with 18 years of experience in conducting EIA's.
- ASCONIT Consultants is a private consulting firm specialized in Water Resource Monitoring and Management and is based mainly in Guadeloupe and Martinique since 2005.
- TERANOV is a consulting firm with expertise in Geothermal Energy.
- Eclipse Inc. is a local Management Consulting Firm which specializes in Natural Resource Management, Environmental Impact Analysis, and Ecological Analysis among others. Their main focus for this EIA study will be as Experts in Flora and Fauna.

3. FUTURE PROSPECTIVE

The future advancement of the geothermal success story for the Commonwealth of Dominica lies in the effort of the GoCD in seeking to develop a 10 – 15 megawatt Geothermal Power Plant within the Roseau Valley Geothermal field in keeping with the initial objective laid out in this project. It is envisaged however, that this development will occur in incremental phases, which will be determined in the production planning stage, and based to a large extent on the productive capacity of the wells, the scale at which a base-load geothermal power plant can be absorbed on the local grid and to the dictates of local demand.

The development of the Small Geothermal Power Plant (SGPP) is intended to reduce the cost of electricity to consumers, and will also serve as a pilot and demonstration plant which would allow for further assessment of the resource and to observe the reaction of the reservoir to commercial exploitation, thereby guiding the planning and management of the further exploitation and development of the resource to provide electricity for Martinique and Guadeloupe by way of a 100 – 120 MW Large Geothermal Power Plant (LGPP).

Technical Assistance Team ELC is carrying out this feasibility study with assistance from the World Bank and other international experts. Similarly the GoCD is working closely with the Dominica Electricity Services Limited (DOMLEC) and the Independent Regulatory Commission (IRC) in terms of integrating geothermal energy into the current energy mix and to assess whether any regulatory changes to the existing concession agreement would be deemed necessary. The first phase of the SGPP is slated to be commissioned by the end of 2015 or first quarter of 2016.

The development strategy as put forward in the 2008 study under the INTERREG III B programme proposed 10-20 MW for the Dominican Market and 50 MW each for Martinique and Guadeloupe.

The proposed configuration would include 4 x 30 MW units situated in the community of Laudat (Figure 3).

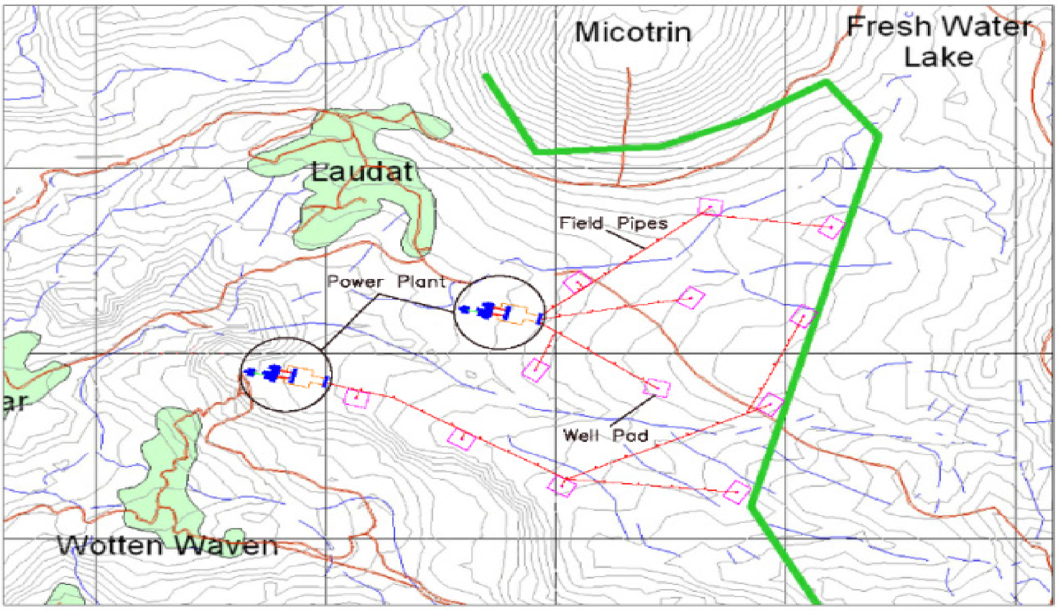


FIGURE 3: Proposed locations for drilling pads and power plant Facilities

A tentative time schedule for the large scale development of the geothermal project (portion to be exported) are:

- 60 MW, Units 1 and 2 on line – 4th Quarter of 2018; and
- 60 MW, Units 3 and 4 on line – 4th Quarter 2020

The total estimated cost to develop the large scale geothermal project for the export of electricity to Guadeloupe and Martinique including the interconnection between the three islands is US $450 M – $500 M.

4. IMPLICATION FOR THE OTHER EASTERN CARIBBEAN COUNTRIES

The bold steps taken by this small island state has open the eyes of the neighbouring islands in that the creation of a Caribbean interconnection grid can be a real and practical solution to the staggering increase in fuel prices on the international arena (Nexant, 2010). After 30 years from the installation of a 4.5 MWe double flash geothermal plant in Bouillante in Guadeloupe (Maynard-Date and Farrell, 2011), the Caribbean Region is now seeing its second commercially viable geothermal plant to be installed in short order in the Commonwealth of Dominica.

According to a series of studies done in the Caribbean Region (Huttrer, 1996; 1998a; 1998b; 2000) collectively, these islands have the potential to produce geothermal energy in excess of 16 GWe. And based on work done by Nexant (2010), the peak demand forecasted for the region including countries from the Republic of Dominica in the North to Grenada in the South is only half this amount (8.1GWe) at peak by 2028.

The distances between the islands in the Caribbean are relatively short and the countries are already deeply entwined sharing common climatic challenges; economic hurdles etc; and organisations such as CARICOM are becoming acutely aware that energy independence can help to eradicate some of the

Region's problems and strategically position the Region for economic and social growth. This can be easily done with the development of geothermal energy on the islands that has the potential (those islands found on the inner arc) and then creating an interconnection with submarine cables. The longest distance from island to island will remain shorter than the longest submarine cable found in the world.

Work envisioned in the Commonwealth of Dominica with the addition of the French territories of Guadeloupe and Martinique to their electrical grid is expected to start the process of this Regional interconnection grid. With future geothermal development in islands such as Nevis (Maynard-Date and George, 2013), Montserrat (Jamaica Observer, 2012) , St. Lucia (Kaye, 2010), St. Vincent and Grenada (Battocletti, L., 1999) the Region is place to reduce its dependency on fossil fuel and contribute significantly to the reduction of green house effect not to mention improve on the economic standing of the Region.

5. CONCLUSION

In the case of the Commonwealth of Dominica, the island is poised to develop its first commercial geothermal power plant and only the second geothermal plant of that type in 30 years within the Caribbean Region. The results from the exploratory phase have confirmed the existence of a commercially viable geothermal resource which can address the high energy costs that currently exists not only for this country but for neighbouring territories. Attaining the objectives listed in the development of its geothermal resource would also start the Region's Electrical Power Interconnection Grid with the addition of French territories by 2020.

This success story for the Commonwealth of Dominica can be motivational to other countries in the Region that share similar resources and through the development of these resources, the Caribbean can see a significant reduction for some and total for others as it related to fossil fuel dependency for energy generation.

REFERENCES

Battocletti, L., 1999: *Geothermal resources in Latin America and the Caribbean.* Bob Lawrence & Associates Inc. and US Department of Energy, Office of Geothermal Technology, 95-120.

Huttrer, G., 1996: *Final report regarding prefeasibility studies of the potential of geothermal development in St. Vincent, W.I.* Report for Lockheed Martin Idaho Technologies Company and US/ECRE.

Huttrer, G., 1998a: *Final report regarding prefeasibility studies of the potential of geothermal development in St. Kitts, W.I.* Report for Lockheed Martin Idaho Technologies Company.

Huttrer, G., 1998b: Geothermal small power generation opportunities in the Leeward Islands of the Caribbean Sea. *Proceedings Geothermal Resources Council's Geothermal Off–Grid Power Workshop, Reno, Nevada,* 4 pp.

Huttrer, G., 2000: Geothermal activity status in the volcanic Caribbean islands. *Proceedings World Geothermal Congress 2000, Kyushu - Tohoku, Japan,* 217-228.

Kaye, L., 2010: *Caribbean island closer to becoming geothermal energy exporter*. TiplePundit. Webpage: www.pleundit.com/2010/08/caribbean-st-lucia-closer-to-becoming-geothermal-energy-exporter-qualibou/

Jamaica Observer, 2012: *Montserrat 'ready' for geothermal energy developers*. Jamaica Observer. Webpage: http://www.jamaicaobserver.com/business/Montserrat--ready--for-geothermal-energy-developers_10741787

Maynard-Date, A., and Farrell, C.N., 2011: Geothermal activity and development in East Caribbean Islands. *Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador,* 8 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-12-07.pdf

Maynard-Date, A., and George, A., 2013: Geothermal status, progress and challenges in the Eastern Caribbean Islands. *Presented at "Short Course V on Conceptual Modelling of Geothermal Systemss', organized by UNU-GTP and LaGeo, in Santa Tecla,, El Salvador,* 7 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-16-05.pdf

Nexant, 2010: *Caribbean regional electricity generation, interconnection and fuel supply strategy – Final report*. Nexant, report 59485 submitted to the World Bank, 427 pp.

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS UNIVERSITY
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GEOTHERMAL DEVELOPMENT IN BOLIVIA

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ABSTRACT

Bolivia is located in the center of South America; and currently has two important electricity policies: to secure electricity generation for internal consumption, and to diversify the energy matrix encouraging renewable energy projects including geothermal.

Bolivia started geothermal development in the '70s with a reconnaissance study in the western region. This study concluded that there is a significant geothermal potential in the southwest region and Laguna Colorada could have the most important geothermal potential. Then six geothermal wells were drilled from 1988 to 1992.

After some changes in electricity policies in 2010, the government of Bolivia started discussions to finance the construction of the 50 MW Laguna Colorada Geothermal Power Plant project. In 2011 the preparatory phase (called phase zero) of the project started. The well testing from November 2012 to May 2013, using different methods of analysis: tracer flow test method (TFT), PTS logging, lip pressure (James-Tube method), capillary tubing and others, confirmed the productivity and reinjectivity of existing wells.

In 2015, it is planned to start the procurement process for drilling new wells, the construction of power plant and the steam pipeline. A total of 100 MW is expected to be constructed.

1. BACKGROUND INFORMATION

1.1 Location and description

Bolivia is located in the center of South America, between the meridians 57°26´- 69°38´western longitude and 9°38´- 22°53´ southern latitude; and along with Paraguay are the only two landlocked countries in that part of the continent.

The South American tectonic plate is bordered by the Nazca and Antarctic plates to the west. These three plates meet at the Chile triple junction, and Bolivia is located above the subduction of the Nazca Plate.

Bolivia is divided into the Andes to the west and Amazon land to the east. The Bolivian Andes are comprised of three main ranges: Cordillera Occidental to the west (on the border with Chile) and Cordillera Central or Oriental to the east.

In addition to these mountain ranges, the Altiplano plateau extends over a large area between the Cordillera Occidental and the Cordillera Central. The plateau is around 700 km long and has a maximum width of approximately 200 km. The average elevation is close to 3,750 m a.s.l.

1.2 Policies and electricity situation

As of 2014, Bolivia relies mainly on hydro and thermoelectricity (33.5% hydro and 66.5% thermo). From 2008, in order to change this situation, Bolivia has two new important energy policies: to secure electricity generation for internal consumption and to diversify the energy matrix encouraging renewable energy projects such as geothermal, wind power and solar energy.

The peak demand reached 1,242.7 MW in February 2014 (CNDC, 2014). According to the Optimal Expansion Plan of the National Interconnected System (SIN) from 2012 to 2022, electricity demand forecasts indicate that total of 2,787 MW will be required in 2022.

The National Interconnected System (SIN) is an electric system comprised of facilities of generation, transmission and distribution which provides electricity to 7 of the 9 provinces of the country. The electrification was approximately 79.4% (95.0% of urban areas and 50.5% in the rural areas) (INE, 2012).

2. GEOTHERMAL EXPLORATIONS AND DEVELOPMENT IN BOLIVIA

2.1 Background

Bolivia started its history of geothermal development in the ‘70s with a reconnaissance study in Cordillera Occidental in the Western Andes Mountains that constitutes the border with Chile, 42 major geothermal manifestations have been studied and it has been concluded that there is significant geothermal potential in the south-western region.

In 1976, Empresa Nacional de Electricidad, ENDE (National Electricity Company) and the Ministries of Energy and Hydrocarbons, with funds from the United Nations Development Programme–UNDP, began evaluating Bolivian geothermal potential, seven prospective geothermal areas were identified: Volcán Sajama, Empexa, Salar de la Laguna, Volcán Ollague-Cachi, Laguna Colorada, Laguna Verde and Quetena. Three of seven fields were considered the most prospective: Laguna Colorada, Sajama and Valle de Río Empexa. They are located along the Occidental Cordillera of the Andes.

From 1978 to 1980, ENDE carried out the prefeasibility study for a geothermal power plant construction project at Laguna Colorada (it should be noted that Laguna Colorada is not the name of the geothermal field, but the name of the area where ENDE has its field camp – Sol de Mañana is the geothermal field’s name), with an Italian consultant. In 1982 a technical-economic evaluation was done considering the installation of a 30 MW plant.

In 1988, the government of Italy through ENEL and with the technical cooperation of the YPFB (Bolivian Oil Company) drilled first geothermal well in Bolivia, Apacheta–1, then continuous wells SM-01, SM-02, SM-03 and SM-04 were drilled from 1988 to 1989, resulting in steam production. Only SM-04 resulted in no steam, but good permeability as a reinjection well.

From 1991 to 1992, ENDE deepened the reinjection well SM-04 from 1474 to 1726 m and drilled the production well SM-05. The wells' production varies between 350 and 370 t/h of geothermal fluid (steam and brine), reservoir temperature and pressure are 250-260°C and 30-48 bar respectively.

Unfortunately, due to a change in the political situation the project was suspended in 1993.

From 1996 to 1997, ENDE contracted the Engineering Services of CFE of México to define the geothermal resource potential. CFE's study confirmed the minimum potential of the field is 100 MW.

CFE concluded that the potential of the field is 120 MW for 25 years with the required development of 20 production wells and 7 reinjection wells for approximately 4400t/h of brine.

In 2010, Japan International Cooperation Agency, JICA and the government of Bolivia started discussions to finance the construction of the 50 MW Laguna Colorada Geothermal Power Plant. As of now, 1st project is considered as the construction of 50 MW, while the total project would be 100 MW, based on the feasibility studies done in 2008 and 2010 by West–JEC with JICA cooperation.

In April 2010, the Environmental Impact Assessment for the Laguna Colorada Geothermal Project and transmission line finished.

2.2 Preparatory phase of the project.

In May 2011 the preparatory phase (called phase zero) of the project started. The main field activity of this phase, the well testing of the production wells SM-01, SM-02, SM-03 and reinjection well SM-04 was carried out from November 2012 to May 2013 (Figure 1). Due to obstacles in well SM-05, it was not possible to do well testing

FIGURE 1: Installation of MicroMod Tracer Injection Unit (TFT method) during well testing of SM – 03 in February 2013

Production tests were done for three wells with good results. During these production tests two different methods were used: TFT method and James–Tube method, both results corresponded very well as shown in Figure 2. (The green curve indicates the total flow by James, the blue curve is the total flow by TFT, respectively. The red curve indicates the steam flow and the purple curve is the brine flow both by TFT).

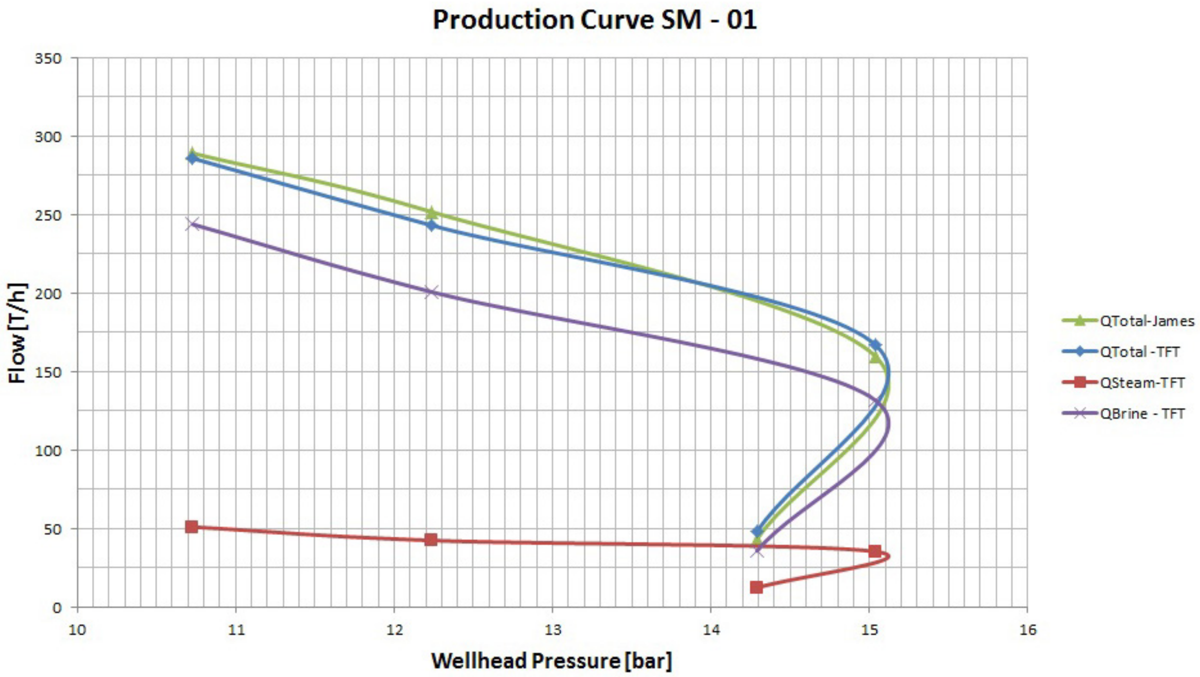

FIGURE 2: Production curve of SM-01 obtained using the TFT method and James–Tube method in December 2012

During phase zero well logging was also done for four wells with Kuster PTS memory tools. Dynamical and static logging confirmed the state of wells and a bottom temperature higher than 250°C (Figure 3). During reinjection to SM-04 the water level was monitored and confirmed good permeability of this well.

For the interference test, the pressure of two wells was always monitored during production. The results were very low interference between the wells (Figure 4). This implies that the size of reservoir could be large enough.

2.3 Current status of the geothermal project and future plan

Currently, ENDE continues environmental monitoring from 2011, with geotechnical studies, topographical studies, MT surveys, and others. All of them were done in the Sol de Mañana field.

In 2015, it is planned to start drilling procurement process for production and reinjection wells, in total 7 wells are planned to be drill. The construction of the power plant and necessary steam pipelines for 50MW will be also expected to start immediately.

Another 50 MW of development is expected after the 1st construction of the power plant, 100 MW in total is expected to be constructed.

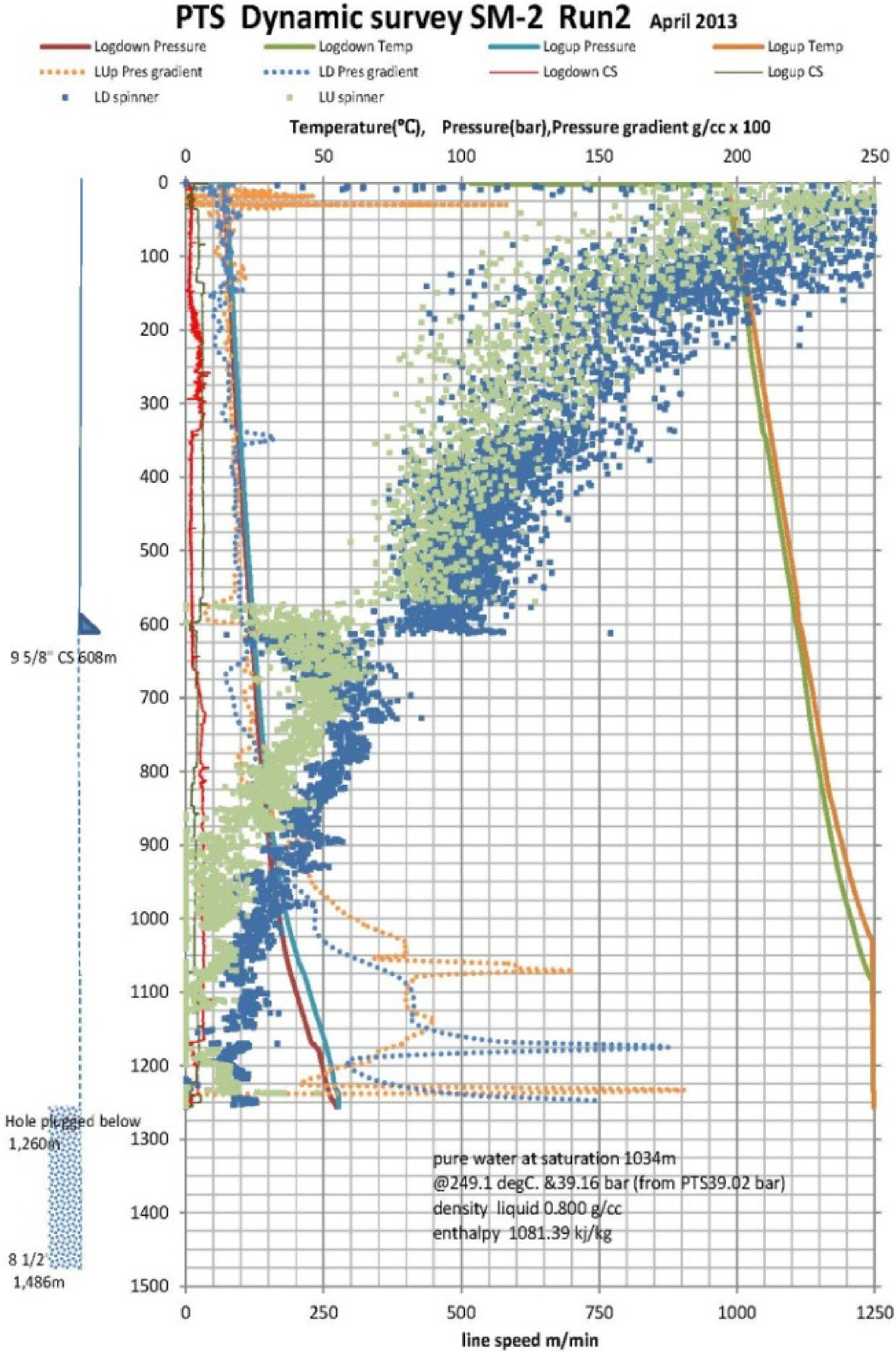

Figure 3: Logging PTS during production well SM-02 in April 2013

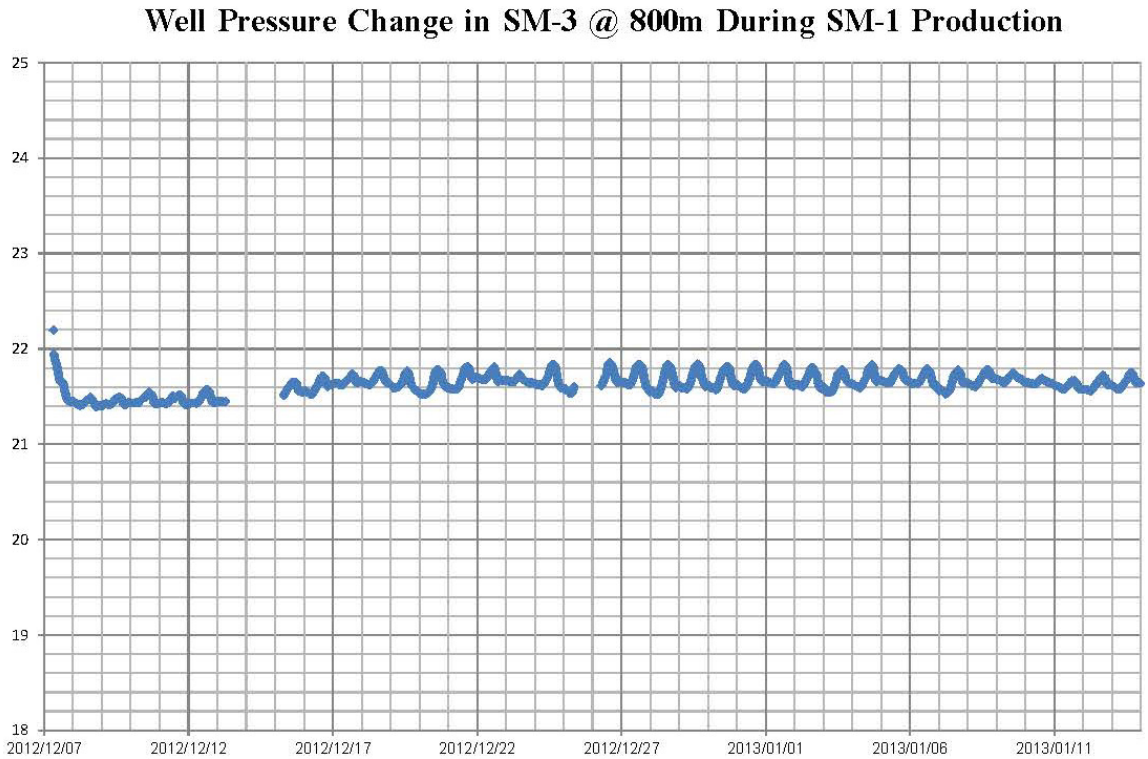

FIGURE 4: Monitoring pressure (bar) at 800m depth in SM-03 during SM-01 production

REFERENCES

CNDC, 2014: *Plan óptimo de expansión del sistema interconectado nacional 2012 - 2022.* Comité Nacional de Despacho de Carga (National Load Despatch Committee).

INE, 2012: *De 2,8 milliones de viviendas particulares, 2,2 milliones cuentan con energía eléctrica en el país*. Instituto Nacional de Estadística (National Institute of Statistics). Web: http://www.ine.gob.bo/pdf/boletin/NP_2013_32.pdf

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GEOTHERMAL DEVELOPMENT IN CHILE

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ABSTRACT

Chile has over 15% of the world's active and dormant volcanoes which form a continuous line about 4,000 km long. As a result, over 300 geothermal areas have been identified throughout the country. Geothermal resource potential is in the range of 16,000 MW, according to a preliminary estimate, while market based studies place the potential in a range of 1,750-5,200 MW for the year 2030. Chile has regulated geothermal development for private sector involvement since the year 2000 and although there have been more than US$ 380 million of investment commitment for exploration and over 85 exploration and exploitation concessions granted, currently, there are no projects in operation. The two most advanced projects are Cerro Pabellón and Curacautín, both with tested production wells and environmental approval for a 50 and 70 MW geothermal power plants respectively. The nature of the Chilean electricity market and the remote location of geothermal resources create high up-front cost for the development of any projects. Although these barriers may seem hard to overcome, unprecedented government and international support for geothermal have the potentials to accelerate projects to start the operation of the most mature projects by 2018. As for low-enthalpy geothermal, the lack of a proper regulation has clearly slowed the deployment of this technology, limiting its use to recreational purposes.

1. INTRODUCTION

Geothermal exploration in Chile was first conducted in 1907 in a geyser field in the northern region of Chile; soon after, Italian pioneers started the first geothermal exploration program in Antofagasta in the 1920s. However, systematic exploration started between 1968-1976 with a series of geological, geophysics and geochemistry studies in determined locations in the northern part of the country supported by a cooperation agreement between the Chilean Economic Development Agency (CORFO) and the United Nations. The exploration ended with the drilling of a well in the zone el Tatio, afterward economic crisis triggered the end of State driven exploration. From then on, only two institutions carried out occasional research and further studies, the University of Chile and the National Service of Geology and Mining (SERNAGEOMIN).

In the year 2000, the first law that regulated geothermal energy was enacted, but it was not until 2004 that rules of procedure for the implementation of the law were published. The law promotes the exploration and exploitation of geothermal resources by the private sector and establishes the existence of exploration and exploitation concessions. Further improvements in the rules of procedure were made in the year 2013, to streamline the concession process and provide developers with long-term certainty over development rights.

Because of the need of diversifying sources of energy, the government of Chile has a continued interest to promote geothermal development. Currently, the government is actively mobilizing different states agencies and engaging international cooperation to form an unprecedented support for geothermal in Chile, which may finally move projects into operation.

2. GEOTHERMAL RESOURCE AND MARKET POTENTIAL IN CHILE

Geothermal resources of the Andean region of Chile occur in close spatial relationship with active volcanism, which arises by the convergence of the Nazca and South America Plates. Chile is located in the pacific Fire Belt, a belt of volcanoes and earthquake epicentres where abundant resources of thermal energy can be found. The country has over 15% of the world's active and dormant volcanoes, forming a continuous line over 4,000 km long. As a result, Chile is one of the largest under-developed geothermal countries in the world.

Geological and geochemical reconnaissance surveys in the north a south regions have allowed to make a preliminary estimate of geothermal potential in Chile, approximately of 16,000 MW at least for 50 years of geothermal fluids with temperature exceeding 150°C, located at a depth less than 3,000 meters (Lahsen, 1986). On the other hand, market based studies estimate that the potential for geothermal is between 810 and 3,105 MW by the year 2021 (Comisión Asesora para el Desarollo Eléctrico (CADE), 2011) and most recently, in a joint platform that integrated different stakeholders of the electricity market, estimated between 1,750 and 5,200 MW of geothermal installed capacity by the year 2030 (Comité Técnico de la Plataforma Escenarios Energéticos Chile 2013, 2013).

3. REGULATORY FRAMEWORK AND GEOTHERMAL DEVELOPMENT IN CHILE

In January of 2000, the Law 19.657 that regulates geothermal energy was enacted, establishing a framework for the exploration and exploitation of geothermal energy in Chile. The law states that geothermal energy is a good susceptible of exploration and exploitation after the proper concession is granted.

The exploration concession gives the developer the right to carry out exploration work to determine geothermal potential. It has a validity of 2 years extendable for 2 more, with a maximum area of concession of 100,000 ha. The exploitation concessions awards the developer the right to carry out all the activities required for geothermal energy generation, including drilling, construction, commissioning and operation of an extraction system; the production and processing of geothermal fluids in electrical or thermal energy. It has an indefinite duration, with a maximum area of concession of 20,000 ha.

So far exploration is most intensive in the northern volcanic zone, were there about 90 thermal areas, and over 47 exploration concessions (Figure 1). However, the exploration in central-southern volcanic zone is also quite active, there are over 200 geothermal areas (Lahsen et al., 2010) and over 32 exploration concessions.

Table 1 shows the developments made so far in terms of hectares and investment commitment.

Almost 14 years have passed after the approval of the law, and there are so far no high enthalpy geothermal projects in operation. The main reason is high up-front cost and access to the electricity market; there are several reasons to explain this situation.

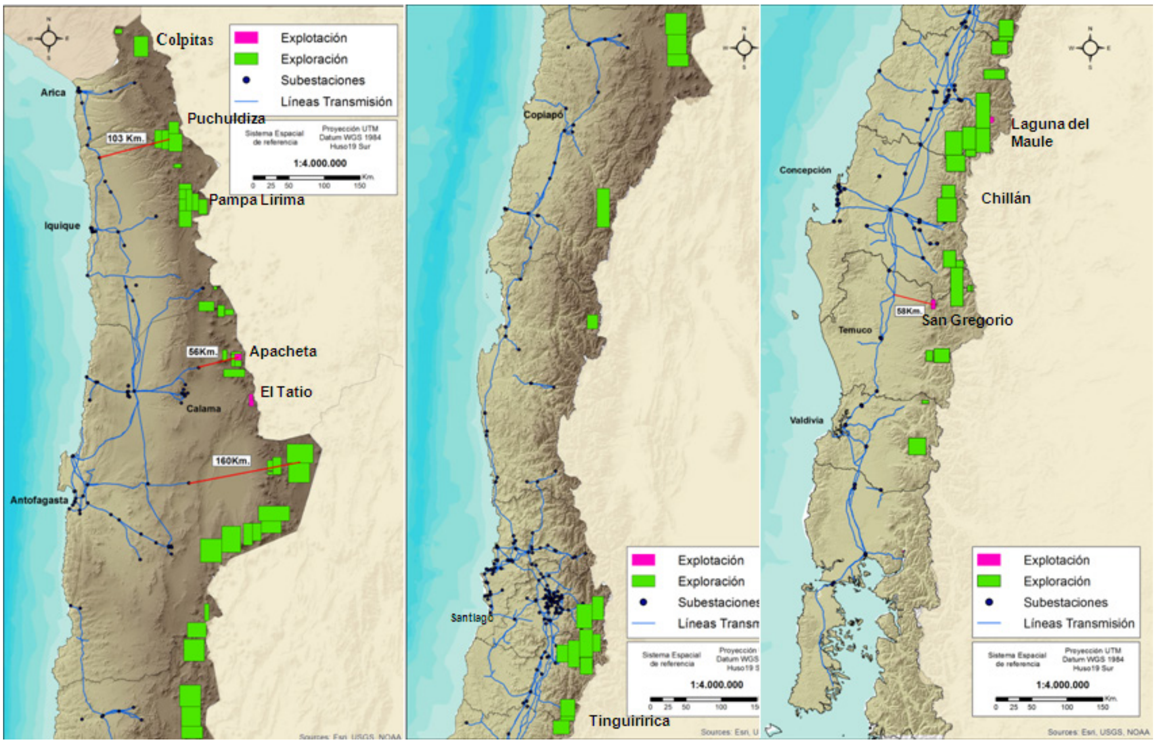

FIGURE 1: Geothermal concessions by area, data as of November 2013
Source: Ministry of Energy.

TABLE 1: Geothermal energy concessions, data as of November 2013. Source: Ministry of Energy.

Status	Quantity	Hectares	Commitment US$
Exploration Concessions	79	3 million	380 million
Exploitation Concessions	7	38.000	1160 million

The high altitudes and arid environment of the north create logistic difficulties for the location of camps and the extraction of industrial sites. On the other extreme, the glacial morphology of the south complicates access and there is also a limited window of time when work can be carried out. This cost can be more expensive given the absence, at this moment, of a consolidated geothermal industry. Additionally, as geothermal resources are remotely located, companies need to find big resources that can justify long transmission lines (Barria, 2013). Finally, geothermal developers that are in a very advanced stage are experiencing problems to participating in the electricity market, as for financing they require long term PPAs, and therefore are unable to participate in the spot market (Hiriart and Santa Rita, 2013).

As for low-enthalpy geothermal, the lack of a special regulation can explain in many ways the absence of projects. The law that regulates geothermal does not address in any specific way to low-enthalpy geothermal, although it does exclude thermal waters for touristic and medical purposes. As a result, low enthalpy geothermal has to struggle with the high demanding prerequisites and regulations established for large geothermal projects. Thus, so far low-enthalpy geothermal has been limited to recreational purposes and occasionally in demonstrative projects. However, since 2009 there is a proposed bill in congress willing to address this problem by creating special regulation for the development of low-enthalpy geothermal.

Even though there are considerable challenges for the development of geothermal, there are two project that are well advanced in terms of exploration, Cerro Pabellón and Curacautín, located in the northern and central-south volcanic zone respectively.

Cerro Pabellón (Apacheta concession)
Enel Green Power

Located in the northern volcanic-geothermal zone, the initial geothermal exploration at Cerro Pabellón (Figure 1) was conducted by ENG, the National Geothermal Company (ENAP-ENEL).

The company has conducted exploration in the area with favourable results. Two production wells (1,800 m, 245°C), 2 injector wells and 1 slim hole (700 m, 210°C). Results from the wells show a potential for 5-10 MW per well.

FIGURE 2: Geothermal project Cerro Pabellon. Source: Enel Green Power.

This was the first project to obtain environmental approval for a 50 MW geothermal plant and a 70 km high voltage line, which will connect to the Northern Interconnected Power Grid (SING). The projects consist of a 40 MW condensation plant and binary plant with a 10 MW additional capacity; it has an estimated cost of US$ 180 million and is planned to be operational by 2018.

Curacautín (San Gregorio concession)
Mighty River Power

The Curacautín project (Figure 3) is located in the central-southern volcanic zone, in the limits between Biobío and La Araucania Region, near the Tolhuaca volcano.

FIGURE 3: Geothermal project Curacautín. Source: Mighty River Power.

The company has conducted exploration in the area with promising results. Two production wells have been drilled (2,500 m, 290°C), 4 slim holes (1,100 m, 300°C), with a potential between 3-12 MW per well. In well Tolhuaca N4, a high-temperature, high-pressure, low-gas steam reservoir was discovered. The well was extensively flow tested over a period of 38 days and it is capable of producing at least 13 MW.

Since May 2013, the project has an environmental approval to build a 70 MW geothermal plant which will be connected to the Central Interconnected Power Grid (SIC). The project has an estimated cost of US$ 330 million and is planned to start operation in 2018.

4. INSTITUTIONAL SUPPORT, INTERNATIONAL FINANCING AND COOPERATION

The Ministry of Energy through its renewable energy division is continuingly creating the optimal market condition to boost renewable energy projects, which can guarantee their involvement in the energy mix. The Ministry of Energy is responsible for the administration of geothermal concessions as well producing new regulation to foster geothermal projects. In late 2013, a new study started, conducted by the Ministry, called "Strategic development plan for geothermal energy in Chile for 2050" to provide a long term framework for the development of geothermal projects, which will cover regulatory aspects, incentive mechanism, new procedure and short, medium and long-term plan to boost the development of the geothermal industry. Additionally, the Ministry has been able to leverage international cooperation, specifically, the Clean Technology Fund, in which in its last revision plan the government proposed to reallocate US$ 33 million to a Geothermal Risk Mitigation Program (MiRiG) (Clean Technology Fund, 2013). The proposed MiRiG Program would encourage private investors in geothermal energy through risk transfer mechanism reducing exploration cost and risks, and mobilizing private capital to ensure a sustainable growth in the long term.

The Renewable Energy Center (CER), the implementing arm of the Ministry of Energy, continues to promote renewable energy through market orientation for private investors, knowledge management for decision makers, capacity building and co-financing renewable energy initiative. Is important to note that CER is currently financing pre-investment studies for grid-connected large scale renewable energy projects, in which geothermal energy is applicable and financing self-supply renewable energy projects where low-enthalpy geothermal energy can also participate. Specifically for geothermal, CER has conducted efforts in capacity building for the public sector involved in the environmental assessments of geothermal projects, studies for the application of low enthalpy geothermal, as well as continuous work with the industry to provide inputs for policy design for the Ministry of Energy.

SERNAGEOMIN is a decentralized service that advices the Ministry of Mining; it contributes to governmental programs by developing mining and geological policies and offering geological information to governmental agencies, private investors and general public. SERNAGEOMIN is one of the public institutions that have done geothermal exploration, mainly geochemical, vulcanological studies, as well as detail geology of geothermal areas. In 2008, SERNAGEOMIN signed a contract with the German Bank KFW for the development of a geothermal program, with the objective of generating geological information orientated to the development of geothermal projects, specifically directed to: diminish the high exploration risk, spread the application and uses of geothermal and create technical and professional capacity in geothermal.

In 2011, the Andean Geothermal Centre of Excellence (CEGA) began its operations, funded by the National Commission of Research and Technology (CONICYT) comprised of a team of researchers from the Faculty of Physical and Mathematical Sciences at the University of Chile, along with scientists from other national institutions such as Pontificia Universidad Católica de Chile, Universidad Católica del Norte, Universidad de Concepción and UDA, and also international institutions. Its seven main research fields are: Magmatic Systems, Heat-Water-Rock Interaction, Fluids Geochemistry, Reservoir Architecture and Geofluid Dynamics, Structural Geology and Tectonics, Geophysics, and Surficial Processes and Environmental Impact. CEGA seeks to generate the necessary scientific knowledge to turn geothermal energy into a sustainable, environmentally friendly and economically competitive resource, in order to help increase the energy matrix of Chile and the Andean countries.

5. CONCLUSIONS

Chile has exceptional geothermal resources and over 13 year of regulatory framework for geothermal energy and has currently no projects in operation. Currently, geothermal exploration is very active, with over 86 exploration and exploitation concessions and with two projects in an advanced stage, Cerro Pabellón and Curacautín, with 50 and 70MW planed capacity, respectively.

The lack of projects in operation can be explained due to the high up-front cost created by the remote location of resources, lack of consolidated industry and the difficulty to participate in the electricity market.

Although these challenges are not be easily overcome, the need to diversify sources of energy and the high potential of geothermal is driving the government and international cooperation to actively invest in geothermal development. Optimistically, the committed support will be enough to mobilize the most advanced projects and to accelerate the projects that are in an exploration stage.

If low-enthalpy geothermal is to be develop soon, a special regulation needs to be in place to avoid the high prerequisite that small projects have to suffer; a proposed bill by the government already in congress seems to be the answer.

AKNOWLEDGEMENT

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REFERENCES

Barria, C., 2013: *Geothermal energy in Chile.* Ministry of Energy, presentation at the Global Geothermal Development Plan Roundtable, 21 pp. Web: https://www.esmap.org/sites/esmap.org/files/5-1%20GGDP%20Day2_Chile.pdf

Clean Technology Fund, 2013: *Investment plan for Chile – Revision*. Report, 29 pp. Web: https://www.climateinvestmentfunds.org/cif/sites/climateinvestmentfunds.org/files/CTF_IP_Revision_Chile_Sept2013.pdf

Comisión Asesora para el Desarrollo Eléctrico (CADE), 2011: *Informe final.* Ministry of Energy, report, 180 pp. Web: http://www.minenergia.cl/documento/descargar/id/5472

Comité Técnico de la Plataforma Escenarios Energéticos Chile 2030, 2013: *Visiones y temas clave para la matriz eléctrica.* Escenarios Energéticos Chile 2030, 112 pp. Website: http://escenariosenergeticos.cl/wp-content/uploads/Escenarios_Energeticos_2013.pdf

Hiriart, G., and Santa Rita, A., 2013: *Reporte del estado de la geotermia: Chile.* Agencia Internacional de Energías Renovables(IRENA), 52 pp.

Lahsen, A., 1986: Origen y potencial de energía geotérmica en los Andes de Chile. In: Frutos, J., Oyarzún, R., and Pincheira, M. (editors), *Geología y recursos minerales de Chile.* Universidad de Concepción, Chile, 423-438.

Lahsen, A., Muñoz, N., and Parada, M. A., 2010: Geothermal deveopment in Chile. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 7 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0118.pdf

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GEOTHERMAL DEVELOPMENT IN COLOMBIA

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ABSTRACT

Geothermal energy in Colombia is mostly exploited by direct uses, in tourism - bathing and swimming, and minor uses in heating; however, it is necessary to explore the potential of other uses such as power generation. Although Colombia is rich in energy generation, where its main production source is hydroelectric, other sources of renewable energy, such as geothermal energy are strategic to diversify the energy matrix and to increase the reliability associated with hydroelectric power generation.

Initial reconnaissance studies of geothermal resources in Colombia were held in the 1970s, in spite of that, geothermal development in this country is considered incipient, and there is no installed geothermal power capacity yet. Currently, with support of different entities, national and abroad, there are two projects in the prefeasibility and feasibility stages in progress in the country, with 190 MW of geothermal potential in the Macizo Volcánico del Ruiz and Tufiño-Chiles-Cerro Negro areas. Other studies have been developed by the Colombian Geological Survey (SGC), which has conducted reconnaissance and prefeasibility studies in some areas, such as the Paipa, Azufral Volcano, San Diego Maar, Cerro Machín Volcano, and others, in order to increase the knowledge of the geothermal potential of the country.

1. INTRODUCTION

Colombia has a privileged geographical position and a favourable geological setting, because it is located in the Pacific Ring of Fire, an area where the natural temperature of the ground, close to the surface is high due to the volcanic activity associated with features suitable for geothermal exploitation.

Recognition studies supported by the Latin American Energy Organization (OLADE) and the Colombian Institute of Electricity (ICEL) concluded that Colombia has at least nine areas of interest for geothermal electricity generation or direct use of steam for industrial processes or tourism.

Since 2008 and with the support of different entities, ISAGEN has been supporting the Basic Feasibility Study for the Development of a geothermal project in the Macizo Volcánico del Ruiz Volcanic Massif. In addition and in order to develop a Bilateral Agreement signed by Colombia's and Ecuador's Presidents, ISAGEN and Corporación Eléctrica del Ecuador (CELEC EP) began together the prefeasibility studies to develop a geothermal project along the border region between the two countries.

1.1 The current state of energy

Colombia has an installed electricity capacity close to 14,500 MW, from which 9,800 MW are based on hydroelectric power, 4,680 MW based on thermal power and about 18 MW based on wind energy.

The country finds it necessary to develop renewable energy projects that are cleaner and friendlier towards the environment. These are the reasons why the Colombian State has established a National Energetic Plan with the following objectives: Expand and warrant the energy provision; Promote regional and local development; Introduce new sources and technologies of energy generation; Contribute to reduce the greenhouse gas emission and climate change; Promote the use of renewable energy sources. For these reasons the Colombian Government is interested in the study and development of non-conventional renewable energy sources, to diversify the energy matrix and increase the reliability associated with hydroelectric generation.

1.2 Colombian geothermal potential

Volcanism in Colombia is part of a complex tectonic framework generated by the interaction between the South American, Nazca and Caribbean plates. The convergence of the Nazca oceanic plate under the South American collides obliquely in this segment of the Andes at speeds of about 54 mm per year (Trenkamp et al., 2002). This process conform a seismically active zone with trenches and volcanism along the axis of the Central Colombian Cordillera and in the south in Western Cordillera, with at least 15 active volcanoes. Seismological studies have agreed to propose a discontinuous character in the Colombian-Ecuadorian subduction, causing segmentation of Colombian Volcanism in: the north volcanic segment (Volcanic complex Cerro Bravo – Cerro Machín), the central volcanic segment and the south volcanic segment.

Colombian geothermal capacity is evident in zones around the Chiles, Cerro Negro, Cumbal, Azufral, Galeras, Doña Juana, Sotará, Puracé, Nevado del Huila, Nevado del Ruiz and Nevado del Tolima volcanoes. These volcanoes are quaternary volcanoes, with hot springs, fumaroles, superficial hydrothermal alteration, and other thermal features, that could be evidence of the existence of a geothermal resource, probably with adequate characteristics for being used in power generation. Other non-volcanic areas, which could have some potential, are found in the Los Llanos basin (high geothermal anomaly) and along the Caguan-Putumayo basin and the Magdalena Valley (Vargas et al. 2009) (Figure 1, yellow circles). Colombia's geothermal potential has been estimated at 2,210 MW (Battocletti, 1999), and current installed capacity in direct use is about 14.4 MW, for a total annual use 287.0 TJ/year (Alfaro et al., 2005).

2. BACKGROUND FOR GEOTHERMAL ENERGY DEVELOPMENT IN COLOMBIA

In the past, Central Hidroeléctrica de Caldas (CHEC), Geoenergía Andina (GESA) and entities like the Latin American Energy Organization (OLADE), Planning and Promotion of Energetic Solutions Institute (IPSE), Geological Colombian Survey (SGC previously known as INGEOMINAS) and the Mining and Energy Planning Unit (UPME) have made studies to explore the potential of the geothermal resource, such as:

- Reconnaissance Study of geothermal fields in Colombia and Ecuador (OLADE, AQUATER, BRGM and GEOTÉRMICA ITALIANA, 1979 to 1982).
- Prefeasibility studies for geothermal development in the Tufiño-Chiles-Cerro Negro area (INECEL-OLADE, 1982; OLADE-ICEL, 1986-1987).
- Prefeasibility studies for geothermal development in the Nevado del Ruíz Volcano area (CHEC, 1983; GEOCÓNSUL, 1992; GESA, 1997). Drilling Nereidas-1 Geothermal Well.

FIGURE 1: Geothermal potential zones in Colombia

- Research studies of the geothermal systems in the Azufral and Cumbal volcanoes areas (INGEOMINAS, 1998-1999, 2008-2009; INGEOMINAS - Universidad Nacional de Colombia, 2006).
- Research studies of the geothermal systems of the Paipa and Iza areas (INGEOMINAS, 2005, 2008-2009).

- Additional researches of the geothermal resource in the Tufiño area and the geothermal development plan in Ecuador (MEER, 2008 – 2009).
- Feasibility studies for the generation of geothermal energy in Colombia (ISAGEN-USTDA-BPC-INGEOMINAS, 2008-2009).
- Report of the well PGT-1, perforated in Aguas Hediondas (MEER, 2010).
- Strategic program for the modelling of the hydrothermal-magmatic system of the Nevado del Ruíz volcano (ISAGEN-UNAL-INGEOMINAS, ISAGEN, COLCIENCIAS, 2010-2012).
- Prefeasibility studies to develop the Tufiño-Chiles-Cerro Negro Binational Geothermal Project (ISAGEN-CELEC EP, 2010-2012).
- Modeling of the resistive structure by magnetotelluric studies (ISAGEN-INGEOMINAS-CIF-UNAM-COLCIENCIAS, 2011-2012).
- Prefeasibility studies of the Macizo Volcánico del Ruiz Volcanic. Drilling of three TGW, between 174 to 300 m in depth (ISAGEN-BID-NIPPON KOEI-GEOTHERMAL-INTEGRAL, 2011-2012).
- Catalytic Investments for Geothermal Energy. Complementation of a resistive model, advice and support during exploratory drilling stage (ISAGEN-BID/GEF, 2011-2014).

3. RESEARCH AND EXPLORATION OF GEOTHERMAL RESOURCES

Geothermal research in Colombia is led by entities like ISAGEN, Geological Colombian Survey (SGC), Empresas Públicas de Medellín (EPM) and the Mining and Energy Planning Unit (UPME), which are developing prefeasibility and regulatory studies regarding geothermal use in the country.

The studies developed by electrical companies and government agencies are in the early stages of development (Table 1).

ISAGEN is developing two specific projects: Macizo Volcánico del Ruiz and Tufiño-Chiles-Cerro Negro. (i) The Macizo Volcánico del Ruíz Project is ending the prefeasibility studies and establishing and preparing the contractual documents required for exploratory drilling. (ii) The Tufiño-Chiles-Cerro Negro; Binational Geothermal Project which is in the prefeasibility stage, which consists of geological, geochemical, hydrogeological and geophysical studies; deep slim hole drilling or thermal gradient holes and the design of exploration wells, infrastructure and environmental impact studies.

On the other hand, the Geological Colombian Survey (SGC)'s plan of geothermal research (SGC, 2014) includes reconnaissance and prefeasibility studies in some areas, such as the Paipa, Azufral Volcano, the Nevado del Ruíz Volcano, San Diego Maar, the Cerro Machín Volcano and the Santa Rosa zone. In general, studies have been focused on the acquisition of geophysical information and to update the conceptual models. Moreover, it has projected five thermal gradient wells and one deep drilling well in the Paipa area and another one in the Azufral Volcano area.

Empresas Públicas de Medellín E.S.P. (EPM) and its subsidiary Central Hydroelectric de Caldas S.A. (CHEC) are presently evaluating the geothermal potential within the Nereidas Valley near to the Nevado del Ruiz volcano. Currently, it appears that the survey area has significant geothermal potential.

Likewise, the Mining and Energy Planning Unit (UPME) has advanced some regulatory studies in order to promote non-conventional energy sources, including geothermal, through the elaboration of the geothermal potential map and a study about current state of renewable energy and its development plan (UPME, 2013).

3.1 The Macizo Volcánico Nevado del Ruiz Project

Since 2010 to the present, ISAGEN has developed exploration studies in an area of 200 km^2 around the Nevado del Ruiz Volcano. The activities include a cartographic restitution, 1:5,000 scale, a detailed structural geology, hydrothermal alteration, fluid inclusion analysis, geochemistry of thermal waters, hydrogeology and geophysics. Overlay anomalies of magnetometric and gravimetric surveys, and the structural lineaments, allowed to identify areas with potentially anomalous thermal gradients near the surface (Figure 2). In 2011, ISAGEN drilled three thermal gradient wells, reaching 300 m in depth (Figure 3).

Table 1: State of current geothermal project develop in Colombia. N.D.: Not defined

Project	Estimated Capacity	Current Status	Inversion (USD)
Macizo Volcánico Nevado del Ruíz	50 MW	Prefeasibility studies is finished. EIA in approbation, by National Environmental Agency Licenses. ISAGEN. 3 TGW perforated 2011-2012.	6 Million
Binational Project: Chiles–Tufiño–Cerro Negro	138 MW	Prefeasibility studies in progress. ISAGEN-CELEC.	4 Million
Paipa	N.D.	Prefeasibility studies. SGC.	N.D.
Azufral Volcano	N.D.	Prefeasibility studies. SGC.	N.D.
San Diego Maar	N.D.	Prefeasibility studies. SGC.	N.D.

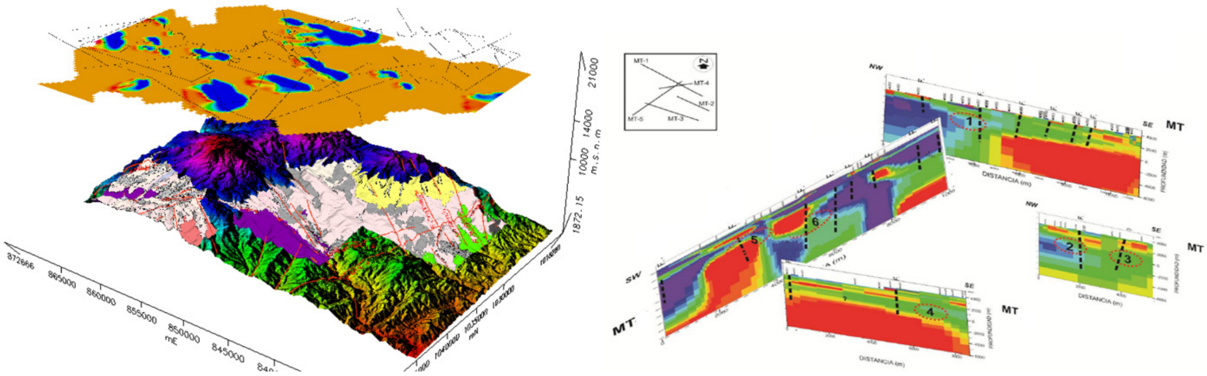

FIGURE 2: Left, 3D modelling with geologic and structural mapping overlap and index overlay anomalies based on geophysics surveys. Right, MT profiles of the Nevado del Ruiz area.

A MT survey consisting of 200 soundings was made and a 3D inverse model has been processed. As a result, a Geothermal Conceptual model was obtained, and five targets for exploratory deep wells were chosen. The selected exploratory wells are 1700 m to 2700 m depth, the expected temperature of the reservoir is about 200°C, which targets some fault zones and a fractured reservoir. Currently, the National Agency of Environmental License is evaluating the Environmental Impact Study (EIA), for exploratory wells, including the design of the wells, platforms and access roads.

The next stage, planned to be executed in the next two years, is drilling exploratory wells and reservoir evaluation, field planning development and plant design. It is expected that construction and operation of a power plant of 50 MW could be ready in 2018.

An important result of the studies performed in association with the Geological Colombian Survey (SGC), the Administrative Department of Science, the Technology and Innovation of Colombia (COLCIENCIAS), and the Universidad National de Colombia, is the institutional strengthening and technical capacity building of the country. Research institutions were provided with modern laboratory and field equipment for geothermal exploration and other applications; received training in geothermal exploration techniques and attended courses and scientific events abroad; and tightened inter-institutional ties. This leads to the creation of shared value for the development of geothermal energy in the country.

FIGURE 3: Left, rig used for TGW 1; Right, cores obtained, mainly andesites with fracture zones and propilitic alteration crossed by calcite veins

3.2 The Binational Tufiño-Chiles-Cerro Negro Project

In the execution of a Binational Agreement signed by the governments of Colombia and Ecuador on July 2010, to study the potential use of the geothermal resource identified at the border between both countries, ISAGEN S.A. and Corporación Eléctrica del Ecuador CELEC EP signed a Technical Cooperation Specific Agreement on April 5th of 2012, for the purpose of proceeding with pre-feasibility studies of the Tufiño-Chiles-Cerro Negro Binational Geothermal Project. The area to be developed extends throughout 49,000 ha, and a potential of 138 MW is expected.

Since 2012 to present, both ISAGEN and CELEC EP have developed activities such as compilation and a review of geothermal exploration studies, project socialization, 1:5,000 scale cartographic restitution, and the shooting of aerial photographs at a 1:15,000 scale. Currently, both companies are conducting with a consultant support the geological, structural, hydrothermal alteration mapping and geochemistry sampling (cold water and gas) for continuing with magnetotelluric studies, elaboration of geothermal conceptual modelling, drilling of slim hole or thermal gradient wells, selection targets for exploratory deep wells, design of wells, platforms and road access and finally preparation of the Environmental Impact Study (EIA).

4. BARRIERS TO GEOTHERMAL DEVELOPMENT

The experience of the evaluation of geothermal projects under development has identified some barriers that are listed in the following paragraph (BID-ISAGEN, 2013):

- Geothermal development requires specialized studies for characterization and exploitation of the resource.
- Colombia has a limited technical and scientific capacity for the development of the geothermal resource.
- Preliminary phases of exploration involves high investment costs and high risks, therefore it requires financial assistance.
- Geothermal areas are located in volcanic zones without infrastructure for access and connection to the National Transmission System (NTS).
- It is necessary to adjust the environmental regulation for the development and exploitation of the geothermal resource and its participation in the energy market.
- It is important to recognize externalities or intangibles that could not be assessed in a typical financial analysis, such as: Reduction of vulnerability of the electrical system against climate change; Complementarity of Hydropower; Reduction of greenhouse gas emissions; Decreasing the demand and consumption of fossil fuels.

REFERENCES

Alfaro, C., Velandia, F., and Cepeda, H., 2005: Colombian geothermal resources. *Proceedings World Geothermal Congress, Antalya, Turkey*, 11 pp. Website: http://www.geothermalenergy.org/pdf/IGAstandard/WGC/2005/0137.pdf

Battocletti, L. 1999: *Geothermal resources in Latin America and the Caribbean*. BoB Lawrence & Associates, Inc., 214 pp. Website: http://bl-a.com/ecb/PDFFiles/GeoResLAC.pdf

BID-ISAGEN, 2013: *Emprendimiento de la energía geotérmica en Colombia*. Banco Interamericano de Desarrollo, Washington D.C., 211 pp.

SGC, 2014: *Informe de gestión 2013*. Servicio Geológico Colombiano, 201 pp. http://www.sgc.gov.co/Nosotros/Planes,-Presupuesto-y-Gestion/archivos/Informe-de-Gestion.aspx

Trenkamp, R., Kellogg, J.N., Freymuller, J.T., and Mora, H.P., 2002: Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. *Journal of South American Earth Sciences, 15*, 157-171.

UPME, 2013: Plan de Expansión de Referencia Generación – Transmisión 2013 – 2027. *Unidad de Paneación Minero Energética*, 465 pp.

Vargas, C., Alfaro, C., Briceño, L., Alvarado, I., Quintero, W., 2009: Mapa geotérmico de Colombia 2009. *X Simposio Bolivariano Exploración Petrolera en Cuencas Subandinas – Abstract, Cartagena, Colombia*, 1-5.

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GEOTHERMAL DEVELOPMENT IN ECUADOR: HISTORY, CURRENT STATUS AND FUTURE

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ABSTRACT

Exploration of geothermal resources in Ecuador began in 1979. Three decades later, the high enthalpy geothermal projects of Chachimbiro, Chacana and Chalpatán have reached the advanced prefeasibility stage, while the Tufiño-Chiles-Cerro Negro and Chalupas projects are currently under research. The present exploitation of geothermal resources in Ecuador is restricted to bathing resorts, balneology and swimming pools. The total geothermal potential of the country is estimated at 3000 MWe. Nothing unusual, considering the fact that the country is traversed by more than 40 active volcanoes. The total installed capacity of geothermal energy for direct heat applications in 2009 was 5 MWt, with a slight increase over the last five years. Currently, a plan to carry out prefeasibility studies on twenty two undeveloped prospects is being discussed.

1. INTRODUCTION

Reconnaissance and exploration of geothermal resources in Ecuador is not relatively new. Nonetheless, the search for geothermal energy has found several obstacles that have inevitably delayed its exploitation. The dissolution of state entities that lead geothermal research activities along with the financial cutbacks and lack of specialists in geothermal engineering branches were some of the main drawbacks in the past. Consequently, they caused a slow development of research studies in the prospects with the most promising potential for electricity generation purposes. At the present, three prospects have reached a drilling point stage and at least one is expected to be operational within the next 5 years. Attention has also been put on developing mid and low temperature research projects for alternate uses such as fish hatchery, greenhouse heating, space heating and industrial applications. The following sections are intended to give a basic overview of historical geothermal activity and the state of geothermal development in the country.

2. BACKGROUND

2.1 Geothermal exploration in Ecuador 1979-2013

Reconnaissance studies for geothermal resources in Ecuador began in 1979. The "Geothermal Investigation Project" was the first of its kind carried out by the Latin American Energy Organization (OLADE), the Ecuadorian Institute of Electrification (INECEL), the Bureau de Recherches Geologiques et Mineres (BRGM) and the private company AQUATER. The objective was to select areas suitable for geothermal exploration of high enthalpy resources for electricity generation purposes. The project was executed following the guidelines established by OLADE, to undertake a geothermal reconnaissance study (OLADE, 1978). The study comprised a two stage research. The first stage involved field surveys to study detailed geology, petrology and volcanology along the Ecuadorian Andes chain affected by a development of the Plio-Quaternary volcanic activity. This region is divided into 3 areas, shown in Figure 1: from the Columbian border to Cotopaxi, the area around the Chimborazo mount and the Cuenca-Azogues area.

Other geological areas of the country were not considered due to a lack of recent volcanic activity or constrained access. Preliminary reconnaissance activities which include air photos, field observation, laboratory analyses of rock samples, chemical elements in water and datings using different methodologies, were carried out. As a result, a geo-vulcanological report identified areas with the most favorable geothermal conditions in the country.

The second stage consisted of a hydrogeology analysis based on the reconstruction of the regional hydrogeological conditions along the country. Meteorological parameters were measured on site and cold/hot water sampling activities were performed where thermal manifestations were spotted. The final report pointed out the need to undertake a more detailed research (prefeasibility) to study permeability characteristics over the most promising geothermal prospects (Tufiño, Chachimbiro, Chalupas). A geochemistry campaign was recommended to determine the origin of the hot springs that were spotted.

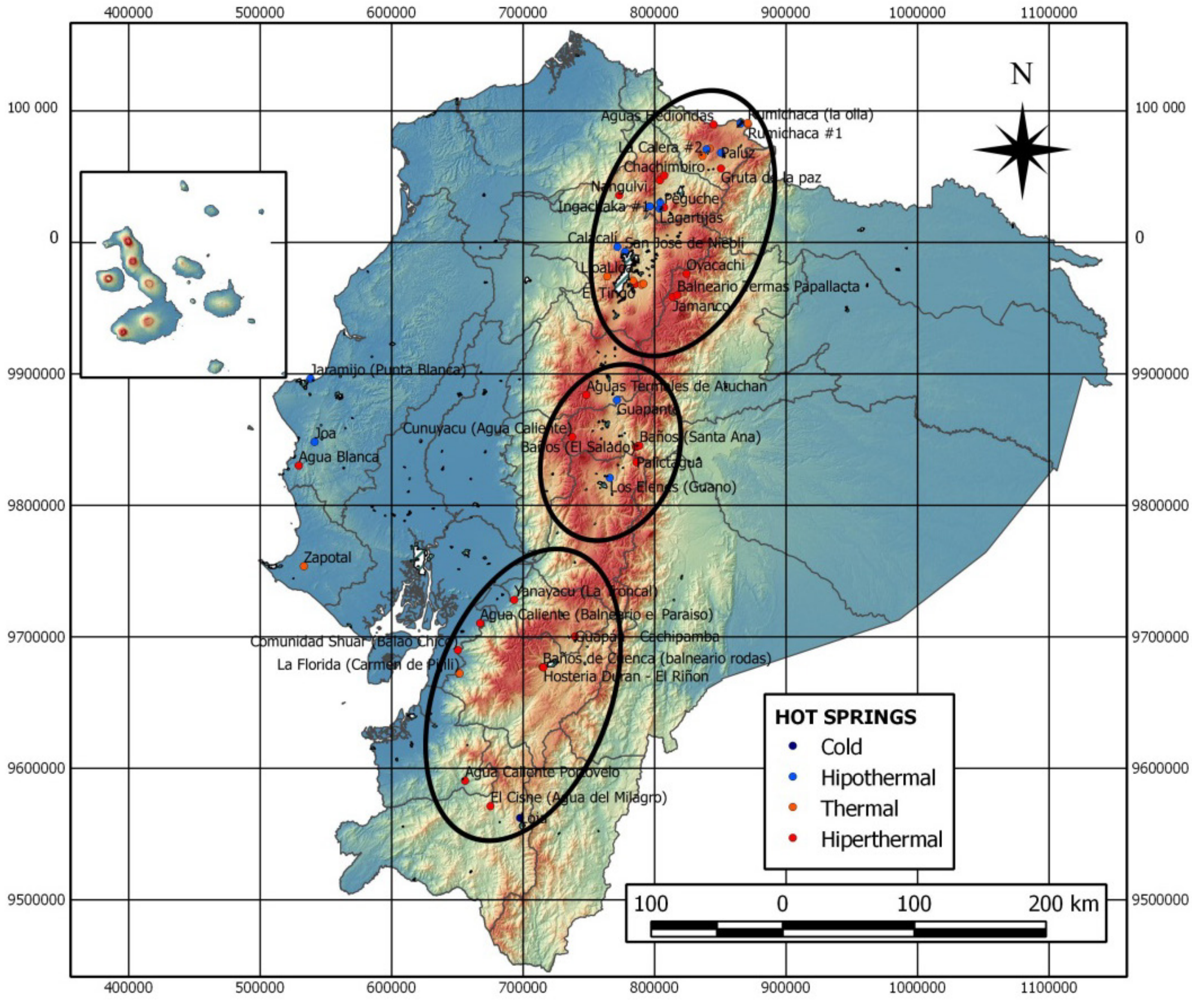

FIGURE 1: Areas analyzed in the reconnaissance study of 1979

2.2 Prefeasibility studies

In 1981, following the recommendations made in the reconnaissance study, a stage one prefeasibility study (geology, hydrogeology and geochemistry studies that end in a preliminary geothermal conceptual model before a geophysics campaign) was executed in Chachimbiro and Chalupas. For the Tufiño prospect, OLADE undertook a simultaneous campaign with INECEL and the Colombian Institute of Energy (ICEL) (OLADE, 1981). The purpose of this campaign was to further develop geothermal research activities in the area. As a result, Chiles-Cerro Negro (within the same area as the Tufiño prospect) was declared by the Colombian government an area of interest for geothermal development. This lead to a joint research agreement, signed between the two countries in 1982. Consequently, Ecuador and Colombia began the exploration phase as a bi-national project in a 250 km^2 area.

AQUATER and OLADE provided technical assistance to continue prefeasibility studies in the now renamed Tufiño-Chiles-Cerro Negro project from 1986 to 1987 (OLADE, 1987). Detailed geological, geochemical and geophysical activities were carried out. As a result, a preliminary high enthalpy resource model was developed. Followed suit, INECEL carried out 53 Vertical Electrical Resistivity Soundings (VES) in the area to identify hydrothermal activity, and to enhance surface data geology obtained in previous studies (Aguilera, 2010). Between 1983 and 1990, INECEL and the International Atomic Energy Agency (IAEA) also carried out geochemical studies in Chalupas and Chachimbiro to gather more information about their potential for generation purposes (INECEL, 1983).

Unfortunately, all scientific research related to geothermal reconnaissance and exploration ceased in 1993 due to political reasons and financial cutbacks. In 1996, the Economic Commission for Latin America and the Caribbean (CEPAL) and the European Union (EU) presented a project called "Development of Geothermal Resources in Latin America and the Caribbean". The project aimed to strengthen the institutional and legal capacity of government bodies to promote a sustainable exploitation of geothermal resources in Latin America. The project ended in 1998, resulting in more than one country being suitable for further studies. Nevertheless, Ecuador was surprisingly listed as first candidate due to its high resource potential, estimated at 534 MWe (Data provided by the Energy Economic Information System, OLADE). The government formally requested technical assistance from CEPAL to develop a strategy for future exploitation of geothermal resources in the country. This plan was finalized by a CEPAL consultant in 1999. Meanwhile, geochemical and isotopic studies were resumed in Chachimbiro and Tufiño, from 1999 to 2001 with the assistance of IAEA. The scope of this research also included other areas recommended in OLADE's reconnaissance study. The results of the geochemical and isotopic samples were discussed by Aguilera et al. (2005), in a scientific report published by Elsevier.

Geothermal exploration was interrupted again in 2002, when Ecuador went through an internal financial crisis. This had a collateral impact on scientific research funding, cutting the resources needed to conclude the studies currently underway. Five years later, in 2007, the need to diversify the country's energy matrix became a national policy. Consequently, attention was put again on geothermal energy due to its high capacity factor. In 2008, CONELEC hired a former INECEL researcher to deliver a project outline for the Chalupas prospect and an abridgment of all geothermal prospects from 1979 up to the present. The final report stated that Chalupas is currently at a prefeasibility stage, and further geophysics (mainly Magneto Telluric surveys) studies were required to estimate the resource's temperature (Beate, 2008). The study also displayed a list of twenty two areas of geothermal interest based on previous studies. One year later, the Ecuador Electric Corporation (CELEC EP) commissioned advanced reconnaissance studies for the Chacana prospect. Aguilera (2010) indicated an estimated potential of 1480 MW_e divided into three areas within the caldera: Cachiyacu, Jamanco and Oyacachi. Later in the same year, the Ministry of Electricity and Renewable Energy (MEER) restarted exploration at the Tufiño-Chiles-Cerro Negro project. The first geothermal exploration slim hole in Ecuador was completed in May 2009, reaching a depth of 554 meters. Research activities continued with funding provided by the National Secretariat for Science and Technology (SENACYT). In 2010, MEER requested a "Plan for the Development of Geothermal Resources", which was entrusted to the same experienced consultant that delivered the prefeasibility studies for the Chalupas prospect. This document had an emphasis on electricity generation purposes, and consequently, ended up ranking geothermal prospects in the country based on its highest potential, taken from previous prefeasibility studies. In 2012, the National Institute for Pre-investment Studies (INP) commissioned the study of the Chalpatán prospect to a private consulting firm (CGS) and CELEC. Prefeasibility studies concluded in 2013, with temperatures estimated to be below 120°C (CGS, 2013). Consequently, the project turned out to be insufficient in terms of electricity generation purposes. However, the location close to the city of Tulcán gives the possibility for direct use of this geothermal resource for industrial and agricultural purposes. Further studies involve drilling exploration wells to prove the resource's potential.

3. CURRENT STATUS OF GEOTHERMAL PROSPECTS IN ECUADOR

The current status of the geothermal prospects is presented in this section, providing a general overview of the most promising prospects and also addressing the prospects in which further development for direct use can be achieved.

3.1 Tufiño-Chiles-Cerro Negro

Many prefeasibility studies have been carried out in specific areas of the Tufiño-Chiles-Cerro Negro prospect, shown in Figure 2. Nevertheless, the prospect has not yet been studied integrally. Therefore, additional geological and geochemical studies are required to enhance the conceptual models of the prospect. Complementary magneto-tellurics (MT) and time-domain electromagnetics (TDEM) surveys will also provide a better understanding of the resistivity anomaly in the main area of the prospect. Re-analysis of geological, geochemical and geophysical surface exploration data was endorsed to a private consulting group which is currently executing field activities.

If these complementary studies are positive and a high temperature resource is proven, feasibility studies must be undertaken to prove the resource's production capacity. Beate (2010) states in his

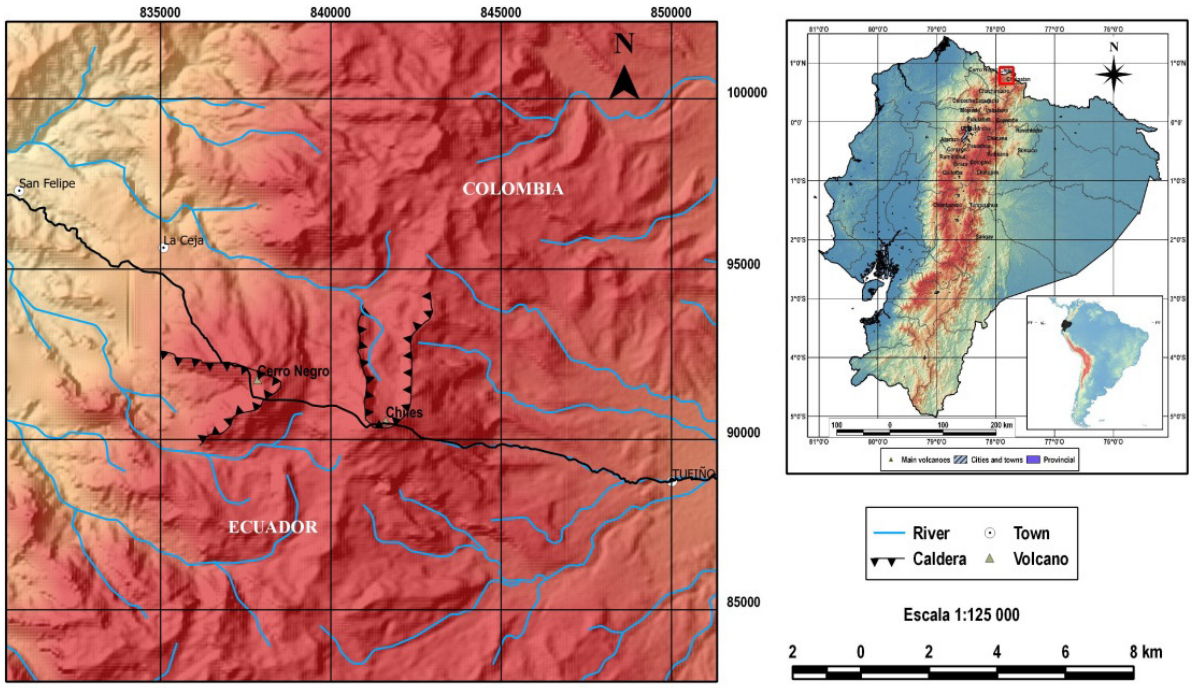

FIGURE 2: Location of the Tufiño-Chiles-Cerro Negro prospect

review an estimate of 138 MWe for the Tufiño prospect, based on surface data geology presented by Almeida (1990).

3.2 Chachimbiro

Preliminary feasibility studies in the Chachimbiro prospect (Figure 3) concluded in 2012. The assessment of risk factors, which include the reservoir temperature, permeability and fluid chemistry, indicate a probability of success of 65%. Drilling of shallow exploration wells will allow the quantification and evaluation of the geothermal reservoir. A low cost 1500 m depth slim hole is recommended to determine the sustainability of the resource for long term production. If the results from exploration wells are positive, advanced feasibility studies must be oriented to determine the suitability of the project for electricity generation purposes or for direct use. The project is currently undergoing environmental impact assessment. The Japan International Cooperation Agency (JICA) has showed interest in financing the feasibility stage. The geothermal potential of Chachimbiro is estimated to be 81 MWe.

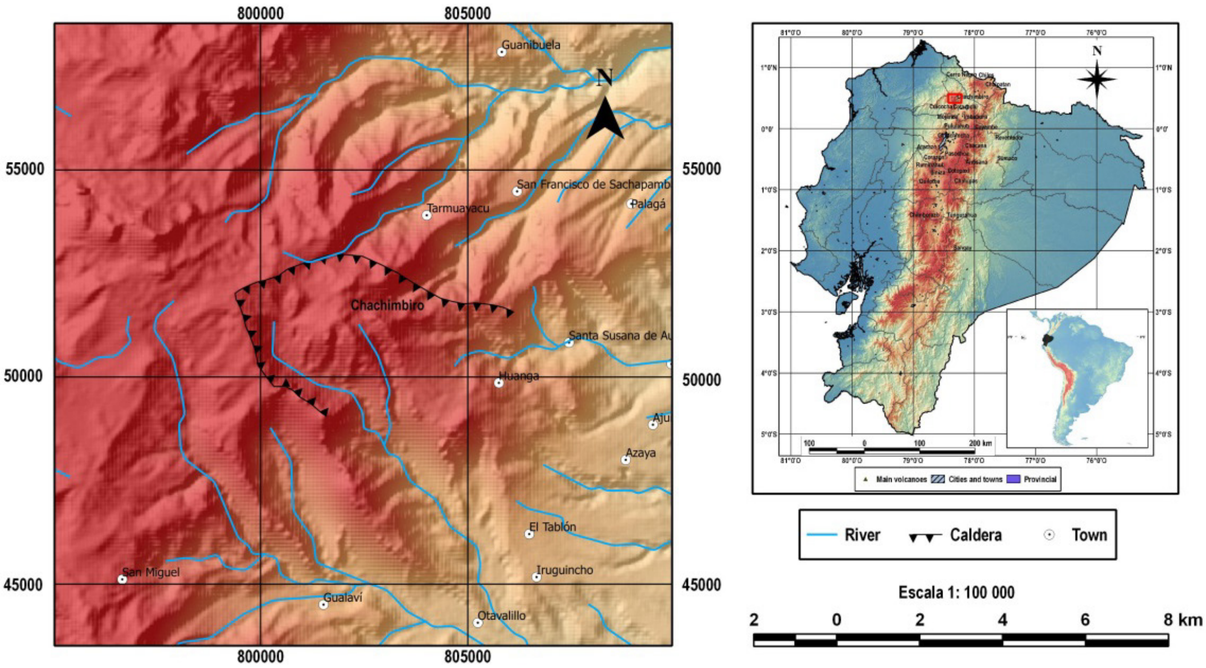

FIGURE 3: Location of the Chachimbiro prospect

3.3 Chacana

Chacana has a good potential for hosting a geothermal reservoir at a shallow depth due to the geological conditions and rhyolite volcanic properties, which are persistent in time. Previous geological, geochemical and geophysical studies resulted in three preliminary conceptual models (Villares, 2010). CELEC EP commissioned prefeasibility studies in the Chacana prospect (Figure 4) in 2011. The next stage consists of drilling two exploratory slim holes to depths of 600 m and 900 m. The purpose of these exploration wells is to intersect the main faults inside the caldera and to reach the reservoirs in Cachiyacu and Jamanco. Once the drilling stage is completed, reservoir temperatures and permeability can be properly verified. The project is currently undergoing environmental impact assessment. The potential expected in Jamanco is 13 MWe and of Cachiyacu is 39 MWe.

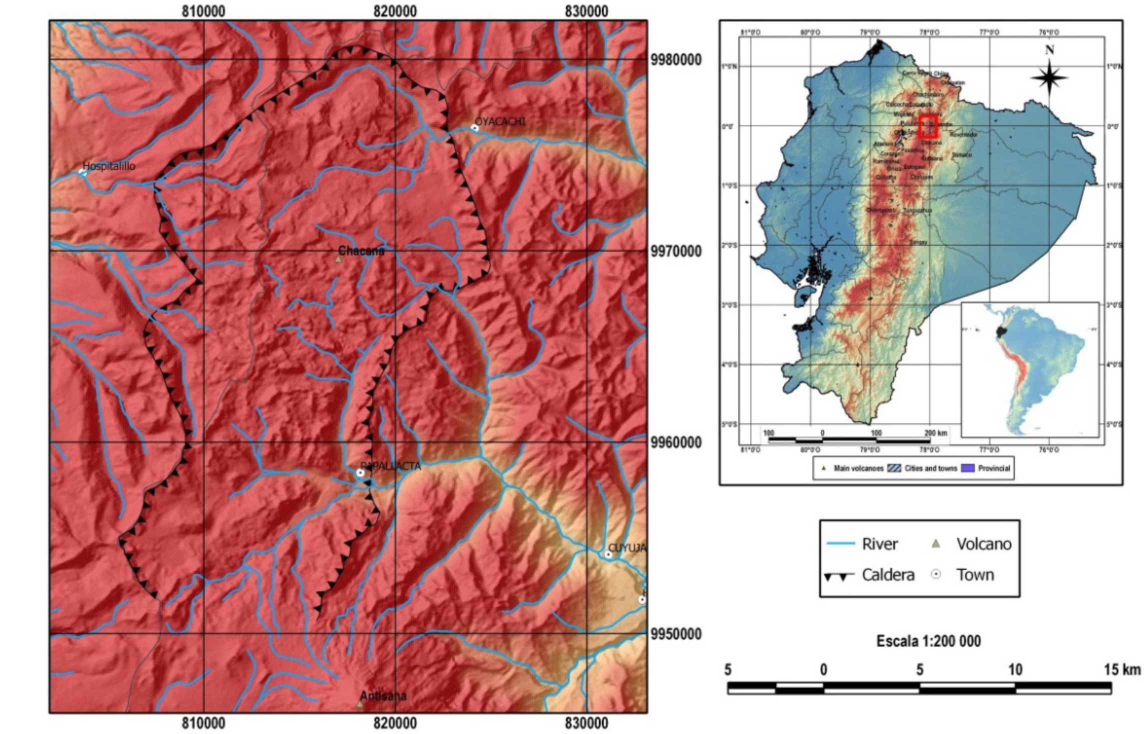

FIGURE 4: Location of the Chacana prospect

3.4 Chalpatán

Due to its proximity to Tufiño–Chiles-Cerro Negro, the Chalpatán caldera (Figure 5) was also studied by OLADE, INECEL and ICEL from 1982 to 1987. Prefeasibility studies were completed in 2013. These studies included the use of state of the art technologies, such as satellite and airborne infrared

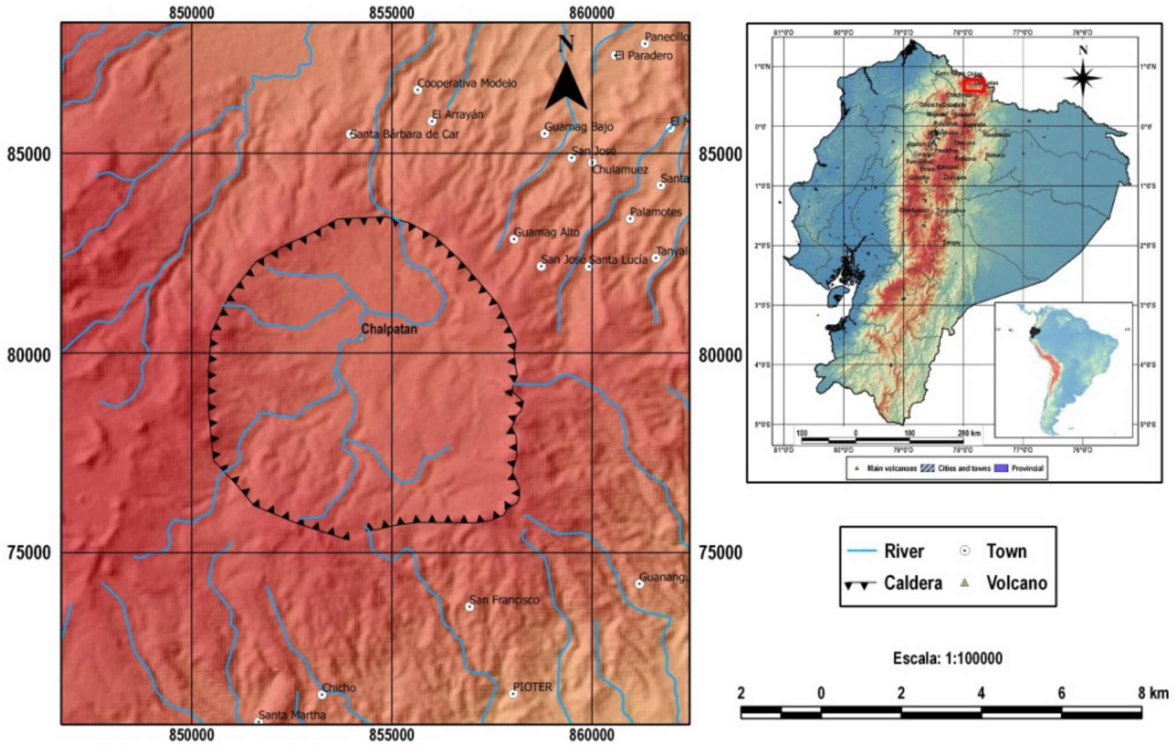

FIGURE 5: Location of Chalpatán prospect

thermal imagery, Audio Magneto Tellurics, and Magnetometry. Preliminary results indicate temperatures below 120°C and an estimated liquid reservoir of 1'850.000 m^3, suitable for industrial, agricultural and direct heat use. The National Institute for Energy Efficiency and Renewable Energy (INER) has showed interest in developing a low enthalpy research project in the area, once the exploratory wells are drilled. The Chalpatán caldera is located 20 km south-west of Tulcán city, with an extension of approximately 130 km^2. Only the caldera has been studied, leaving the El Angel ecological reserve outside the area of interest.

3.5 Chalupas

Although prefeasibility studies were carried out in Chalupas (Figure 6), additional research activities are required to complete the geothermal conceptual model presented by INECEL in 1983. Detailed geology, geochemistry and geophysics measurements must be performed using enhanced methodologies. Future work involves carrying out a Schlumberger resistivity survey with traversing (mapping) measurements at 500 m spacing (Beate and Salgado, 2010). The project has been temporarily delayed by CELEC EP, and will be resumed once the feasibility studies are finalized in Chachimbiro. Almeida (1990) determined an estimated potential of 283 MW$_e$, based on surface data geology.

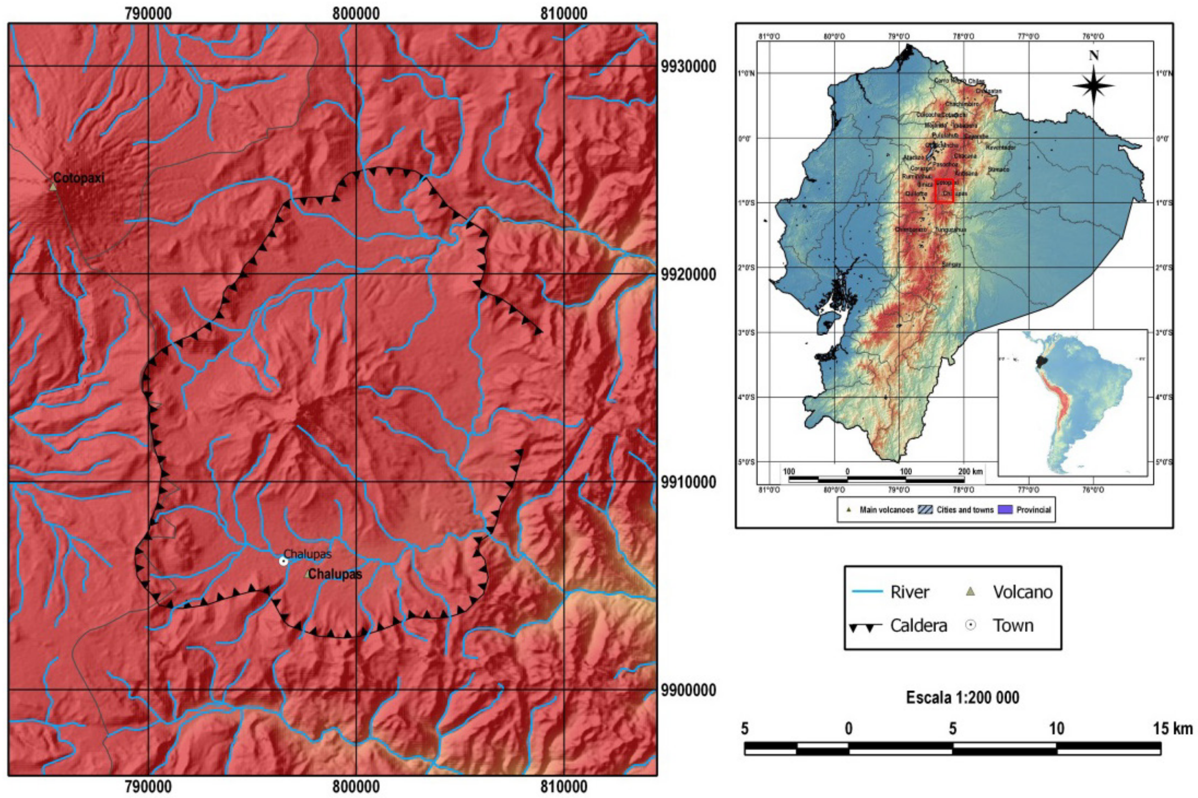

FIGURE 6: Location of the Chalupas prospect

4. UNDEVELOPED PROSPECTS

A study of the geochemical and isotopic characterization of volcanic and geothermal fluids discharged from the Ecuadorian volcanic arc was carried out by Inguaggiato et al. (2010). The authors identified sensible sites to start a systematic geochemical monitoring activity and complementary research for geothermal energy exploration. Beate (2010) also listed twenty one locations in Ecuador worthwhile for geothermal reconnaissance and exploration. Only five of these locations have been studied

(Tufiño-Chiles-Cerro Negro, Chachimbiro, Chacana, Chalpatán, and Chalupas), mostly due to their potential for electricity generation purposes. The following prospects highlighted in Figure 7 remain undeveloped with limited information available: Chimborazo, Baños de Cuenca, Guapán, Alcedo, Guagua Pichincha, Pululahua, Cayambe, Cuicocha, Tungurahua, Ilaló, Salinas de Bolivar, San Vicente, Portovelo, Iguán, Mojanda, and Soche.

A detailed geothermal reconnaissance study must be carried out in the sites that were pointed out by Beate and Inguaggiato (Inguaggiato et al., 2010). It is recommended that the guidelines established by OLADE are followed to assure a compatibility with the methodology used in previous studies. Activities include the assessment of existing data, followed by survey campaigns (detailed geology, hydrogeology, and geochemistry analyses).

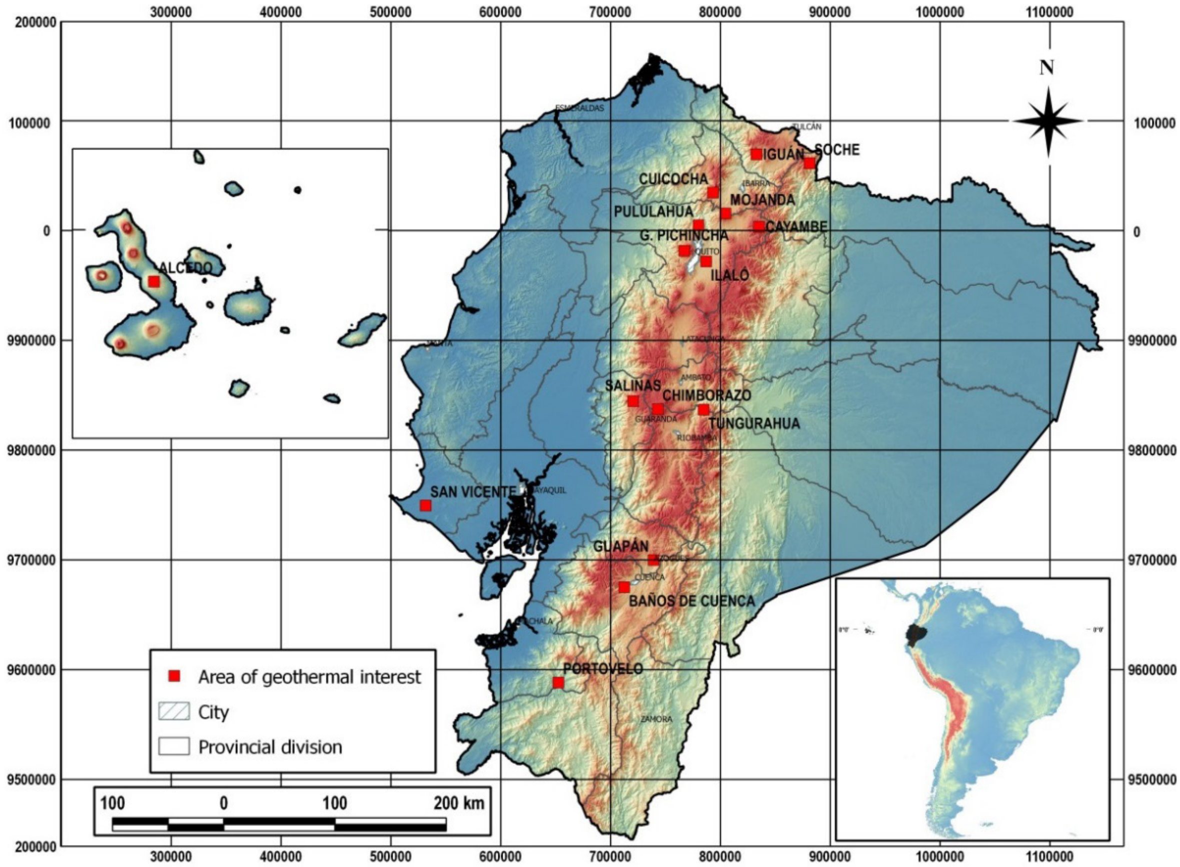

FIGURE 7: Locations of undeveloped prospects

5. OTHER GEOTHERMAL RELATED ACTIVITIES

5.1 Geothermal bilateral technical cooperation

Based on the expertise and experience that Iceland has in geothermal energy exploration and exploitation, the government of Ecuador, through the Ministry of Electricity and Renewable Energy, signed a Memorandum of Understanding with the Ministry of Industry and Tourism from Iceland in 2009. This agreement has the purpose of establishing the institutional relationship which will promote bilateral technical cooperation in matters of geothermal development between Ecuador and Iceland. In 2013, INER was officially designated by the Ministry of Electricity and Renewable Energy to execute the MoU.

5.2 Regulatory framework

The International Renewable Energy Agency (IRENA) and the OLADE have launched an initiative to improve access to geothermal energy in the Andean Region. This initiative, supported with expertise from Iceland, Mexico, New Zealand, France and the International Geothermal Organization (IGA) aims to contribute to the development of the vast geothermal potential in this region. Five countries are participating in this initiative: Bolivia, Chile, Colombia, Ecuador and Peru.

As a result of the workshop held in Iceland on March 4th-5th, 2013 and supported by country status reports, a potential area for further action has been identified as legal and regulatory frameworks for geothermal sector. On November 21st-22nd, a multistakeholder workshop organized by IRENA and OLADE entitled "Promoting the Enabling Environment for Geothermal Development in the Andean Countries – Legal and Regulatory Frameworks" was held in Lima, Peru. The event was designed to share the experiences of the countries that have had a long standing history in the geothermal sector with the Andean countries. The event brought together stakeholders from the governments, private sector and supporting institutions. In addition, links to possible synergies and areas of further support/collaboration derived during the workshop.

An Ecuadorian delegation integrated by members of the government's energy sector attended the workshop where the following commitments were agreed upon:

- Technical assistance from the Inter-American Development Bank (IDB) to develop a regulatory framework based on existing regulations;
- Legal assessment provided by the National Energy Authority of Iceland in the development of new policies and regulations for a geothermal law in Ecuador; and
- Assistance from IRENA to connect financial resources from bilateral and multilateral organizations to support the development of geothermal regulatory framework.

6. FUTURE DEVELOPMENTS

Currently, utilization of geothermal resources in Ecuador is restricted to bathing resorts, balneology and swimming pools. The total installed capacity of geothermal energy for direct heat applications in 2009 was 5 MWt (Beate & Salgado, 2005), with a slight increase over the last five years. Therapeutic benefits provided by medicinal mineral hot springs have been exploited in most resorts and spas all over Ecuador. However, significant alternate uses remain unknown by Ecuadorian society. Currently, a portfolio of projects for direct use in fish hatchery, greenhouse heating, space heating, and industrial applications is being researched by universities and public research institutions. One of the ongoing projects of INER focuses on development of new research lines for future implementation of low enthalpy geothermal projects. Research involves mainly the direct use of geothermal resources for diverse applications, such as greenhouses, space heating and cooling, industrial processes and tourism related activities. INER has started advanced studies in Baños de Cuenca, based on the highest temperature records and previous studies undertaken in this area by De Grys et all (1970) and Burbano et all (2013), in order to determine the origin of the geothermal system. Another of INER's research projects is undergoing in the city of Guayaquil, in collaboration with ESPOL University. The main objective of this project is to determine the soil thermal properties to be used as a heat sink to replace cooling towers and conventional air conditioning systems in commercial buildings with ground source heat pumps.

7. FINAL REMARKS

Geothermal resources represent an opportunity to meet energy needs with a clean, sustainable form of energy in South America. Not surprisingly, Ecuador is located in a privileged location along the

Andean Mountain Range and is traversed by more than 40 active volcanoes. The Geothermal Energy Association (Gawell et al., 1999) estimated the country's geothermal potential at 1700 MWe in 1999. However, it seems that the geothermal potential is much higher. Thus, Stefansson (2005) proposed an empirical relationship between the number of active volcanoes in a determined area and the geo-thermoelectric potential. Based on this relationship, if only 20 active volcanoes are considered within the Ecuadorian volcanic arc, the estimated potential could reach 3000 MWe (Beate, 2010), considering a 3 km depth. If rhyolitic calderas such as Chalupas and Chacana and their equivalent in andesitic magma are also considered, between 30 and 40 volcanoes could increase the overall theoretical potential up to 8000 MWe (Beate, 2010). This exceeds the current installed capacity of Ecuadorian interconnected system, equal to 4700 MWe (CONELEC, 2013).

INER has an active participation in the development of scientific research which contributes to the National Plan for Good Living (SENPLADES, 2013). One of the goals of the strategy is that renewable energies reach 6% share of total energy generation. The development of consolidated national geothermal map with participation of all state research institutes is currently being analyzed.

REFERENCES

Aguilera, E., 2001: *Síntesis y actualización de los datos existentes sobre las áreas de interés geotérmico del Ecuador*. Technical report for CONELEC, 35 pp.

Aguilera, E., 2010: *Geotermia en el Ecuador: Una hoja de ruta para su desarrollo sustentable*. Primera Conferencia Nacional de Energía Geotérmica en el Ecuador, Ibarra, Ecuador, 45 pp. Web: http:// noticias.espe.edu.ec/eaguilera/files/2012/06/Documento_Taller_Ibarra_-_Final11.pdf

Aguilera, E., Cioni, R., Gherardi, F., Magro, G., Marini, L., and Pang Z., 2005: Chemical and isotopic characteristics of the Chachimbiro geothermal fluids (Ecuador). *Geothermics, 34*, 495-517.

Almeida, E., Sandoval, G., Panichi, C., Noto, P., Bellucci, L., 1990: Modelo geotérmico preliminar de áreas volcánicas del Ecuador a partir de estudios químicos e isotópicos de manifestaciones termales (Geothermal investigations with isotope and geochemical techniques in Latin America*). Proceedings of the Final Research Co-ordination Meeting held in San José, Costa Rica*.

Beate, B., 2008: *Perfil del Proyecto Geotérmico Chalupas y resumen de otras áreas geotérmicas en el Ecuador*. Technical Report for CONELEC, 78 pp.

Beate, B., 2010: *Plan para el aprovechamiento de los Recursos Geotérmicos en el Ecuador*. Quito, 177 pp.

Beate, B., and Salgado, R., 2005: Country geothermal update for Ecuador, 2000–2005. *Proceedings World Geothermal Congress, Antalya, Turkey*, 7 pp.

Beate, B., and Salgado, R., 2010: Geothermal country update for Ecuador, 2005-2010. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 16 pp.

Burbano, N., Becerra, S., and Pasquel, E., 2013: *Aguas termominerales en el Ecuador*. Instituto Nacional de Meteorologia e Hidrologia (INAMHI), technical report 1, 95 pp.

CGS, 2013: *Estudio de prefactibilidad del modelo geotérmico integral de la Caldera de Chalpatán.* Preliminary final report for CELEC EP, 471 pp.

CONELEC, 2013: *Plan Maestro de Electrificación 2013-2022*. Perspectiva y Expansión del Sistema Eléctrico Ecuatoriano. Vol. 3, 256 pp. http://www.conelec.gob.ec/contenido.php?cd=10329

Coviello, M.F., 2000: *Estudio para la evaluación del entorno del Proyecto Geotérmico Binacional Tufiño-Chiles-Cerro Negro*. Technical report for OLADECEPAL- GTZ, 75 pp.

De Grys, A., Vera, J., and Goossens, P., 1970: A note on the hot springs of Ecuador. *Geothermics, 2-2*, 1400-1404.

Gawell, K., Reed, M., and Wright, P.M., 1999: *Preliminary report: Geothermal energy, the potential for clean power from the Earth*. Geothermal Energy Association, Washington D.C., United States, 15 pp.

INECEL, 1983: *Estudio de exploración de los recursos geotérmicos en Chalupas, Primera Fase de Prefactibilidad.* Unpublished Technical report, 150 pp.

Inguaggiato, S., Hidalgo, S., Beate, B., and Bourquin, J., 2010: Geochemical and isotopic characterization of volcanic and geothermal fluids discharged from the Ecuadorian volcanic arc. *Geofluids, 10-4*, 525-541.

OLADE, 1978: *Metodología de exploración geotérmica: Fases de reconocimientoy prefactibilidad.*

OLADE, INECEL and AQUATER, 1981: *Estudio de reconocimiento de los recursos geotérmicos de la República del Ecuador*. Informe vulcanológico, 66 pp.

OLADE, INECEL and AQUATER, 1987: *Proyecto Geotérmico Binacional Tufiño-Chiles-Cerro Negro, informe de prefactibilidad, modelo geotérmico, síntesis y recomendaciones.* Technical Report, 61 pp.

Stefansson, V., 2005: World Geothermal Assesment. *Proceedings World Geothermal Congress, Antalya, Turkey*, 6 pp.

Villares, F., 2010: *Estudio geovulcanológico de la zona sur de la Caldera de Chacana, Provincias de Napo y Pichincha*. Borrador Tesis Grado, Escuela Politécnica Nacional, Dpto. Geología, Quito, 203 pp.

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

DEVELOPMENT OF GEOTHERMAL ENERGY AND FACTORS THAT AFFECT ITS UTILIZATION IN PERU

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ABSTRACT

The objective of this paper is to demonstrate the potential of geothermal resources in Peru, the barriers which limit its development, and to propose actions that could promote the development of geothermal energy in Peru through the improvement of geothermal energy and Renewable Energy Resources legislation, to improve the mechanisms that encourage investment for the development of geothermal projects, training of human resources in geothermal energy, and action management of the central government, regional governments, and all the entities that are involved in these processes.

1. LEGAL BASIS

There are several laws and decrees that apply to geothermal development in Peru:

- Law Nº 26848, Organic Law of Geothermal Resources;
- Supreme Decree Nº 019-2010-EM, which approves the Regulation of the Organic Law of Geothermal Resources;
- Decree-Law Nº 25844,Electric Concessions Law;
- Supreme Decree Nº 009-93-EM, Regulation of the Electric Concessions Law;
- Legislative Decree Nº 1002, Promotion for the investment in the generation of electricity through the use of renewable energy; and
- Supreme Decree Nº 012-2011-EM, Regulation of Generation of Electricity through Renewable Energy.

In the aforementioned regulations, the role is established for the State and the private sector to execute any electrical activity in general and particularly renewable energy within which geothermal energy is considered.

To develop geothermal energy, we have established the granting licenses for the exploration of geothermal resources and the granting of concessions for the exploitation of these resources. The exploration consists of a period of three years. In the first phase (which lasts for two years), superficial studies must be done and in the second phase (which lasts for one year), at least three wells with a depth of 1000 meters must be drilled. An environmental study should be approved and a sub-surface fee must be paid in order to enter this phase.

2. BACKGROUND

An overview of the history of geothermal exploration in Peru can be summed up as follows:

- 1970: development began on the project "Assessment of Geothermal Potential of Peru" by the Geological Survey of Peru (INGEOMIN), currently INGEMMET, undertook studies to explore geologically and geochemically the geothermal manifestations, in order to assess the true geothermal potential of the country.
- 1979–1986: Geothermal recognition studies were conducted in southern Peru to identify the areas of interest.
- 1986: Geochemical investigations were carried out between the departments of Tacna and Moquegua with technical assistance from the International Atomic Energy Agency (IAEA) and the United Nations.
- 1994: The geovolcanic study and systematic inventory of geothermal manifestations of the Tutupacalot were performed.
- 1995: An evaluation study was performed in hydrothermal areas in Pampas de Kallapumaand surrounding areas.
- 1996: "Analysis of geochemical data from geothermal areas in the South East of Peru" was conducted with the support of the Electrical Research Institute (IIE) of Mexico.
- 2007-2009: Geothermal explorations of two pilot projects were developed with Japanese cooperation to build geothermal plants: Calientes and Borateras fields.
- 2009-2012: The Master Plan for Geothermal Energy Development was developed with support from JICA (Japan).

The pre-feasibility studies conducted by the international consulting firm West Japan Engineering Consultants in the Borateras and Calientes geothermal fields, located in the south of the country consisted of geological, geochemical, and geophysical exploration, and an engineering evaluation of both fields and demonstrated that they have considerable potential and that the former is within an Regional Reserve Area and the second is partially inside it.

The second investigation that was done was the Master Plan for Development of Geothermal Energy in Peru.It goal was to formulate a master plan to mark the path of development of geothermal energy in Peru, develop a database of potential geothermal resources, perform an economic evaluation, plan optimal development for the generation of electricity, and transfer of technical knowledge to the staff of the counterpart by the same consulting firm through international technical cooperation with the Japan International Cooperation Agency (JICA), whose final report was submitted in May of this year.

3. THE ROLE AND SIGNIFICANCE OF GEOTHERMAL ENERGY

The importance of geothermal energy consists of the following:

- Geothermal energy is not part of the current energy matrix in Peru, but according to the Law of Renewable Resources, is an important alternative for generating electric power, and this is complemented by the Geothermal Energy Act and its Regulations.
- Geothermal energy is important but it is still not a priority given that Peru has other alternatives for energy from renewable sources such as hydroelectric generation.
- It is important to provide training to human resources so that the country is technically capable of developing geothermal energy.
- Due to the sustainable economic growth that Peru is experiencing, which in turn generates increased demand for electric power in the economic sectors, geothermal energy will contribute to diversify the energy matrix from a new renewable energy resource in order to achieve a supply of energy within a framework of sustainable development.

- The goal is to be self-sufficient in the production of energy and have an energy sector with a minimal environmental impact and low carbon emissions, allowing savings on fuel or non-renewable resources such as oil and natural gas in electricity production.
- Potential sources of geothermal energy are being identified, which when added to the existing promotional regulatory framework(which is designed to attract private investments in energy) will make possible the construction of power plants based on this technology.
- An important aspect of geothermal energy is its variety of uses, not only in power generation but for heating and other uses of geothermal heat.

The advantages are:

- There is an explicit regulation for geothermal energy, although for the moment it is only intended for the production electric power.
- There is great geothermal potential and a master plan that directs investment in identified areas.
- There is active private sector participation in the exploration of geothermal resources, something that requires a large and high risk initial investment.
- There is a Geological Metallurgical Mining Institute (INGEMMET) that has preliminary prospective studies, which guide the actors in the development of geothermal energy.

The disadvantages are:

- The slow pace of the environmental authority in defining the environmental instruments to be developed for Phase II of the exploration, which involves drilling.
- The lack of more knowledge in some state entities regarding the scope of geothermal energy. This causes development geothermal development in areas that are within national reserves or protected areas to not receive support. Among these entities we have the National Water Authority, the National Service of Protected Areas, and corresponding entities of regional governments, among others.
- The non-participation of the State in the direct management of the development of a geothermal project, mainly in the drilling phase.
- Lack of skilled professionals in geothermal energy and non-existence of a specialty in this area within Peruvian universities.

4. CURRENT STATUS OF GETHERMAL DEVELOPMENT

4.1 Status of the electrical sector in Peru

Geothermal development is not present in the energy matrix because it is only in the exploration stage. There have been three auctions of energy from Renewable Energy Resources (RER) which currently consists of generating from solar origin and the first wind farms are expected to be installed this year.

At present the total installed capacity of the country is 10,900 MW, of which about 32% is hydroelectric. Also, the total energy production is 43,400 GWh, of which 55% is hydropower. Geothermal development is not present in the energy matrix because it is only in the exploration stage. The distribution of effective power potential is shown in Figure 1.

4.2 Geothermic potential in Peru

The final report of the Master Plan for Development of Geothermal Energy in Peru developed with the support of JICA concludes that Peru has abundant geothermal resources, with an estimated potential of 2 860 MWe situated in different geothermal fields, mostly located in the southern part of the country.

Moreover, that plan shows the following results: selection and determination of sequence of development for 10 promising fields for geothermal development, geological and geochemical information and detailed estimate of the potential in these fields, analysis of demand and transmission network to establish geographical position and time of the entry of geothermal plants, prediction and evaluation of environmental impact and geothermal development database.

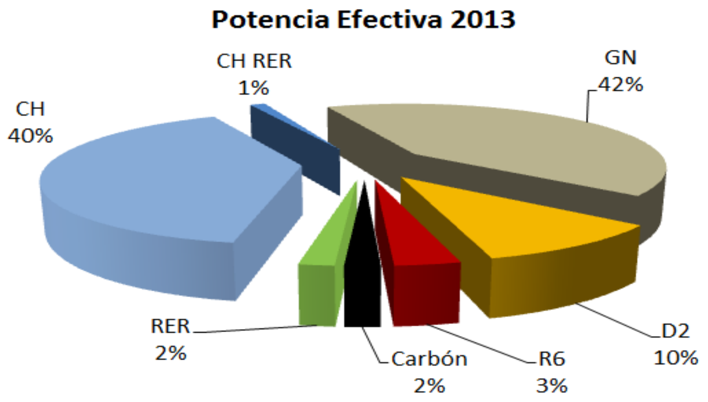

FIGURE 1: Effective power potential in 2013

The Master Plan has divided the country into six regions, from the geothermal potential point of view as indicated in the map presented in Figure 2.

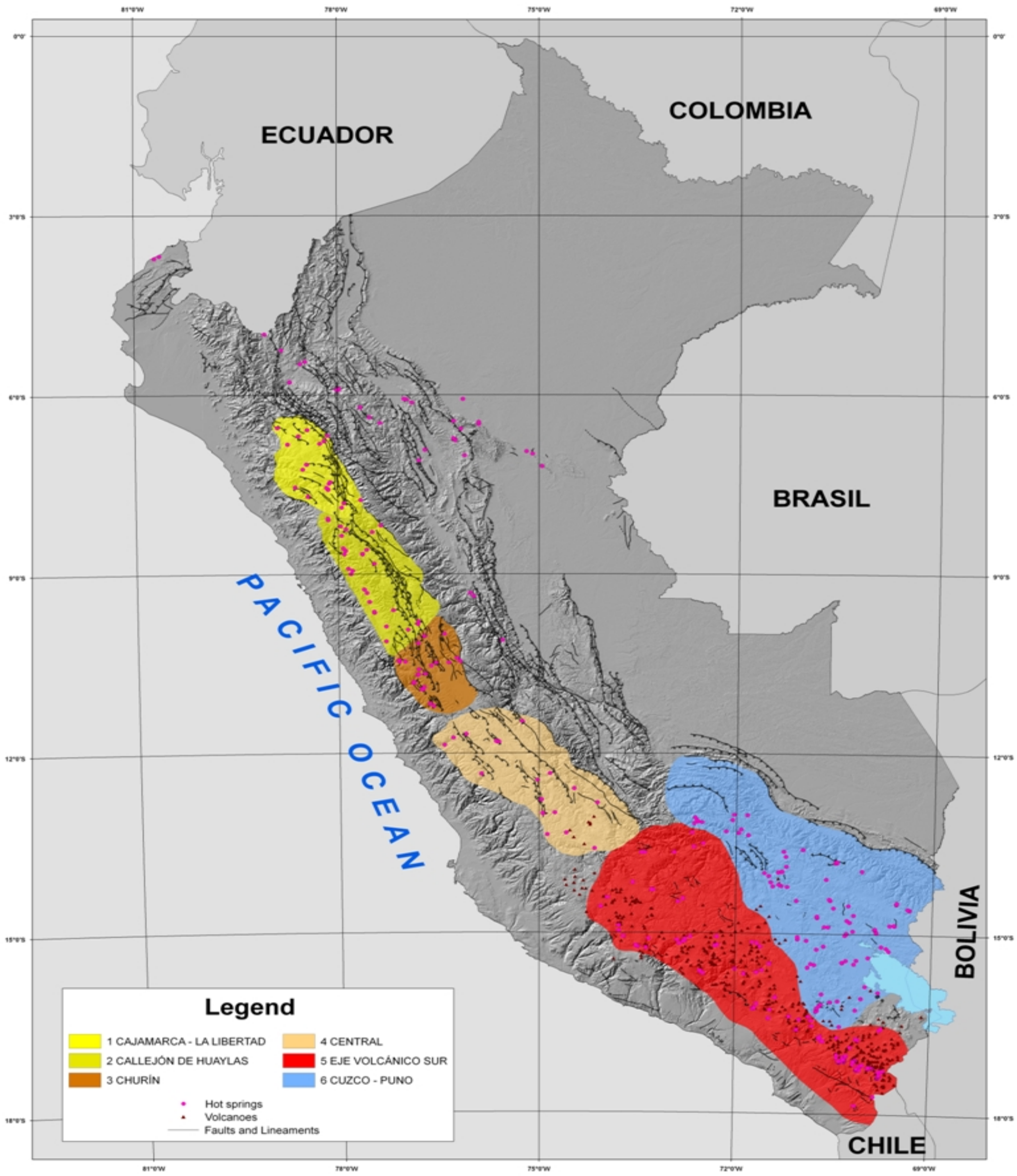

FIGURE 2: The six geothermal regions of Peru as delineated in the Master Plan

Considering the regions presented in the map, the geothermal potential is distributed as shown in Figure 3.

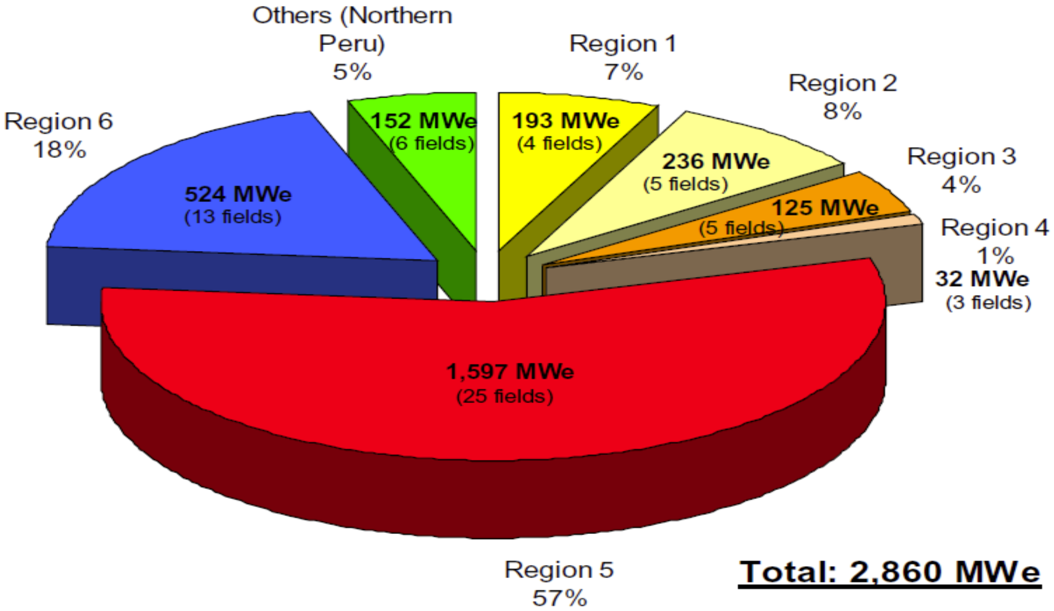

FIGURE 3: Geothermal electricity generation potential of the six geothermal regions of Peru

4.3 Granted geothermal licenses

Currently, only the private sector is participating in the development of geothermal generation and to date, 32 licenses have been granted for the exploration of geothermal resources to the following companies: Magma Energía Geotérmica Perú (Magma Geothermal Energy Peru), Hot Rock Perú S.A. (Hot Rock Peru Inc.), Eco Energy Perú S.A.C. (Eco Energy Peru Inc.), and Andes Power Perú S.A.C. (Andes Power Peru Inc.), Geotérmica Quellaapacheta Perú S.A. (Quellaapacheta Geothermal Peru Inc.), Enel Green Power Perú S.A. (Enel Green Power Peru Inc.), and EMX Geothermal Perú S.A.C. (EMX Geothermal Peru Inc.). For further information on individual licenses, see Appendix I.

5. BARRIERS TO THE DEVELOPMENT OF GEOTHERMAL ENERGY

The following barriers are present to geothermal development in Peru:

- The initial investment cost to build a geothermal generation plant (exploration and drilling phase) is too high compared to other sources of as well as the price of energy at Bus Bar cost (which affects the final rate) that prevents the State from providing financial resources to build a geothermal plant, leaving it to the private sector.
- The risk involved in finding resources and high initial cost of geothermal development itself could possibly prevent further development by the private sector, therefore it is necessary to consider other options such as improvements to the existing legal framework.
- Consultation with indigenous communities or peoples, pursuant to the Prior Consultation Act, will mean a delay in the development of geothermal resources exploration, and more so at the operation stage because it is a new experience and because of the politicization of community social sectors.
- The environmental license for geothermal projects does not clearly define what type of environmental study must be developed for Phase II of the exploration when drilling should be carried out, nor for the exploitation stage. Added to this time it takes for approval of the environmental study that is determined by the corresponding entity.

- The location of geothermal fields within protected areas or conservation areas prevent their development, as is the case Calientes field within the Regional Conservation Area Vilacota-Mauri, and Boraterasfield that affects a part of this area.
- The absence of a strong human resource base capable of developing geothermal energy, such as the lack of specialists in the exploration and exploitation of geothermal resources, and insufficient exchange of information between government institutions.
- No criteria have been established for technical evaluation regarding the methodology, parameters and standards.
- Lack of awareness of the benefits of geothermal energy development in the country on the part of the authorities of the Central, Regional, and Local Governments.

6. POLICIES TO INCREASE THE USE OF RENEWABLE ENERGIES

One of the objectives of the Government is to encourage the use of non-conventional renewable sources in electricity production, so much so that auctions are conducted every two years to cover 5% of demand with renewable energy, but geothermal energy has not participated yet.

Within this, the government has set a target for 2019 for 5% of the energy demand to be supplied by renewable energy, including geothermal energy.

The policies that the government can propose to promote the use of renewable energies in general and geothermal energy in particular are as follows:

- Adopt TUPA (Single Text for Administrative Processes) in the Ministry of Energy and Mining in the processing of geothermal licenses.
- Strengthen the organizational structure of the state in the development of geothermal energy.
- Initiate the process for the definition of environmental instruments for geothermal activities before the environmental authority.
- Initiate the process for the compatibility of geothermal projects in regional conservation areas or protected areas.
- Regulate the process of prior consultation established by Law No. 29785, Law of the right to prior consultation with indigenous or local peoples, recognized in the Convention No. 169 of the International Labor Organization and the Regulations approved by Supreme Decree No. 001-2012-MC in order to do it in the shortest possible time if it is required.
- Approve the list of goods and supplies required by the holders of geothermal licenses, in coordination with the Ministry of Economy and Finance.
- Disseminate the results of the Master Development Plan from Geothermal Energy Peru, prepared under the auspices of JICA.
- Review the regulation for promotion of renewable energy and consider improving them further for better development of geothermal energy (percentage share of renewable energy, time limits for renewable energy auctions, etc.).
- Review the regulation of geothermal energy to introduce the improvements necessary to encourage geothermal projects.
- Promote training courses on geothermal energy at the national level, especially in the southern region of the country.
- Promote the creation of a geothermal engineering specialty with the help of national universities and the College of Engineers of Peru.
- Enter the geothermal projects into a future Energy Auctions for Renewable Energy Resources to ensure the sale of energy to the rate awarded.
- Have an energy matrix that is diversified, competitive, and with emphasis on renewables and energy efficiency.
- Encourage private investment in the development of renewable energy, such as the

exploration and exploitation of geothermal energy by providing economic and tax incentives (with no guarantee in Phase I and exemption from taxes on imported supplies, anticipated recovery of VAT).

7. CONCLUSIONS

From the previous discussion, the following can be concluded:

- Geothermal energy in the country is at an early stage of its development by the private sector, who have the responsibility to continue investing despite the risk this poses.
- Geothermal energy is not a priority in the country's energy matrix, since it has other resources such as hydroelectricity, but it is important because of its multiple uses.
- The main barrier to the development of geothermal energy is the high risk and a significant initial investment in the drilling phase, which results in high rates in relation to other renewable resources.
- An important policy of the government would be the support the development of geothermal energy in the initial phase.
- Peru has great geothermal potential in the southern part of the country according to the Master Plan for the Development of Geothermal Energy, which was developed with support from Japan.
- The main geothermal fields are located in regional reserve areas, and therefore, regional governments should reconsider the priorities of development in relation to natural resources and the needs of their people and country.

APPENDIX I: License holders to geothermal resources in Peru

Nº	Licensee	Zone (Geothermal field)	Location	Directorial resolution	End of studies
1	ANDES POWER PERÚ S.A.C.	TUTUPACA	Tacna	010-2011-EM/DGE (2011.03.18)	2015.07.12
2	ECO ENERGY S.A.C.	GERONTA II	Ayacucho	027-2011-EM/DGE (2011.05.19)	(*)
3	ECO ENERGY S.A.C.	UMACUSIRI I	Ayacucho	028-2011-EM/DGE (2011.05.19)	(*)
4	ECO ENERGY S.A.C.	UMACUSIRI II	Ayacucho	029-2011-EM/DGE (2011.05.19)	(*)
5	ECO ENERGY S.A.C.	GERONTA I	Ayacucho	030-2011-EM/DGE (2011.05.19)	(*)
6	ECO ENERGY S.A.C.	PINAYA I	Puno	002-2011-EM/DGE (2011.02.04)	(*)
7	ECO ENERGY S.A.C.	PINAYA II	Puno	003-2011-EM/DGE (2011.02.04)	(*)
8	ECO ENERGY S.A.C.	PINAYA III	Puno	036-2011-EM/DGE (2011.05.19)	(*)
9	HOT ROCK PERÚ S.A.	RUPHA	Ancash	006-2011-EM/DGE (2011.02.12)	2015.03.01
10	GEOTÉRMICA QUELLAAPACHETA PERÚ S.A.	QUELLAAPACHETA	Moquegua	031-2011-EM/DGE (2011.04.06)	2015.03.01

Nº	Licensee	Zone (Geothermal field)	Location	Directorial resolution	End of studies
11	HOT ROCK PERÚ S.A.	CHOCOPATA	Puno	012-2011-EM/DGE (2011.03.18)	2015.03.01
12	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	LORISCOTA	Moquegua Puno	022-2011-EM/DGE (2011.04,13)	2015.02.01
13	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	CRUCERO	Moquegua Puno	025-2011-EM/DGE (2011.04.13)	2015.02.01
14	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	PASTO	Tacna Moquegua	034-2011-EM/DGE (2011.07.15)	2015.12.28
15	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	SARA SARA	Ayacucho y Arequipa	055-2011-EM/DGE (2011.09.14)	(*)
16	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	PANEJO	Moquegua	060-2011-EM/DGE (2011.09.14)	2015.12.11
17	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	ATARANI	Tacna Moquegua	076-2011-EM/DGE (2011.09.22)	2015.12.24
18	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	SUCHE	Tacna	092-2011-EM/DGE (2011.11.30)	(*)
19	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	TUTUPACA NORTE	Tacna Moquegua	091-2011-EM/DGE (2011.11.30)	(*)
20	HOT ROCK PERÚ S.A.	TURU	Arequipa Cusco	099-2011-EM/DGE (2011.12.05)	2015.07.05
21	HOT ROCK PERÚ S.A.	ACHUMANI	Arequipa	217-2012-EM/DGE (2012.10.17)	2016.02.22
22	ECO ENERGY S.A.C.	PINAYA I V	Puno	239-2012-EM/DGE (2012.12.12)	(*)
23	ECO ENERGY S.A.C.	PINAYA V	Puno	240-2012-EM/DGE (2012.12.12)	(*)
24	ECO ENERGY S.A.C.	PINAYA VI	Puno	249-2012-EM/DGE (2012.12.18)	(*)
25	ENEL GREEN POWER PERÚ S.A.	CARMEN	Ayacucho	009-2013-EM/DGE (2013.02.07)	(*)
26	HOT ROCK PERÚ S.A.	HUISCO	Ayacucho	010-2013-EM/DGE (2013.02.15)	2016.08.20
27	ENEL GREEN POWER PERÚ S.A.	CHILATA	Moquegua	067-2013-EM/DGE (2013.04.19)	(*)
28	EMX GEOTHERMAL PERÚ S.A.C.	TAMBOCHACA	Pasco	074-2013-EM/DGE (2013.04.26)	(*)
29	EMX GEOTHERMAL PERÚ S.A.C.	PUMAHUIRI	Ayacucho	075-2013-EM/DGE (2013.04.26)	(*)
30	EMX GEOTHERMAL PERÚ S.A.C.	SENGATA	Ayacucho	076-2013-EM/DGE (2013.04.26)	(*)
31	EMX GEOTHERMAL PERÚ S.A.C.	COROPUNA	Arequipa	146-2013-EM/DGE (2013.05.26)	(*)
32	MAGMA ENERGÍA GEOTÉRMICA PERÚ S.A.	PINCHOLLO LIBRE	Arequipa	278-2013-EM/DGE (2013.07.07)	(*)

1 Transfer RD 061-2013-EM/DGE, Pub. 12-04-2013
(*) Awaiting for approval of the instrument of the environmental management document accrediting that it is not necessary (DS Nº 015-2013-EM)

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UNITED NATIONS
UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

REGIONAL GEOTHERMAL TRAINING PROGRAMME AT THE UNIVERSITY OF EL SALVADOR

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ABSTRACT

Latin American and Caribbean countries have great geothermal potential located along the volcanic range from Mexico to Patagonia, most of them are leaning towards developing geothermal projects in order to reduce the dependency of the high cost of fossil fuels, protect the environment and to overcome some barriers like inexistent regulations, limited financial resources and limited experienced human resources to develop these kinds of projects.

The reduced training opportunities for young professionals around the world result in a limited knowledge on geothermal specialization. Furthermore, Latin American countries have been limited in their ability to attend some international courses due to the high cost of these courses as well as the living expenses that cannot be afforded by companies or governments with their own financial resources, and sometimes due to the limited language skills (mainly English) of the professionals.

In early 2002, LaGeo in El Salvador made the decision to have an alternative training opportunity for its own professionals who could not attend in a short period of time an international specialized geothermal course, having the former alumni as main lecturers, and organized a course called Diploma in Geothermal Science and Technology. A few years later, LaGeo began to look for international financial support and a partnership with a local university in order to share this specialized knowledge to a new generation of professionals, employed or not, in the geothermal industry. It led to the creation of the First Diploma Course with the partnership of the University of El Salvador.

1. INTRODUCTION

The global geothermal power market has been growing during the 20th century; it is currently fuelled by a number of factors: economic growth, especially in developing markets; the electrification of low-income and rural communities; and increasing concerns regarding energy security, measures against climate change and its potential impact on economic security. Additionally, the majority of the growth in the development of global geothermal resources occurs in countries with large, unexploited, conventional resources. As more countries recognize and understand the economic value of their geothermal resources, their development and utilization becomes a higher priority.

There is a need to create policies in order to support geothermal development in some countries; and the need to continue training and capacitating young professionals as specialized geothermal experts that should promote further development of the potential geothermal resources, which will help grow the economies and develop markets, as well as mitigate potential environmental impacts that cause by climate change.

2. POTENTIAL NEEDS OF LATIN AMERICA AND CARIBBEAN COUNTRIES

The Latin America region along the Pacific Coast has 4 of the 15 geothermal countries in the world that already have geothermal projects with a high temperature resource and are very efficient. They are considered part of the energy matrix in Central America as a base energy with low prices.

Other Latin American and Caribbean countries with no installed capacity have begun to undertake projects on developing their geothermal resources. In South America, Chile has a high geothermal potential due to its location with many volcanic centers in the Pacific Ring of Fire. This allowed them to begin exploration activities, inviting the private sector to elaborate their investment proposals. It is expected that Chile will become the first geothermal producer in South America at the end of 2014. Colombia is also conducting feasibility studies in the area surrounding the volcano Nevado del Ruiz. The project includes the completion of feasibility studies, environmental and financial aspects, exploration and production drilling; and adequate access to infrastructure, connection to the national transmission system, supply of equipment, plant construction and commercial operation.

Another important geothermal area in South America is found in Peru, with an estimated geothermal potential of 28.60 GW, located in the southern part of the country; the private sector will develop the exploration of geothermal resources to produce 10 GW by 2030. Bolivia, with a geothermal potential of 2.5 GW, including the Laguna Colorada area, located in the Andean region of Potosí (southwest), near the border with Chile. Ecuador seems to have geothermal energy as an option for the short term, with an estimated potential of 6 GW, the government holding CELEC EP has made prefeasibility studies of the geothermal projects of Chachimbiro, Chacana and Chalpatán, and also is working with ISAGEN from Colombia to develop prefeasibility studies of the Tufiño-Chiles–Cerro Negro Projects, located at the border.

The continuous reduction of gas production in Argentina during the last seven years, has promoted the search for renewable energy projects, in order to provide energy to a small miner complex and some touristic Andean towns. Argentina will install the first geothermal power plant which will be located in the unpopulated area at Valle del Cura and will contribute to the electrical system of the province of San Juan with 5 MW at an early stage.

In the Caribbean, Dominica, Nevis & St. Kitts and Montserrat are running their own geothermal projects at a low scale; however, each one will have a high impact on their own economies. The most recent and significant progress in this area is located in Dominica with the drilling of 3 wells during 2012 (Maynard-Date, 2012; George, 2012).

Figure 1 shows countries which have started earlier than others in Latin America, developing geothermal projects, such as Mexico in 1959, and Costa Rica and El Salvador during the 70's. This region represents 14% of the installed geothermal capacity in the world.

Due to the growing need in the Latin American and Caribbean countries in pursuing the use of geothermal at a larger extent and controlling the sustainable exploitation of their geothermal resources, the formation of a solid base of trained human resources is indispensable. However, capacitation of technical professionals will not alone help the purpose of promoting the utilization geothermal resources. There are three essential elements needed to produce the expected results: national determination, technical human capacity and financial resources; only the combination of these three elements will work out. The high initial investment cost of geothermal projects, are the main obstacle to struggle in the industry development

FIGURE 1: Latin American and Caribbean countries with geothermal potential

In order to develop the capacity to apply the geothermal energy utilization, the courses are designed to the study of the geothermal systems at high, medium and low enthalpies and the techniques available for their management and exploitation.

Since Latin American and Caribbean countries still lack trained human resources to expand geothermal projects, there is a need to create a Regional Geothermal Training Center, to assist these countries to increase the human capacity building.

3. GROWING IDEAS DOWN TO EARTH

Central America was selected as the region for the Second Millennium Series of Short Courses, and since 2006, El Salvador has been the top host of the specialized short courses on geothermal, with the cooperation and main sponsor, the United Nations University-Geothermal Training Program (UNU-GTP) of Iceland, being recognized throughout El Salvador with abundant experience in conducting these specialized geothermal courses in the region.

The UNU-GTP has been supporting the region through the training of many staff members of geothermal institutions in cooperation with LaGeo, which is responsible for geothermal development in El Salvador since the 1970's and having all the know-how necessary to be an active and strong partner in hosting these courses.

The short courses have covered topics ranging from surface exploration to development, field management and production monitoring. However, it can also be expected to cover a wider area to countries where geothermal resources have not been developed to the same extent.

With the aim of providing geothermal training in the region, the course makes another step forward, and in 2009 a cultural-scientific agreement between the Italian Cooperation, LaGeo, the University of El Salvador (UES), the National Commission of Science and Technology (CONACYT) and the University of Palermo of Italy was signed to run the "First Geothermal Diploma Course in 2010" in El Salvador, which included training in different geothermal areas and performing activities for technical and academic/research for the staff and students of the University of El Salvador (UES), and other public or private institutions which would require it. A total of 39 students were awarded with scholarships, including three students from Nicaragua.

The course was carried out with the support of the Italian Cooperation-Ministry of Foreign Affairs, involving the participation of lecturers from the Geosciences and Earth Resources of the National Research Council of Italy Institute (IGG-CNR), LaGeo Staff, the University of Palermo (UNIPA)-Italy and the University of El Salvador (UES). The technical support through the exchange of educational experts in some specific academic subjects, as well as economic aid for the acquisition of some laboratory equipment, and specialized books were provided with the support of this sponsorship. During the second edition of the Geothermal Diploma Course in 2012, of the 25 registered students, ten were awarded with scholarships, all of them from El Salvador and coming from a wide range of sectors: students, public and some private institutions, who were interested in being trained in the geothermal field.

After the second edition of the Geothermal Diploma Course, students who excelled were given a grant, sponsored by the project, to visit Italy. The aim of the visit is to gain a better understanding of the equipment and activities developed in Pisa and Naples of the National Research Council of Italy Institute (IGG-CNR), and exchange experiences between participants and members of that Institute. The project works were presented by the students in order to promote their technical professional development abroad.

The lecturers came from the parties involved during the previous editions of the Geothermal Diploma Course, and their contribution is presented in Figure 2.

4. THE REGIONAL GEOTHERMAL TRAINING PROGRAMME PROJECT

In order to support Latin American and Caribbean countries to increase the human capacity building, and after looking for more funding for this purpose from some international cooperation agencies, in 2012, the Inter-American Development Bank (IDB) in co-finance with the Nordic Development Fund (NDF), granted more than two million US Dollars, through the National Energy Council (Consejo

Nacional de Energía - CNE) as the main executing organization to assist El Salvador in consolidating the Regional Geothermal Training Center for Latin American and Caribbean countries. In September 2012, an agreement between the Government of El Salvador and the Inter-American Development Bank was signed. Besides that, the institutions involved in this project, that is, CNE, UES and LaGeo signed an agreement with the aim to work together "to make El Salvador become the main venue of the regional geothermal professional development, through a sustainable training project diploma course, that guarantees an accurate investigation and training in the geothermal fields, throughout the efficient execution of the Operation Plan of the Technical Cooperation of the IDB, to support the Regional Geothermal Training Programme for the Latin American and Caribbean countries".

The specific objectives of the Project are to:

- Establish the academic and administrative structure of the Specialized Geothermal Diploma Course of the UES, and adapt to the needs of developing the geothermal regional human capacity building.
- Enhance the capacity of CNE and UES to develop the sustainable geothermal training in El Salvador.
- Increase the regional geothermal expertise through the technical and financial support, in order to develop three diploma courses in 2013-2015 with an updated structure of the curricula and scholarships.

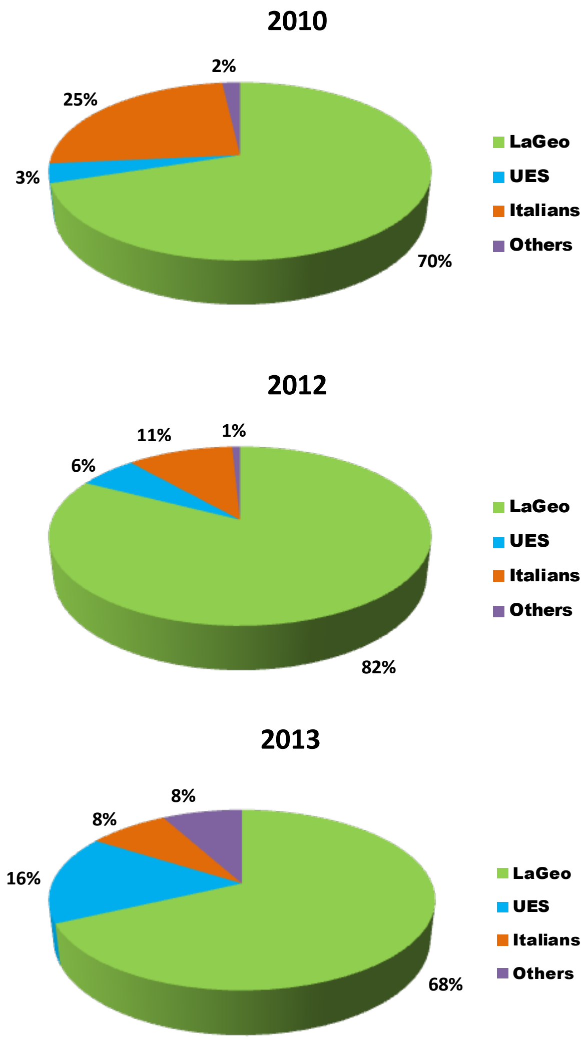

FIGURE 2. Contribution of the different categories of lecturers to the previous courses Source 2010 and 2012: UNU-GTP (Haraldsson et al., 2013)

In order to achieve the objectives mentioned above, the project was divided into three components such as follows:

a) **Component I: Review and analysis of the Geothermal Diploma Course at the University of El Salvador.**

The main objective of this component was to review and evaluate the past 2010 and 2012 Geothermal Diploma Courses at the University of El Salvador and identify the different aspects to improve on based on the academic and administrative points of view.

To perform the activities of Component I, the United Nations University-Geothermal Training Program from Iceland, was hired to carry out the study, finishing the Final Report in March 2013. The outcomes obtained from this report were key inputs to implementing Component III and improve some issues for the 2013 Diploma Course.

b) **Component II: Preparation of a Sustainable Development Plan for the Regional Geothermal Training with the University of El Salvador.**

This component will analyze the future regional geothermal training demand and assure its self-sustainability, with emphasis on the academic and financial analysis and the scholarship structure.

After the bidding process this Component has been carried out by the International Geothermal Centre (GZB) and International Geothermal Association Service Company (IGA Service GmbH), who's experience in these kinds of projects and expected outcomes are going to enrich the future of Geothermal Diploma Course.

c) **Component III: Support to the attainment of the Regional Geothermal Training Courses from 2013 through 2015.**

This component is focused to support the execution of the training courses between 2013 and 2015. The expenses corresponding to the administration, lecturers and scholarships will be supported by this project. The Geothermal Diploma Course is offering thirty scholarships to local students in El Salvador and at the same time, thirty scholarships to geothermal experts from Latin America and the Caribbean countries; priority will be given to participants from countries with geothermal potential.

5. NEXT STEPS OF THE DIPLOMA COURSE

The 2013 Geothermal Diploma Course was reviewed based on the recommendations for the future/guidelines for improvement stated in Chapter 7 of the Final Report written by the UNU-GTP, as a result of the evaluation of Component I. The recommendations touched upon the academic quality and structure of the course, including the amount of time to be spent on different modules/subjects and time of the day for lecturing. Three scenarios were presented, each with a different emphasis and structure, including recommendations on facilities, library and laboratory access, etc., as key input to define the content of the 2013 Edition.

The Third Geothermal Diploma Course was held from August to November 2013, and was the first one that was reflective of the key outcomes of the Component I of the IDB Project. It was the first time that it was open to the Latin American and Caribbean countries that have some geothermal potential and need to prepare technical human capacity to develop geothermal projects. It was held with an evening schedule with internship at LaGeo in the morning, in order to have on-the-job training.

This Edition of the Course registered 25 students from seven Latin American countries: Guatemala (2), Peru (2), Ecuador (1), Argentina (1), Honduras (1); Nicaragua (2), Chile (1) and 15 from El Salvador (Figure 3). As part of the Component III, 10 foreign and 10 local students were awarded with scholarships including: tuition, daily per-diem, transportation, accommodation and other expenses during the Diploma Course.

The 2014 Edition of the Geothermal Diploma Course will cover the areas shown in Table 1.

The next edition of the Geothermal Diploma Course is intended to begin in June 2014, scholarships are available under the same scheme as the 2013 Edition. Students interested in applying to this Programme can get more information at: www.geotermia.edu.sv or send an email to: jarevalo@geotermia.edu.sv or jgarcia@cne.gob.sv.

The aim of the Geothermal Diploma Course is to be an alternative to increasing the capacity building and transfer of technology as key issues in the sustainable development of geothermal resources of the Latin American and Caribbean countries with a self-sustainable course in the long term.

FIGURE 3: Participants of the third Diploma Course

TABLE 1: Structure of the 2014 Edition of the Geothermal Diploma Course

Module	Area	Theoretical hours	Practical hours	Field visit	Lab
I	Geothermal Energy General Concepts	31	12	1	
II	Geological Exploration	32	19	1	4
III	Geochemistry Exploration	31	16	1	
IV	Geophysical Exploration	34	26	2	
V	Geothermal Drilling	25	6	1	
VI	Reservoir Engineering	39	24	1	1
VII	Geothermal Power Plants and Utilization of Low and Medium Enthalpy	30	6	1	
VIII	Environmental and Social Management of Geothermal Projects	26	11	1	
X	Project Work				

REFERENCES

Business News Americas, 2011: *Geotermia en America Latina: Lista para hacer erupción.*

Caprai, A., Flores Díaz, J.A., Montalvo, F., Alegría, R., Giunta, G., Campos, S.E., de Flamenco, C., Ramírez, T., de León Torres, F., Guidos, J., Monterrosa, M., de Arévalo, A.S., 2012: *Proyecto creación de una actividad de formación en geotermia en el Sistema academico Salvadoreño – En el marco del Diplomado de Especialización en Geotermia*. CNR-IGG, UES, Ministerio degli Affari Esteri – Cooperazione Italiana allo Sviluppo, LaGeo S.A. de C.V., Consejo Nacional de Ciencia y Tecnologia, Universitá di Palermo, 109 pp.

De Velis, E., 2006: Plans for geothermal training in Central America. *Presented at Workshop for Decision Makers on Geothermal Projects in Central America, organized by UNU-GTP and LaGeo in San Salvador, El Salvador*, 6 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-02-36.pdf

De Velis, E., and Montalvo, F., 2011: First geothermal diploma course in the academic system in El Salvador and Central America. *Presented at "Short Course on Geothermal Drilling, Resource*

Development and Power Plants", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, 5 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-12-08.pdf

De Velis, E., 2013: Regional Geothermal Training Center project with the support of the Inter-American Development Bank (IDB) in co-finance with the Nordic Development Fund (NDF).

Georgsson, L.S., and Fridleifsson, I.B., 2013: *Geothermal energy in the world and the capacity building activities of the UNU-GTP*. Presented at "Short Course on Conceptual Modelling of Geothermal Systems", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, 18 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-16-01.pdf

Haraldsson, I.G., Axelsson, G., Ragnarsson, Á., Fridriksson, Th., Franzson, H., Fridleifsson, I.B., Georgsson, L.S., 2013: *El Salvador geothermal regional training support program - final report.* United Nations University Geothermal Training Programme, report UNU-GTP/CR-1302, prepared for the Inter-American Development Bank, 156 pp.

Inter-American Development Bank (IDB), 2012: *Convenio de cooperación técnica no reembolsable N° ATN/OC-13235-ES y ATN/NV-13236-ES. Apoyo al Programa de Entrenamiento Geotérmico*.

Jennejohn, D., Hines, B., Gawell, K., and Blodgett, L., 2012: *Geothermal: International market overview report*. Geothermal Energy Association, 25 pp. Web: http://geo-energy.org/pdf/reports/2012-GEA_International_Overview.pdf

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

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ABSTRACT

Due to the increasing geothermal interest and activities in Central America, five partners joined efforts in 2013, and established a Regional Geothermal Office in El Salvador (RGO) with the aim of promoting geothermal projects, enhancing the development of geothermal energy potentials and strengthening the scientific and technological capabilities of governmental entities, scientific institutions and private sector companies. Achieving these objectives involves the creation of expertise, technological development, knowledge transfer, networking and communication, policy development as well as private and public investment into corresponding technologies and human capital, being the link between the region and partnerships worldwide, dedicated to promoting geothermal.

1. INTRODUCTION

The use of geothermal energy has a long history in several countries in Central America. It is currently operating in 8 regional plants connected to the power grid, generating up to 625 MW of electricity. El Salvador, for example, covers up to 24 % of the electricity demand from geothermal sources.

According to estimates, the total potential for generating electricity with geothermal energy in Central America is between 3,000 MW and 13,000 MW. Experience in Central America through this technology is mostly in high enthalpy, i.e. the use of geothermal resources of high temperatures (over 200°C). Additionally, there are opportunities to use geothermal energy for direct use in this region. There is also a lot of potential in low enthalpy geothermal energy, which corresponds to the generation of electrical energy on a smaller scale and for thermal power generation in industrial processes, air conditioning, balneology, agriculture, etc.

In order to strengthen the development of the geothermal energy potential and enhance scientific and technological capabilities of government institutions and the private sectors dedicated to this technology in the region, five entities of great importance in this matter joined together to create a Regional Geothermal Office for Central America (RGO).

2. ORGANIZATION

The Operation Manual of the Regional Geothermal Office for Central America (RGO) was signed between February and April 2013 by the following institutions: International Center for Geothermal

Energy at the University of Bochum (GZB), the German Cooperation in El Salvador (GIZ), the International Geothermal Association (IGA), the National Energy Board of El Salvador (CNE) and the Salvadoran geothermal company, LaGeo. Figure 1 shows the institutions and personnel involved in the organization of the RGO. The RGO will have its base in El Salvador and will work together with an internationally established network of institutions and experts in the field of geothermal energy.

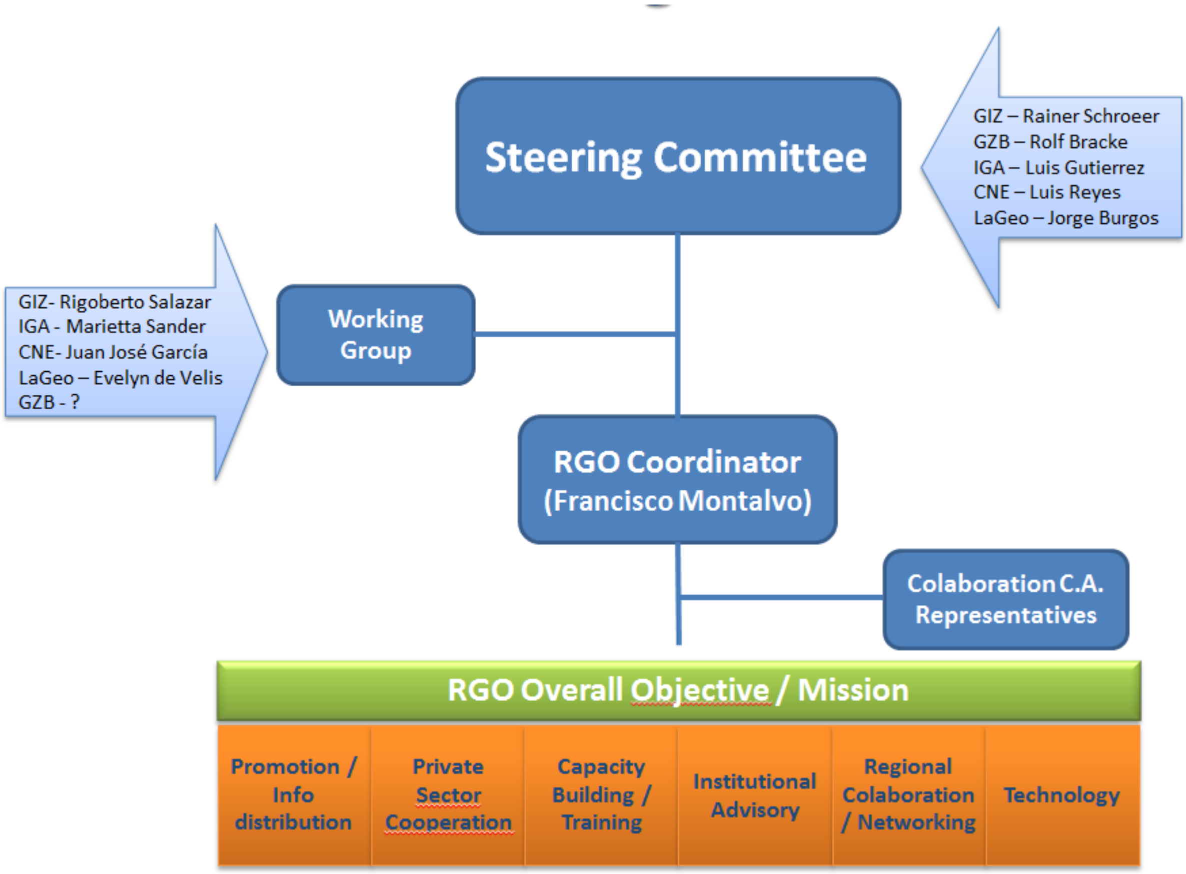

FIGURE 1: Regional Geothermal Office for Central American Organization

Within the organization considered in the Manual Instructions, the main coordinator of communications and activities of the RGO is the Secretary of the RGO, who in turn is headed by an Executive Officer or Coordinator, who is part of the staff of LaGeo (RGO, 2013). The RGO intends to cover in the next future, the entire Latin American region and the Caribbean, after its initial formation in Central America.

A brief description of the mentioned institutions supporting RGO is described below:

The **German Cooperation in El Salvador (GIZ)** has carried out the Program “4E Renewable Energies and Energy Efficiency in Central America”, working mainly in the implementation of strategies for the dissemination of renewable energy (RE) and energy efficiency measures (EE), and increase in investments in RE and EE. The creation of the RGO is another effort driven by the German government through the 4E-GIZ program, which aims to increase and strengthen together with its donors, the local capacity and investment technologies of renewable energy in Central America (GIZ, 2014). GIZ works hand in hand with the energy department of the General Secretariat of SICA (Central American Integration System). Within the program, the geothermal energy plays an important role as GIZ is an active participant in the establishment, organization and operation of the RGO.

The **International Geothermal Center at the University of Bochum (GZB)** is a joint research establishment of science and economics, involving administration and politics. The GZB provides a competence and information center to the public with regards to all queries concerning the utilization and extraction of geothermal energy (GZB, 2014). Among other objectives, the GZB works in transfer technology, know-how and information between universities, the economy and the public sector as well as to conduct and to foster application-oriented geo-research between various universities, to supply education and advanced training and the establishment of a scientific network of associated universities and research bodies on the national and international scale.

The RGO is supported also by the **International Geothermal Association (IGA)**. The IGA is a scientific and educational organization established to operate worldwide (IGA, 2014). It has more than 5,200 members in over 65 countries. Its mission is to encourage research, development and utilization of geothermal resources worldwide through the publication of scientific and technical information among the geothermal specialists, business community, governmental representatives, UN organizations and civil society. The International Geothermal Association (IGA) has operated its Secretariat since January 1st, 2011 in Bochum, Germany. Furthermore, the IGA Secretariat currently is part of the RGO's Technical Committee. On the 14th of November 2013, the IGA announced the foundation of the geothermal learning centre, the IGA Academy. The IGA Academy offers training courses with different focus and depth at existing international geothermal training institutes and universities. The RGO is planning to organize a geothermal specialized course with experts from the IGA Academy by the end of 2014 in Costa Rica.

The National Energy Council of El Salvador (CNE) is an autonomous non-profit state institution of public service that provides normative and regulatory national energy policy, with the aim of encouraging the rational use of energy sources in the country (CNE, 2014a; CNE, 2014b). It is also part of the RGO's Steering and Technical Committee and the management of the Regional Geothermal Training Programme (RGTP).

The geothermal Salvadoran company **LaGeo**, a company of excellence in this area currently operates two geothermal fields in the country with 38 years of experience in development and management the geothermal resources. Besides the exploitation of the geothermal resources, LaGeo, as an additional merit, is supporting the promotion and capacity building through the RGO and the RGTP.

The **RGO,** as mentioned above, will have its headquarters for the region in El Salvador and will work with an international network of institutions and experts in the field of geothermal energy and coordination of scientific research and capacity building, to help reduce the gap in this technology, in terms of technological development and all its potential application in the region, and encouraging the use of geothermal energy in the region.

The vision to create this office is to strengthen the networks between the countries of the Central American Integration System (SICA) and its entities; encourage cooperation within the academic and technological sector among member countries of SICA. A fundamental part of its action is to harness the geothermal resource present in Central America to further develop projects in this area in order to make it a viable market to attract local and international investors to the region.

3. OBJECTIVES

The Regional Geothermal Office for Central America (RGO) was established to promote and strengthen the development of the geothermal potential in Central America, as well as scientific and technological capabilities of the government entities, academic and scientific institutions and industries.

One of the main activities carried out by the new entity's documentation of information is the promotion of education and training for public and private entities in order to increase human capital in the regional geothermal industry, and implementation of new projects in cooperation with other institutions.

In addition to establishing guidelines for collaboration, reporting results and distribution of best practices in technical, social, environmental and regulatory issues, conducting seminars, workshops and conferences on such topics are carried out.

The main goals involve the transfer of knowledge, experience and technology, suitable for the development of geothermal resources policies, public and private investment in the corresponding technological and human capital.

The main strategic objectives can be described as follows:

- Promotion / distribution of technical and general information:
    - Establish guidelines for collaboration, reporting experiences and distributing documents on best technical, social and environmental practices.
    - Disseminate best practices of geothermal development and lessons learned, including policies, financing and investment guarantees.

- Cooperation with the Private Sector / Institutional Advisory:
    - Promote the facilitation and implementation of development projects and research.
    - Promote the implementation of financial support schemes in geothermal projects.

- Human Resources and Training / Institutional Advisory:
    - Promote education and training programs to increase the human capital in the regional geothermal industry.
    - Initiate and conduct seminars, workshops and conferences.
    - Promote the creation of a Centre of Excellence Geothermal in Central America.

- Regional Collaboration / Networking Groups:
    - Increase communication activities and develop networks between the countries of Latin America and the Caribbean and their respective institutions.
    - Provide the link between the region of Latin America and other global partnerships to promote geothermal energy.

- Technology / Cooperation with the Academic and Private Sector:
    - Sign academic cooperation between countries and technological sectors in the region.
    - Promote attendance of the Central America countries in research, development and implementation of projects for low and medium enthalpies.

The RGO will work to facilitate technological development and policy, strengthening skills and knowledge transfer of this energy resource. In addition, it will encourage private and public investment in this sector.

In summary, the strategic objectives are presented in Figure 2.

4. OPERATIONAL PROGRAMME

According to the Operational Programme, the main activities carried out for the RGO in 2013 and in the future are focused on:

- Organization and planning:
    - Visit to GZB at Bochum University, working in the organization and planning programme with GZB, IGA and CNE.
    - Technical Coordination Group meetings providing progress of activities.
    - Meetings of Directors – Steering Committee.

- Review / validation of Organizational Structure of the RGO 2013.
- Presentation of Periodic Progress Reports / Results.
- Strategic Development Plan 2013-2017, which intends to hire a consultant to develop the plan where the sustainability of the RGO is included.

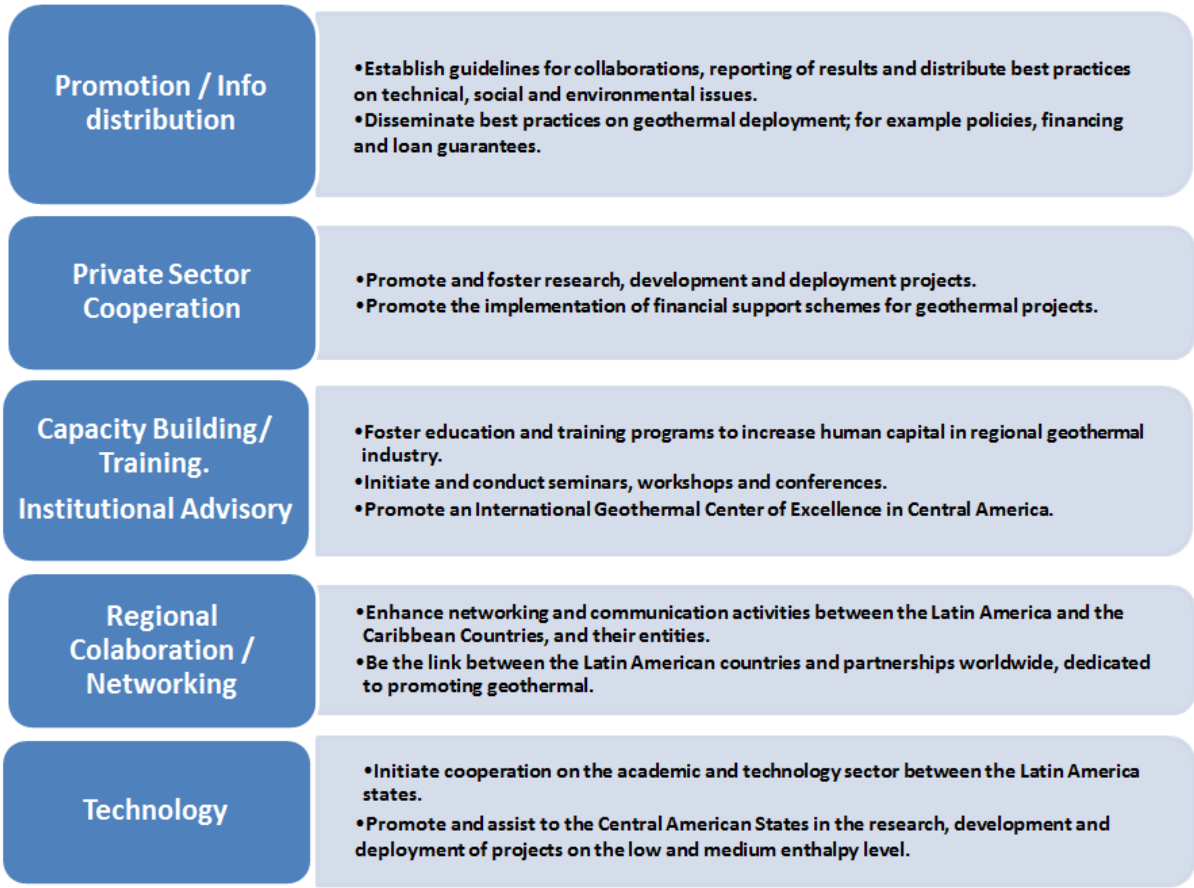

FIGURE 2: Regional Geothermal Office strategic objectives
Note: Possible further Members / Partners: Stakeholders from
Central America, IRENA, IDB, BCIE, etc.

- Promotion / Release:
  - Prepare activities for the participation of representatives of C.A. in Geo-T Expo Fair in Essen, Germany 2013 (Figure 3).
  - Advertise through internet websites (Figure 4) and magazines (IGA News, Piensa en geotermia, GIZ, LaGeo, CNE, GEOLAC, etc.), preparing articles and news on a regular basis.
  - Participate in the World Geothermal Congress 2015, in Melbourne Australia.

- Networking:
  - Develop a list of experts and specialized companies in the geothermal industry in Central America, Latin America and the Caribbean.
  - Develop a list of experts and specialized companies in the geothermal industry in Germany. Preliminary list presented in Report related to the visit GZB, Bochum.
  - GEOLAC website (Figure 5), by establishing network of experts, academic and research institutions and companies in the geothermal industry in C.A., L.A. and the Caribbean.

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Centroamérica dispone ya de una oficina para la promoción de la geotermia en la región, además expondrá sus experiencias en feria internacional en Europa.

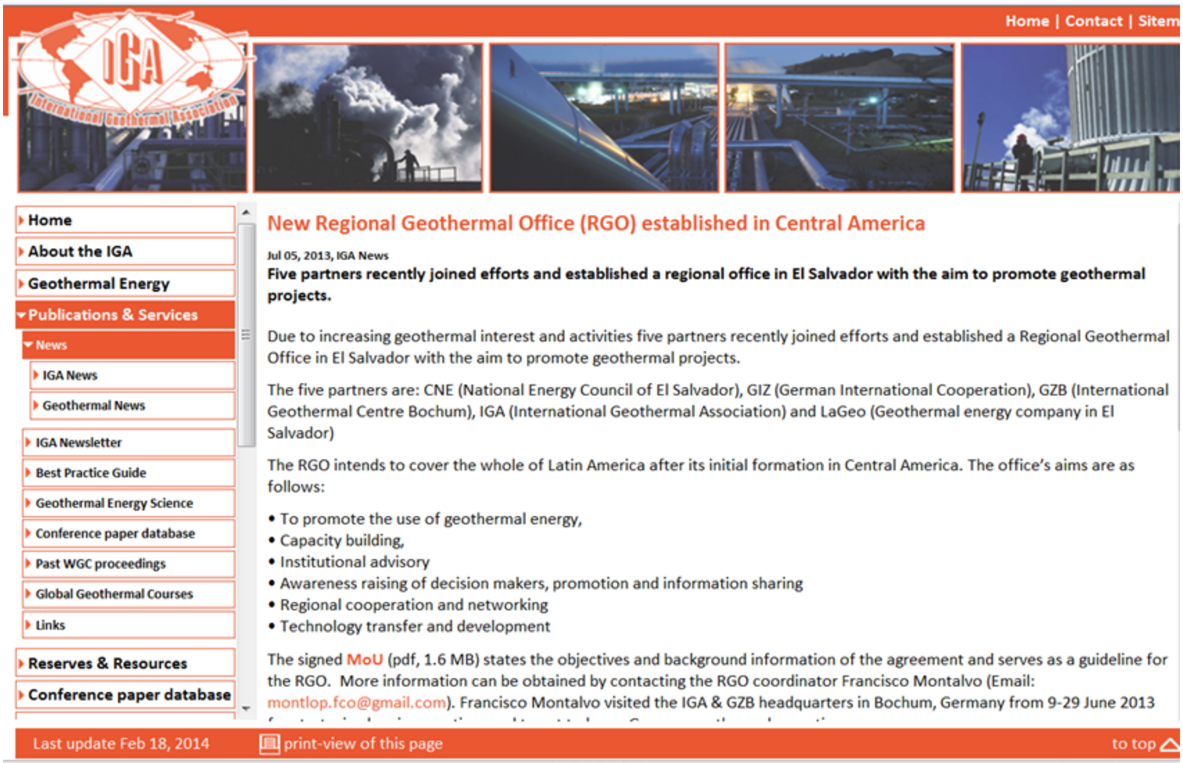
La RGO trabajará para facilitar el desarrollo tecnológico y de políticas, el fortalecimiento de competencias y la transferencia de conocimientos con este recurso energético.

28 Oct 2013 | Noticias del Programa

La oficina regional dedicada a la rama de la geotermia, trabajará para facilitar el desarrollo tecnológico y de políticas, el fortalecimiento de competencias y la transferencia de conocimientos y experiencias con este recurso energético. Además incentivará la inversión público privado en este sector.

El uso de la energía geotérmica tiene una larga tradición en Centroamérica. Actualmente se encuentran operando en la región 8 plantas conectadas a la red, generando hasta 625 MW de energía eléctrica. El Salvador por ejemplo, cubre hasta el 25% de la demanda de energía eléctrica con fuentes geotérmicas. Según estimaciones, el potencial total de la generación de energía eléctrica con geotermia en Centroamérica es entre 3000 MW y 13.000 MW.

FIGURE 3: Promotion of the Regional Geothermal Office (GIZ, 2013a)



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New Regional Geothermal Office (RGO) established in Central America

Jul 05, 2013, IGA News

Five partners recently joined efforts and established a regional office in El Salvador with the aim to promote geothermal projects.

Due to increasing geothermal interest and activities five partners recently joined efforts and established a Regional Geothermal Office in El Salvador with the aim to promote geothermal projects.

The five partners are: CNE (National Energy Council of El Salvador), GIZ (German International Cooperation), GZB (International Geothermal Centre Bochum), IGA (International Geothermal Association) and LaGeo (Geothermal energy company in El Salvador)

The RGO intends to cover the whole of Latin America after its initial formation in Central America. The office's aims are as follows:

- To promote the use of geothermal energy,
- Capacity building,
- Institutional advisory
- Awareness raising of decision makers, promotion and information sharing
- Regional cooperation and networking
- Technology transfer and development

The signed MoU (pdf, 1.6 MB) states the objectives and background information of the agreement and serves as a guideline for the RGO. More information can be obtained by contacting the RGO coordinator Francisco Montalvo (Email: montlop.fco@gmail.com). Francisco Montalvo visited the IGA & GZB headquarters in Bochum, Germany from 9-29 June 2013

Last update Feb 18, 2014 print-view of this page to top

FIGURE 4: News about the Regional Geothermal Office (IGA, 2013)

FIGURE 5: Web site GEOLAC, networking tool. Source: IDB-LaGeo

- Training:
  - Support and participate in the implementation / development of the Regional Training Center of the National University of El Salvador (Figure 6). Coordination of the Working Group (Technical) of the RGO has active participation in the Diploma in Geothermal Energy, Regional Geothermal Training Programme (CNE-UES-LaGeo-IDB-NDF).
  - Promote the creation of a Geothermal Centre of Excellence. Similarly it is participating in the establishment of the Regional Centre for Geothermal Energy, which will set the foundation to make it in the future a Geothermal Centre of Excellence in C.A.
  - Participate in the UNU-GTP & LaGeo Short Courses.
  - Organize an Advanced Seminar - 2014 IGA Academy. Define issues and a seminar for advanced geothermal technology in the second quarter of 2014 in Costa Rica.

- Technology:
  - GIZ Consulting Report prepared on Medium and Low Enthalpy Geothermal Projects barriers.
  - Development of a national plan for the promotion of geothermal energy of low and medium enthalpy in El Salvador (see map in Figure 7). Starting the project in El Salvador and later expand to other countries.
  - Investigate and support the creation, implementation and development of a new project for hedging risk activities for Geothermal Drilling. Project presented to the German Development Bank (KfW).
  - Implementation of a Comprehensive Regional Geothermal Development Master Plan.


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El Salvador gradúa a 26 en geotermia.

26 alumnos se graduaron del primer diplomado en geotermia. El curso busca posicionar al país como líder en capacitación técnica y científica de recurso humano para el aprovechamiento de los recursos geotérmicos.

13 Dec 2013 | Geotérmica

Unos 26 alumnos nacionales e internacionales se graduaron del primer diplomado en geotermia impartido en El Salvador.

Con la certificación de los 26 profesionales nacionales y extranjeros, las autoridades del Consejo Nacional de Energía (CNE), Universidad de El Salvador (UES) y LaGeo, dieron por concluido el Diplomado de Especialización en Geotermia, Edición 2013, el cual busca posicionar a El Salvador como un país líder en la capacitación técnica y científica de recurso humano para el aprovechamiento de los recursos geotérmicos; y representa los primeros pasos para constituirse en un Centro Regional de Investigación y Entrenamiento Geotérmico.

Este diplomado forma parte del componente de formación profesional de la cooperación técnica brindada por el BID y el Fondo Nórdico de Desarrollo (FND) para la consolidación de un Centro Regional de Capacitación.

Durante los cinco meses del diplomado, los estudiantes se formaron en temas como: la exploración geológica, geoquímica y geofísica, además se capacitaron en el campo por medio de visitas a las instalaciones de LaGeo (única empresa en el país que genera electricidad a partir de la geotermia o lo que es lo mismo, el calor del subsuelo) y el estudio de las técnicas de perforación de pozos

FIGURE 6: Diploma in Geothermal Energy, Regional Geothermal Training Programme (CNE-UES-LaGeo- IDB-NDF) (GIZ, 2013b)

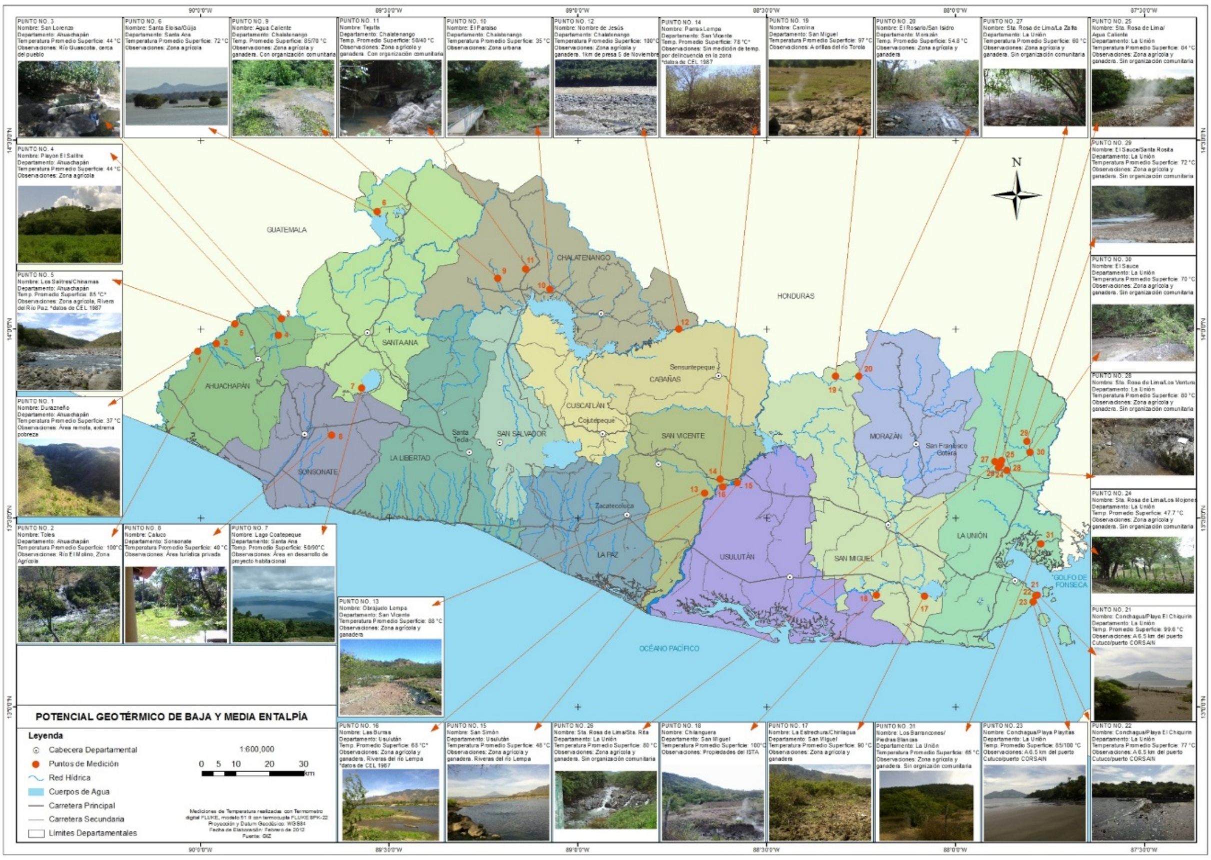

FIGURE 7: Map of Medium and Low enthalpy resources in El Salvador. Source: GIZ

- Development of the RGO
  - Evaluation of the RGO's future to be considered in structuring the Strategic Plan (Vision, Mission, Values , structure, resources, etc .).
  - Affiliation and Memberships RGO (Strategic Plan and sustainability mechanisms). In the future through the institutions affiliated to it, for instance Geothermal National Associations may be represented at IGA, through a Central American Branch.

- Regional collaboration
  Activities relating to the IGA
  - Divulge information in Central America to incorporate new members for the IGA. Recently incorporated new members such as Nicaragua and other countries in L.A. (Honduras, Chile, Ecuador and Peru).
  - Facilitate / act as a leader in the Central American region to exchange information / queries to the IGA and disseminate information of the Association between all actors and others interested in the topic. The RGO, which leads to closely mention the IGA, due it participates as a support for the Office, thus having the same goals.
  - Support the establishment / formalization of a Regional Geothermal Association. Currently already has the Geothermal Association of El Salvador, the Geothermal Association of Costa Rica, both recognized by the IGA and recently has begun the process for the formation of the Geothermal Association of Nicaragua. This is one of the medium-term objectives, forming the first "Branch" of the IGA in L.A.
  - Assistance to IGA to publicize the progress of RGO and regional collaboration.

- Institutional advisory
  - Promote the establishment of financial support schemes in geothermal projects.
  - Promote the implementation of rules or laws of geothermal through contacts between entities in different countries. Some countries already have regulations or laws, so it is necessary to know the institutional and industrial landscape of each country, and to establish the roles and responsibilities of different institutions.

- Private sector cooperation
  - Promote the facilitation and implementation of development projects and geothermal geoscience research or technology between companies and research institutions or academic.
  - To promote contacts between people / institutions interested in geothermal generating companies with products or services to the geothermal industry.
  - Identify synergy of business networks and other institutions: education, research etc.

REFERENCES

CNE, 2014a: Consejo Nacional de Energía. Website: http://www.cne.gob.sv/index.php?option=com_ content&view=section&id=5&Itemid=54

CNE, 2014b: Energías renovables. Website: http://www.cne.gob.sv/index.php?option=com_ content& view=section&id=5&Itemid=54

GIZ, 2013a: *Centroamérica dispone ya de una oficina para la promoción de la geotermia en la region, además expondrá sus experiencias en feria internacional en Europa*. Energías Renovables y Eficiencia Energética en Controamerica. Website: http://www.energias4e.com/noticia.php?id=2164

GIZ, 2013b: *El Salvador gradúa a 26 en geotermia*. Energías Renovables y Eficiencia Energética en Controamerica. Website: http://www.energias4e.com/noticia.php?id=2268

GIZ, 2014: *El programa*. Energías Renovables y Eficiencia Energética en Controamerica. Website: http://www.energias4e.com/elprograma.php

GZB, 2014: *Portrait*. Geothermie Zentrum Bochum. Website: http://www.geothermie-zentrum.de/en/portrait.html

IGA, 2013: *New Regional Geothermal Office (RGO) established in Central America*. International Geothermal Association. Webpage: http://www.geothermal-energy.org/publications_and_services/news/article/new-regional-geothermal-office-rgo-established-in-central-america.html

IGA, 2014: *Welcome to the International Geothermal Association*. International Geothermal Association. Website: http://www.geothermal-energy.org/

RGO, 2013: Operation manual for the Regional Geothermal Office for Central America (RGO). Regional Geothermal Office.

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS
UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

GEOTHERMAL POWER PLANTS

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ABSTRACT

The paper gives an overview of the existing power plant technology. It addresses various problems that have been encountered, and outlines countermeasures that have been applied. Two main types of geothermal power plants are common, the condensing power plant, using fluid from reservoirs with temperatures in the range 200–320°C, and the binary fluid power plant using temperatures as low as 120°C. Also featured are the principal advantages appropriate to the utilisation of geothermal resources for production of electricity.

The paper moreover touches upon some of the advantages accruable from the integrated use of geothermal resources (using the same resource for electricity production in cascade or parallel with production of hot water for alternative uses), taking hybrid conversion as a case in point.

Also featured is a worldwide overview of the geothermal power plants by Bertani (under the auspices of IGA in 2010). The survey categorises the power plants by country and type of conversion system used, giving the installed capacity, annual electricity produced, number of units and the role of the geothermal generation with respect to the country's total electricity generation and total power demand. Also addressed is the worldwide distribution of geothermal power plants by plant type and the distribution of unit capacity and turbine inlet pressure. Finally an earlier survey presented by Bertani in 2005 features the effect of resource temperature on the power generation density.

Environmental abatement measures, such as re-injection of the spent (denuded of most of its thermal energy) geothermal fluid and methods of minimising atmospheric contamination by CO_2 and H_2S gases are also outlined, and so are the main associated technical problems.

The paper closes with a comprehensive list of the parameters that should be considered in designing a sustainable geothermal application scenario.

1. INTRODUCTION

The generation of electrical power using the thermal energy contained in the fluid circulating in deep lying formations in geothermal areas is typically quite feasible in the fluid temperature range of 200°C to 320°C, which characterises so called high-temperature (high enthalpy) geothermal areas. Geothermal fluid of this temperature is generally mined using current technology at resource depths between about 1200 m to 2500 – 3000 m in Iceland and most other geothermal areas of the world, for instance the USA, the Philippines, Indonesia, Japan, New Zealand, Mexico, Kenya and El Salvador to name a few.

Geothermal energy is renewable, when measured relative to human age spans, and generally categorised as such. It is environmentally benign ("green") and has many advantages over other renewable energy resources, such as hydro, wind, bioenergy and wave energy. The following are the more important of these advantages:

- High degree of availability (>98% and 7500 operating hrs/annum common);
- Low land use;
- Low atmospheric pollution compared to fossil fuelled plants;
- Almost zero liquid pollution with re-injection of effluent liquid;
- Insignificant dependence on weather conditions; and
- Comparatively low visual impact.

In compliance with current environmental, resource and economic sustainability principles it (Axelsson et al., 2001, 2003, and 2005) is important to select technologies and operational systems for the highest possible over all thermal efficiency for extracting the useful thermal energy, contained in the fluid, before it is returned back to the reservoir. The advantage of adopting such policies is the reduced number of production and injection wells required, less replacement drilling, higher level of sustainability, and greater environmental benefits.

These advantages may be attained in several ways, the optimal of which are multiple use (e.g. simultaneous electricity plus hot water production) systems and hybrid power plants.

The following chapter addresses the most common types of technologies applied in the conversion of geothermal energy into electric power; reviews some of the associated problems, and available countermeasures.

2. OVERVIEW OF POWER PLANT DESIGNS

This chapter addresses the geothermal to electrical power conversion systems typically in use in the world today. These may be divided into three basic systems, wiz:

- **Flashed steam/dry steam condensing system**; resource temperature range from about 320°C to some 230°C.
- **Flashed steam back pressure system**; resource temperature range from about 320°C to some 200°C.
- **Binary or twin-fluid system** (based upon the Kalina or the Organic Rankin cycle); resource temperature range between 120°C to about 190°C.

In addition to the above three basic power conversion systems, there are in use, the so called hybrid systems, which are in fact a combined system comprising two or more of the above basic types in series and/or in parallel.

Condensing and back pressure type geothermal turbines are essentially low pressure machines designed for operation at a range of inlet pressures ranging from about 2 – 20 bar, and saturated steam. The back pressure turbines have low thermal efficiency and are manufactured in relatively small sizes i.e. 0.5-5 MW. The condensing turbines are more efficient (by factor of 2 to 4) than the back pressure turbines. They are generally manufactured in larger output module sizes, commonly of the following power ratings: 25 MW, 35 MW, 45 MW, 55 MW and 105 MW (the largest currently manufactured geothermal turbine unit is 117 MW). Binary type low/medium temperature units, whereof the Kalina Cycle or Organic Rankin Cycle type, are typically manufactured in smaller modular sizes, i.e. ranging from 250 kW to 10 MW_e in size. Larger units specially tailored to a specific use are, however, available typically at a somewhat higher price.

Typical geothermal back pressure, condensing, binary and hybrid systems are depicted in diagrams on Figures 1, up to 6.

2.1 Back pressure type systems

Back pressure type systems (Figure 1) are the simplest of the above, least expensive and have the lowest overall thermal efficiency. Currently they are largely used in multiple use applications (such as combined electricity and hot water production), to provide temporary power during resource development, in the mineral mining industry where energy efficiency has low priority, and most importantly as part of a hybrid system. Their stand-alone scope of application covers the whole of the normally useful geothermal resource temperature range, i.e. from about 320°C to some 200°C.

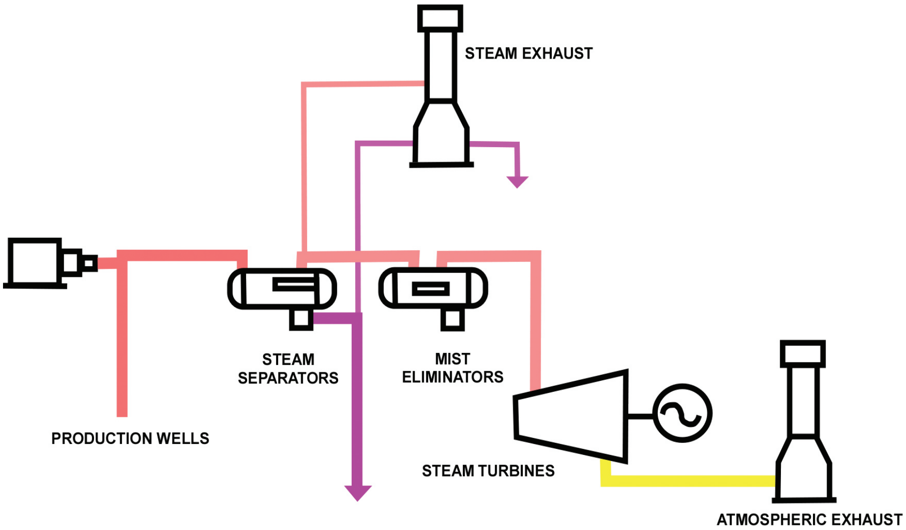

FIGURE 1: Typical backpressure turbine/generator conversion system

2.2 Condensing type systems

Condensing type systems (Figures 2 and 3) are somewhat more complex in as much as they require a condenser, and gas exhaust system. This is the most common type of power conversion system in use today. The turbine is an expansion machine and the unit normally comprises two turbine sets arranged coaxially cheek to cheek (hp end to hp end) to eliminate/minimise axial thrust. To improve its thermal efficiency and flexibility, the unit is also available in a twin pressure configuration (say 7 bar/2 bar), where the lower pressure (say 2 bar) steam is induced downstream of the third expansion stage. When these condensing turbines are used in a co-generation scheme they may be fitted with extraction points to provide low pressure steam to the district heating side. The hallmarks of the condensing system are long and reliable service at reasonable over all thermal efficiency, and good load following capability. Their stand-alone scope of application covers the high to medium (200–320°C) geothermal resource temperature range.

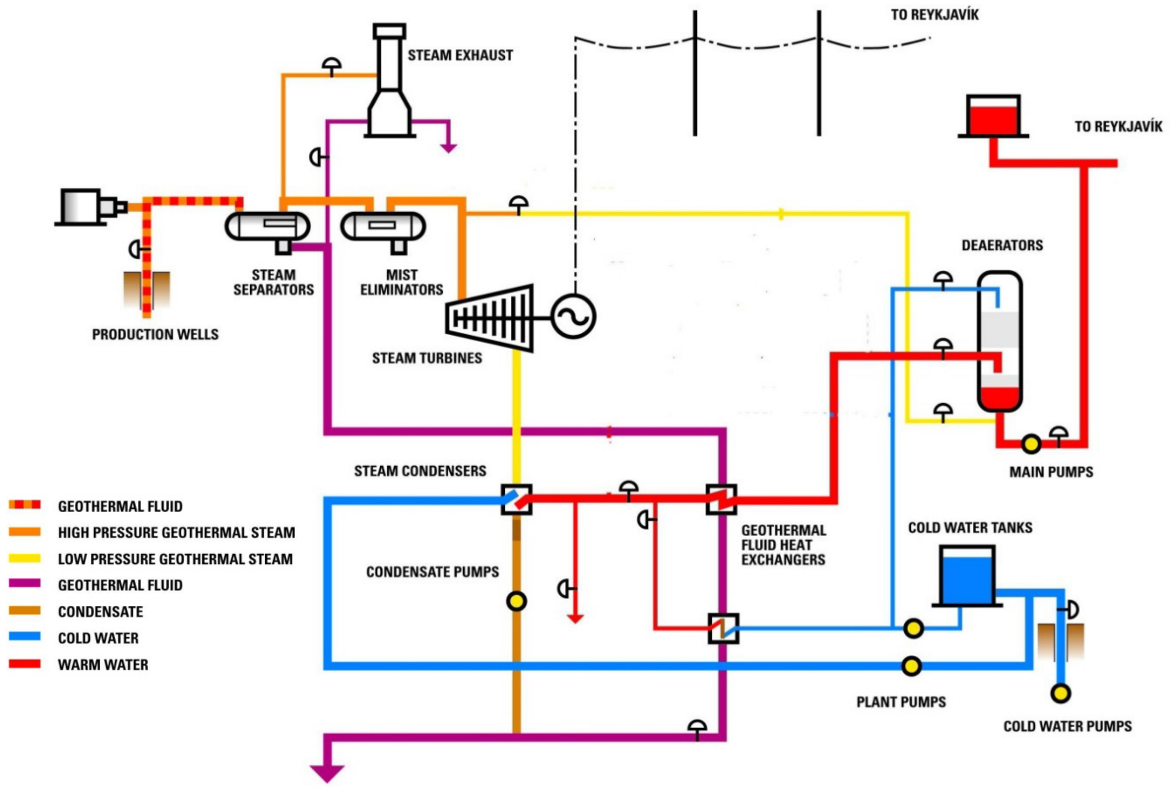

FIGURE 2: Condensing type turbine/generator unit in combined utilisation (courtesy of Reykjavík Energy)

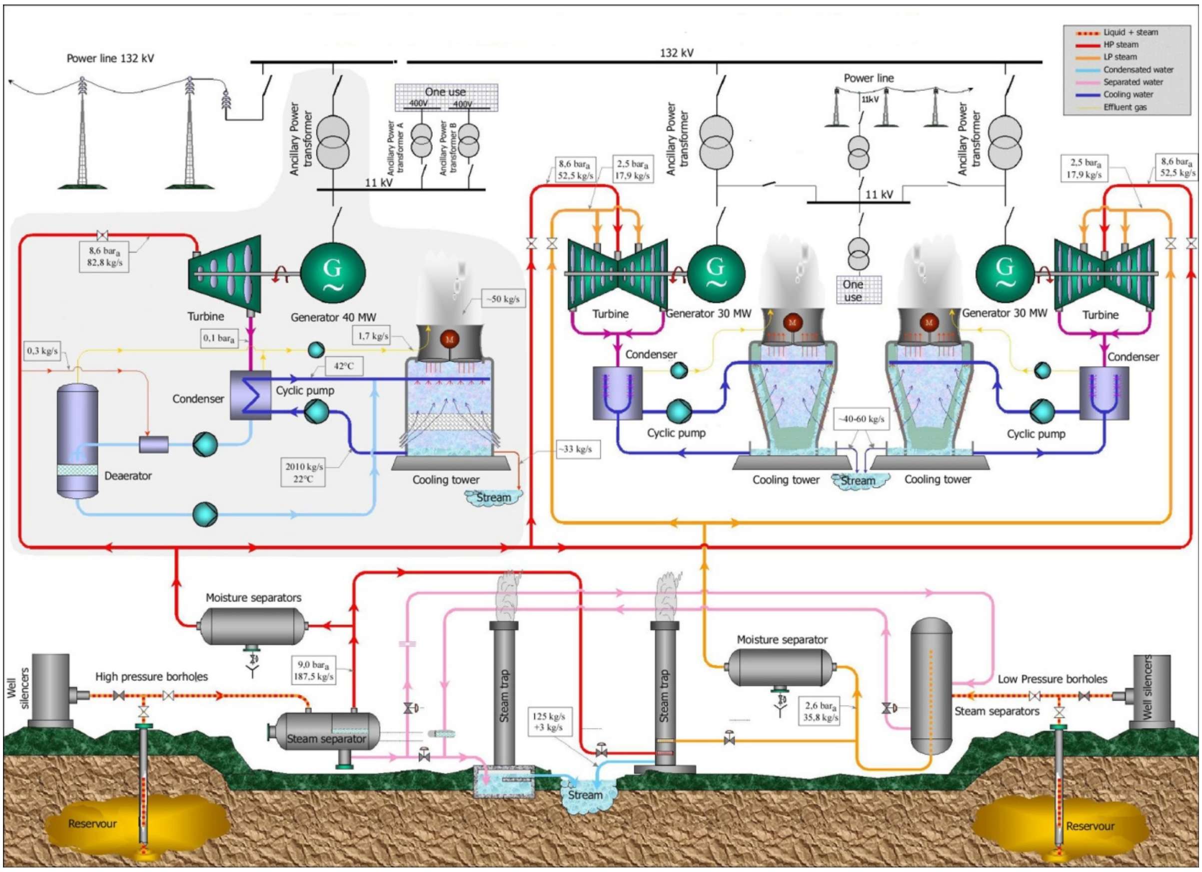

FIGURE 3: Condensing single and twin pressure t/g unit (courtesy of Landsvirkjun, Iceland)

2.3 Binary type systems

Binary type systems are of a quite different concept. The thermal energy of the geothermal fluid from the production well field is transferred to a secondary fluid system via heat exchangers. The geothermal fluid is thus isolated from the secondary fluid, which comprises a low boiling point carbohydrate (butane, propane etc.) or specially designed low boiling point fluid, which complies with low ozone layer pollution constraints, in the case of the Organic Rankine Cycle (Figure 4). In the case of the Kalina Cycle (Figure 5), the secondary or motive liquid comprises water solution of ammonia. This heated secondary fluid thereupon becomes the motive fluid driving the turbine/generator unit. The hallmark of the binary system is its ability to convert low-temperature (120–190°C) geothermal energy to electric power albeit at a relatively low overall thermal efficiency, and to isolate scaling, gas and erosion problems at an early point in the power conversion cycle in a heat exchanger. The binary system is quite complex and maintenance intensive.

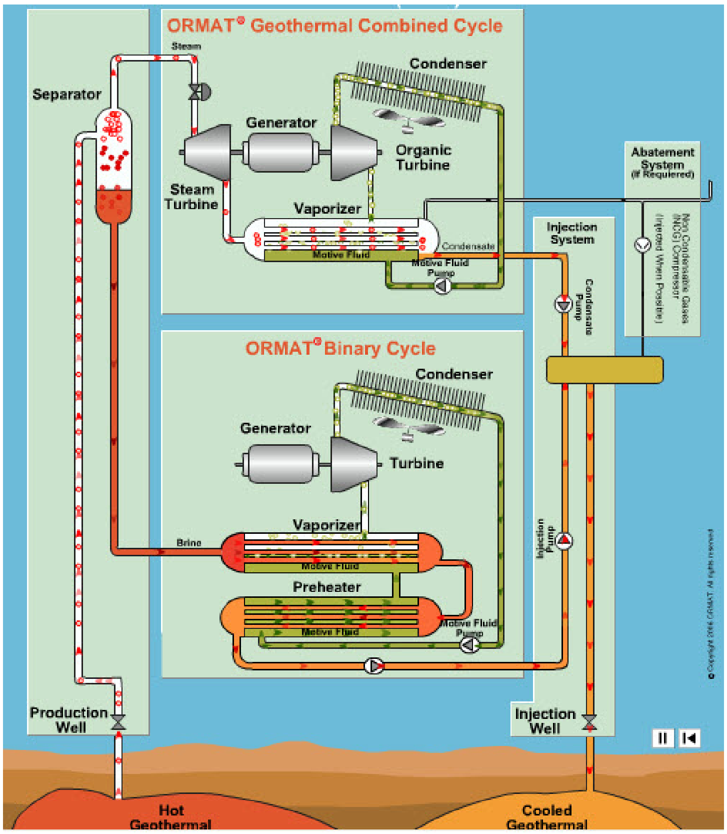

FIGURE 4: Ormat type Organic Rankine cycle (courtesy of Ormat Technologies Inc.)

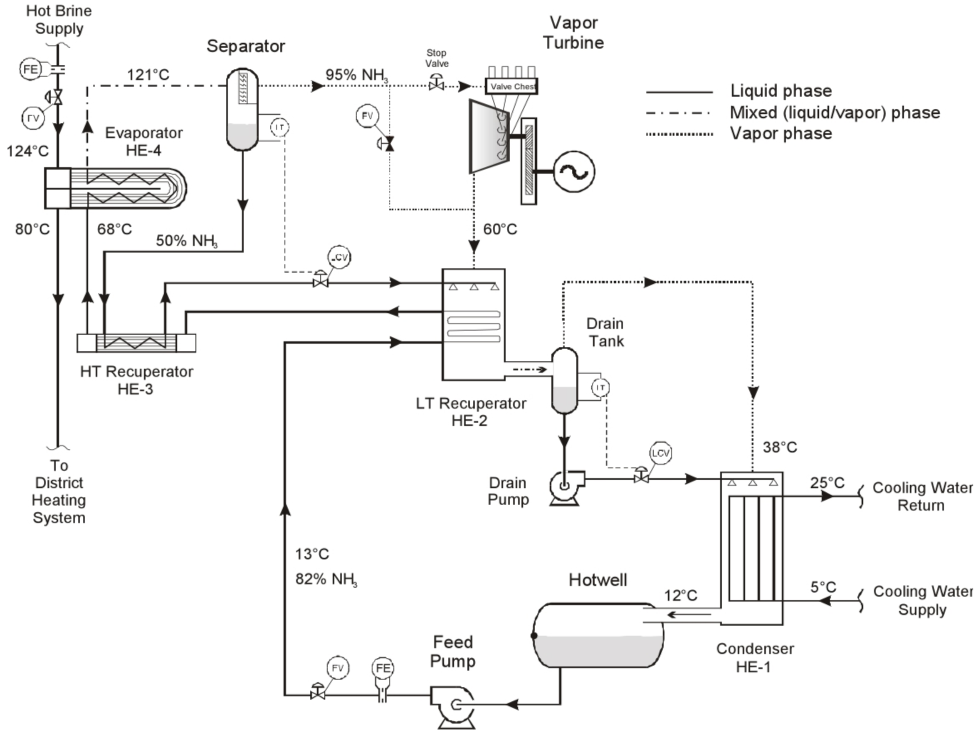

FIGURE 5: Kalina cycle converter (courtesy Xorka Ltd.)

2.4 Hybrid conversion system

The hybrid conversion system is a combined system, as said before, encompassing two or more of the basic types in series and/or in parallel. Their hallmark is versatility, increased overall thermal efficiency, improved load following capability, and ability to efficiently cover the medial (200–260°C) resource temperature range (Tester, 2007). To illustrate the concept a hybrid configuration encompassing a backpressure flashed steam turbine/generator unit and three binary units in series is depicted in Figure 6. Two of the binary units utilise the exhaust steam from the back pressure unit, and the remaining binary t/g unit utilises the energy content of the separator fluid. The fluid effluent streams are then combined for re-injection back into the geothermal reservoir, so maintaining sustainability of the resource in a most elegant manner.

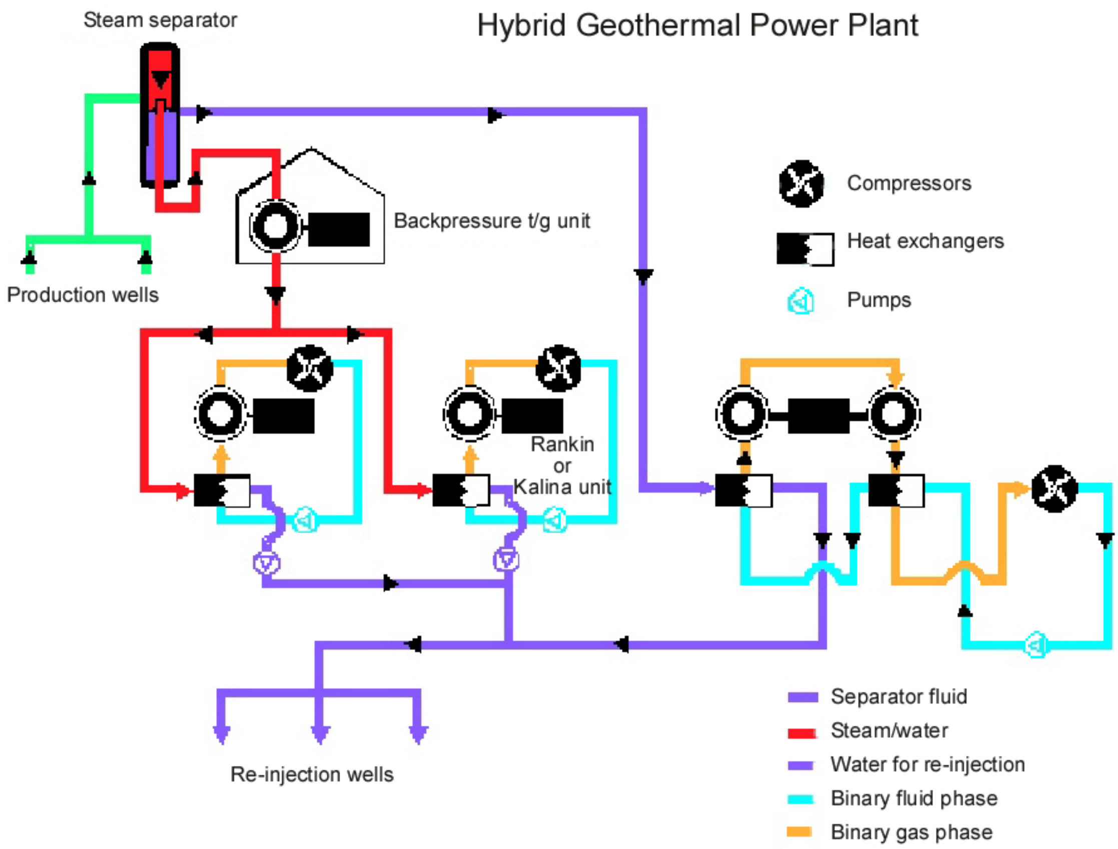

FIGURE 6: Hybrid conversion system

3. WORLD SURVEY ON GEOTHERMAL POWER PLANTS

Summary reports of the worldwide geothermal utilisation are presented at the World Geothermal Congresses organized by the International Geothermal Association (IGA) every five years. In Table 1 the electricity generation from geothermal resources in 2010 presented at the WGC 2010 in Bali, Indonesia, is reproduced (Bertani, 2010). Figure 7 shows the installed capacity in MW and the total number of units for each category from the same source, based on the standard plant classification. It shows that the largest installed capacity corresponds to single-flash units.

Figure 8 shows data from a worldwide survey made by the Japan Geothermal Energy Association in 2001. It shows the distribution of unit capacity of geothermal power plants (left) and the distribution of inlet pressure of all turbine units included in the survey (right). The sizes of 5, 20 and 55 MWe are clearly the most common, although several small units are in operation as well as a small number of much larger units. The inlet pressure lies generally in the range 6-8 bars, but also here a wide range of values is reported.

TABLE 1: Geothermal power generation worldwide in 2010 (Bertani, 2010)

	Installed capacity MW_e	**Annual electricity produced GWh/year**	**Number of units**
Australia	1.1	0.5	2
Austria	1.4	3,8	3
China	24	150	8
Costa Rica	166	1,131	6
El Salvador	204	1,422	7
Ethiopia	7.3	10	2
France (Guadeloupe)	16	95	3
Germany	6.6	50	4
Guatemala	52	289	8
Iceland	575	4,597	25
Indonesia	1,197	9,600	22
Italy	843	5,520	33
Japan	536	3,064	20
Kenya	167	1,430	14
Mexico	958	7,047	37
New Zealand	628	4,055	33
Nicaragua	88	310	5
Papua New Guinea	56	450	6
Philippines	1,904	10,311	56
Portugal	29	175	5
Russia	82	441	11
Thailand	0.3	2	1
Turkey	82	490	5
USA	3,093	16,603	210
TOTAL	**10,715**	**67,246**	**526**

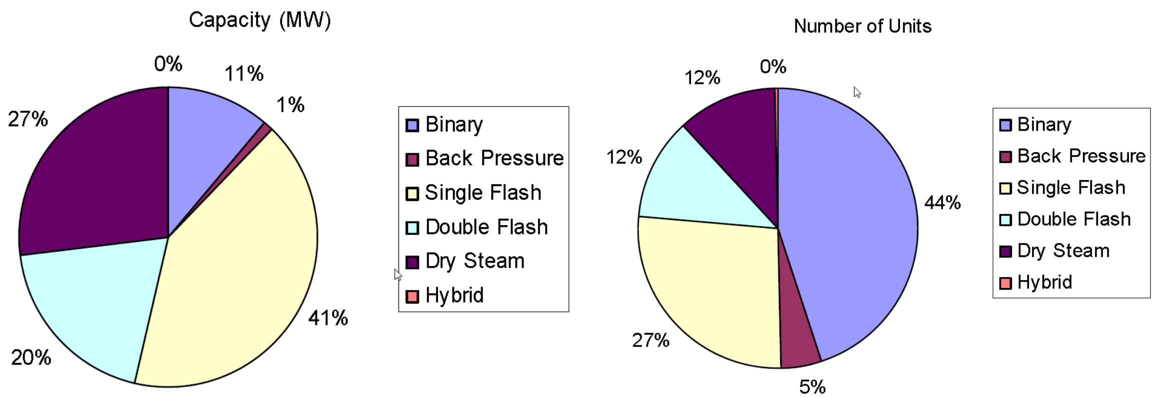

FIGURE 7: Worldwide distribution of geothermal power plants by plant type, based on installed capacity (left) and number of units (right)

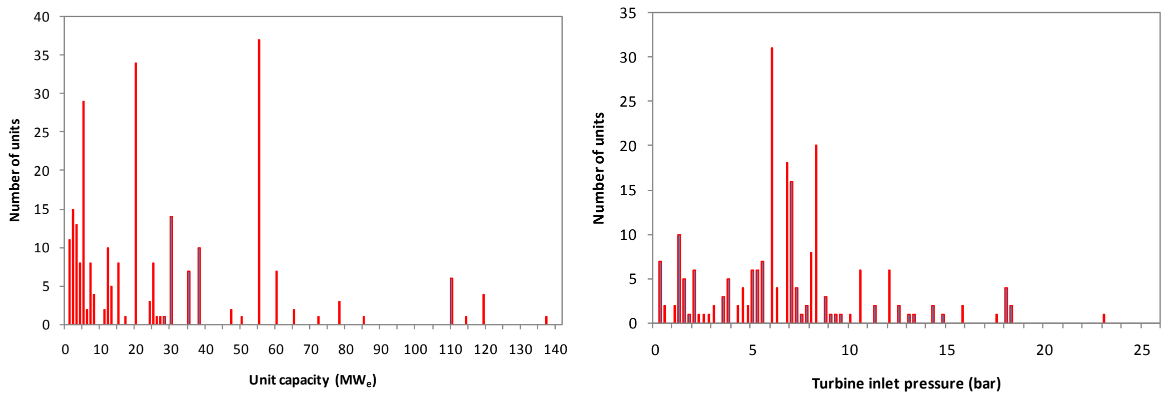

FIGURE 8: Distribution of unit capacity (left) and turbine inlet pressure (right) in geothermal electricity production worldwide (Japan Geothermal Energy Association, unpublished data sheets)

Bertani's paper from WGC-2005 gives calculated values for power density (MW_e/km^2) as well as the number of productive wells per square kilometre; see Table 2.

TABLE 2: Effect of reservoir temperature on production indices. Hotter >250°C, and cooler <250°C. Values in the second and third column are mean and standard deviations (Bertani, 2005)

Index	**Hotter**	**Cooler**
Power density (MW_e/km^2)	7.8 ± 6.4	6.5 ± 5.2
Well density ($Wells/km^2$)	1.9 ± 1.4	1.9 ± 1.6
Well productivity (MW_e/well)	4.7 ± 3.3	4.2 ± 2.2

4. PREVAILING PROBLEM TYPES AND COUNTERMEASURES IN OPERATION OF POWER PLANTS

Different parts of the surface components of power generation system have associated different problem flora. It is therefore expedient to divide the system into the following seven principal portions:

- **Power house equipment:** Comprising of turbine/generator unit complete with condenser, gas exhaust system.
- **Automatic control and communication system:** Consisting of frequency control, servo valve control, computer system for data collection, resource and maintenance monitoring, internal and external communication etc.
- **Cooling system:** Cooling water pumps, condensate pumps, fresh water (seawater) cooling, or cooling towers.
- **Particulate and/or droplet erosion:** This is an erosion problem that is typically associated with the parts of the system where the fluid is accelerated (e.g. in control valves, turbine nozzles, etc.) and/or abruptly made change direction (e.g. via pipe bends, T-fittings or wanes).
- **Heat exchangers:** These are either of the plate or the tube and shell type. These are generally only used in binary and hybrid type conversion systems, and/or in integrated systems.
- **Gas evacuation systems:** High temperature geothermal fluid contains a significant quantity of non-condensable gases ($C0_2$, N_2, H_2S, and others). These have to be removed for instance from the condensing plant for reasons of conversion efficiency. Some countries require the gas to be cleaned of H_2S or Hg to minimise atmospheric pollution.

- **Re-injection system:** Comprising liquid effluent collection pipelines, injection pumps, injection pipelines, injection wells and control system.
- **Chemical injection systems:** These are applied in order to reduce and control corrosion and scaling in production/re-injection wells and surface equipment.

The problem areas typical for each of these conversion components are now outlined in turn each under its own chapter heading. It must, however, be emphasised that the featured problems and counter measures can only be addressed in general terms because of their site and locality specific nature. A locality specific case by case pre-engineering study is decidedly required in order to address this subject matter in any detail.

4.1 Power house equipment

4.1.1 Turbine

The problems potentially associated with the turbine are scaling of the flow control valve and nozzles (primarily in the stator inlet stage); stress corrosion of rotor blades; erosion of turbine (rotor and stator) blades and turbine housing.

The rate and seriousness of scaling in the turbine are directly related to the steam cleanliness, i.e. the quantity and characteristics of separator "carry-over". Thus the operation and efficiency of the separator are of great importance to trouble free turbine operation. Prolonged operation of the power plant off-design point also plays a significant role.

Most of the scaling takes place in the flow control valve and the first stator nozzle row. The effect of this scaling is:

- A significant drop-off in generating capacity as sufficient steam cannot enter the turbine; and
- Sluggish response to load demand variations.

This situation is easily monitored, since the build-up of scales causes the pressure in the steam chest between the control valve and the inlet nozzles to increase over time.

Significant turbine and control valve scaling is avoided by the adoption of careful flasher/separator plant operating practices that minimise "carry-over", and moreover selecting a high efficiency mist eliminator by the power plant.

Significant scaling in turbine and control valve requires scheduled maintenance stops for inspection and cleaning, every second or third year.

Another means of reducing turbine cleaning frequency, is to inject condensate into the inlet steam during plant operation and run the turbine at say 10% wetness for a short period. This washes away nozzle scaling, in particular the calcite component thereof, and simultaneously weakens the silica scale structure, which then tends to break off. This cleaning technique if properly applied has been found to reduce the frequency of major turbine overhaul.

4.1.2 Generator

It must be pointed out here that high-temperature steam contains a significant amount of carbon dioxide CO_2 and some hydrogen sulphite H_2S and the atmosphere in geothermal areas is thus permeated by these gases. All electrical equipment and apparatus contains a lot of cuprous or silver components, which are highly susceptible to sulphite corrosion and thus have to be kept in an H_2S free environment. This is achieved by filtering the air entering the ventilation system and maintaining slight overpressure in the control room and electrical control centres.

The power generator is either cooled by nitrogen gas or atmospheric air that has been cleaned of H_2S by passage through special active carbon filter banks.

4.1.3 Condenser

The steam-water mixture emitted from the turbine at outlet contains a significant amount of non-condensable gases comprising mainly CO_2 (which is usually 95–98% of the total gas content), CH_4 and H_2S, and is thus highly acidic. There is a condenser that receives the steam directly from the turbine which is a large piece of equipment, either of the direct contact type (water spray) or indirect contact (heat exchanger). The direct contact type is more common. Condensation of the steam creates a vacuum (about 80-90%, 0.1-0.2 bar a) inside the condenser which improves the turbine efficiency markedly. The vacuum level is controlled by the temperature of the cooling water. Thus in warm weather or hot climates the vacuum cannot be maintained as high which causes a decline in the turbine output. Vacuum pumps are required to extract the non-condensable gases in order to maintain the level of vacuum. Since most high-temperature geothermal resources are located in arid or semi-arid areas far removed from significant freshwater (rivers, lakes) sources, the condenser cooling choices are mostly limited to either atmospheric cooling towers or forced ventilation ones. The application of evaporative cooling of the condensate results in the condensate containing dissolved oxygen in addition to the non-condensable gases, which make the condenser fluid highly corrosive and require the condenser to be clad on the inside with stainless steel; condensate pumps to be made of stainless steel, and all condensate pipelines either of stainless steel or glass reinforced plastic. Addition of caustic soda is required to adjust the pH in the cooling tower circuit. Make-up water and blow-down is also used to avoid accumulation of salts in the water caused by evaporation.

A problem sometimes encountered within the condenser is the deposition of almost pure sulphur on walls and nozzles within the condenser. This scale deposition must be periodically cleaned by high pressure water spraying etc.

4.2 Automatic control and communication system

Modern power plants are fitted with a complex of automatic control apparatus, computers and various forms of communication hardware. These all have components of silver and cuprous compounds that are extremely sensitive to H_2S corrosion. They are therefore housed inside "clean enclosures", i.e. airtight enclosures that are supplied with atmospheric air under pressure higher than that of the ambient atmospheric one and specially scrubbed of H_2S. Entrance and exit from this enclosure is through a clean air blow-through antechamber to prevent H_2S ingress via those entering the enclosure. A more recent design is to clean all the air in all control rooms by special filtration and maintain overpressure.

Most other current carrying cables and bus bars are of aluminium to prevent H_2S corrosion. Where copper cables are used a field applied hot-tin coating is applied to all exposed ends.

4.3 Cooling tower system

4.3.1 Cooling tower and associated equipment

Most high-temperature geothermal resources are located in arid or semi-arid areas far removed from significant freshwater (rivers, lakes) sources. This mostly limits condenser cooling choices to either atmospheric cooling towers or forced ventilation ones. Freshwater cooling from a river is, however, used for instance in New Zealand and seawater cooling from wells on Reykjanes, Iceland.

In older power plants the atmospheric versions and/or barometric ones, the large parabolic ones of concrete, were most often chosen. Most frequently chosen for modern power plants is the forced ventilation type because of environmental issues and local proneness to earth quakes.

The modern forced ventilation cooling towers are typically of wooden/plastic construction comprising several parallel cooling cells erected on top of a lined concrete condensate pond. The ventilation fans are normally vertical, reversible flow type and the cooling water pumped onto a platform at the top of the tower fitted with a large number of nozzles, through which the hot condensate drips in counter-flow to the airflow onto and through the filling material in the tower and thence into the condensate pond, whence the cooled condensate is sucked by the condenser vacuum back into the condenser. To minimise scaling and corrosion effects the condensate is neutralised through pH control, principally via addition of sodium carbonate.

Three types of problems are found to be associated with the cooling towers, i.e.

- Icing problems in cold areas;
- Sand blown onto the tower in sandy and arid areas; and
- Clogging up by sulphitephylic bacteria.

The first mentioned is countered by reversing the airflow cell by cell in rotation whilst operating thus melting off any icing and snow collecting on the tower.

The second problem requires frequent cleaning of nozzles and condensate pond. The last mentioned is quite bothersome. It is most commonly alleviated by periodic application of bacteria killing chemicals, and cleaning of cooling tower nozzles by water jetting. The sludge accumulation in the condensate pond, however, is removed during scheduled maintenance stops. A secondary problem is the deposition of almost pure sulphur on walls and other surfaces within the condenser. It must be periodically cleaned by high pressure water spraying etc., which must be carried out during scheduled turbine stops.

4.4 Condenser pumping system

The condensate pumps must, as recounted previously, be made of highly corrosion resistant materials, and have high suction head capabilities**.** They are mostly trouble free in operation.

The condensate pipes must also be made of highly corrosion resistant materials and all joints efficiently sealed to keep atmospheric air ingress to a minimum, bearing in mind that such pipes are all in a vacuum environment. Any air leakage increases the load on the gas evacuation system and thus the ancillary power consumption of the power plant.

4.5 Particulate/droplet erosion and countermeasures

Geothermal production wells in many steam dominated reservoir have entrapped in the well flow minute solids particles (dust), which because of the prevailing high flow velocities may cause particulate erosion in the well head and downstream of it. Such erosion in the well head may, in extreme cases, cause damage of consequence to wellhead valves, and wellhead and fittings, particularly in T-fittings and sharp bends in the fluid collection pipelines. This is, however, generally not the case and such damage mostly quite insignificant. It is, however, always a good practice to use fairly large radius pipe bends to minimise any such erosion effects.

Droplet erosion is largely confined to the turbine rotor and housing. At exit from the second or the third expansion stage the steam becomes wet and condensate droplets tend to form in and after the expansion nozzles. Wetness of 10% to 12% is not uncommon in the last stages. The rotor blades have furthermore reached a size where the blade tip speeds become considerable and the condensate droplets hit the blade edges causing erosion. The condensate water which has become acidic from the dissolved non condensable gas attaches to the blades and is thrown against the housing. This water has the potential to cause erosion problems. The most effective countermeasures are to fit the blade edges of the last two stages with carbide inserts (Stellite) that is resistant to the droplet impingement and the housing with suitable flow groves that reduce the condensate flow and thereby potential erosion damage.

In addition to the erosion the blades and rotor are susceptible to stress corrosion in the H_2S environment inside the turbine housing. The most effective countermeasure is to exercise great care in selecting rotor, expansion nozzle and rotor blade material that is resistant to hydrogen sulphite corrosion cracking. The generally most effective materials for the purpose are high chromium steels.

4.6 Heat exchangers

In high-temperature power generation applications heat exchangers are generally not used on the well fluid. Their use is generally confined to ancillary uses such as heating, etc. using the dry steam. In cogeneration plants such as the simultaneous production of hot water and electricity, their use is universal. The exhaust from a back pressure turbine or tap-off steam from a process turbine is passed as primary fluid through either a plate or a tube and shell type heat exchanger. The plate type heat exchanger was much in favour in cogeneration plants in the seventies to nineties because of their compactness and high efficiency. They were, however, found to be rather heavy in maintenance. The second drawback was that the high corrosion resistance plate materials required were only able to withstand a relatively moderate pressure difference between primary and secondary heat exchanger media. Thirdly the plate seals tended to degenerate fairly fast and stick tenaciously to the plates making removal difficult without damaging the seals. The seals that were needed to withstand the required temperature and pressure were also pricy and not always in stock with the suppliers. This has led most plant operators to change over to and new plant designers to select the shell and tube configurations, which demand less maintenance and are easy to clean though requiring more room.

In low-temperature binary power plants shell and tube heat exchangers are used to transfer the heat from the geothermal primary fluid to the secondary (binary) fluid. They are also used as condensers/and or regenerators in the secondary system.

In supercritical geothermal power generation situation it is foreseen that shell and tube heat exchangers will be used to transfer the thermal energy of the supercritical fluid to the production of clean steam to power the envisaged power conversion system. In all instances it is very important to select tube and/or plate material in contact with the geothermal fluid that will withstand the temperature, pressure and corrosion potential of the fluid. Some Inconel, titanium and duplex stainless steel alloys have given good service. It is also important to make space allowance for tube withdrawal for maintenance and/or tube cleaning procedures. High pressure water-jet cleaning has for instance proved its value.

Scaling will normally be present. Provisions should therefore be made timely for scale abatement such as by hydrothermal operation by not allowing the geothermal water to become supersaturated with silica or chemical scale inhibitor injection, and/or mechanical cleaning.

4.7 Gas evacuation system

As previously stated the geothermal steam contains a significant quantity of non-condensable gas (NCG) or some 0.5% to 10% by weight of steam in the very worst case. To provide and maintain sufficient vacuum in the condenser, the NCG plus any atmospheric air leakage into the condenser must be forcibly exhausted. The following methods are typically adopted, viz.:

- The use of a single or two stage steam ejectors, economical for NCG content less than 1.5% by weight of steam;
- The use of mechanical gas pumps, such as liquid ring vacuum pumps, which are economical for high concentration of NCG; and
- The use of hybrid systems incorporating methods 1 and 2 in series.

The advantages of the ejector systems are the low maintenance, and high operational security of such systems. The disadvantage is the significant high-pressure steam consumption, which otherwise would be available for power production.

The advantages of the vacuum pumps are the high degree of evacuation possible. The disadvantage is the electric ancillary power consumption, sensitivity to particulate debris in the condenser, and high maintenance requirements.

To reduce the ambient level of H_2S in the proximity of the power plant, the exhausted NCG is currently in most countries discharged below the cooling tower ventilators to ensure a thorough mixing with the air as it is being blown high into the air and away from the power plant and its environs. In the USA, Japan and Italy H_2S abatement is required to meet air quality criteria, and in Italy also mercury (Hg) and thus require chemical type abatement measures.

In some of the older Geysers field power plants the H_2S rich condenser exhaust was passed through a bed of iron and zinc oxide to remove the H_2S. These proved a very messy way of getting rid of the H_2S and were mostly abandoned after a few years. In a few instances the Stretford process and other equivalent ones have been used upstream of the power plant to convert H_2S gas into sulphur for industrial use. This has proved expensive and complex and is not in use in other geothermal fields than the Geysers field in California.

The main H_2S abatement methods currently in use worldwide are (only some are currently used for geothermal NCG):

- AMIS process of ENEL;
- Claus (Selectox);
- Haldor Topsöe – WSA process;
- Shell-Paques Biological H_2S removal process/THIOPAC;
- LO-CAT (wet scrubbing liquid redox system);
- Fe-Cl hybrid process;
- Aqueous NaOH absorbent process;
- Polar organic absorbent process;
- Photo catalytic generation process;
- Plasma chemical generation process;
- Thermal decomposition process; and
- Membrane technology.

4.8 Re-injection system

In most geothermal areas the geothermal fluid may be considered to be brine because of the typically high chloride content. It may also contain some undesirable tracer elements that pose danger to humans, fauna and flora.

In considering the most convenient way of disposing of this liquid effluent other than into effluent ponds on the surface, the idea of injecting the liquid effluent back into the ground has been with the geothermal power industry for a long time (Stefánsson, 1997). Initially the purpose of re-injection was simply to get rid of the liquid effluent in a more elegant way than dumping it on the surface, into lakes or rivers, and even to the ocean. Many technical and economic drawbacks were soon discovered. The more serious of these were the clogging up of injection wells, injection piping and the formations close to the borehole; the cold effluent migrated into the production zone so reducing the enthalpy of the well output with consequent fall-off in power plant output. Injection into sandstone and other porous alluvial formations was and is fraught with loss of injectivity problems that are still not fully understood.

Soon, however, it became generally understood and accepted that returning the effluent liquid back into the reservoir had even greater additional benefits, viz.:

- Greatly reducing the rate of reservoir pressure and fluid yield decline;
- Improved extraction of the heat content contained within the reservoir formations; and
- Reducing the fluid withdrawal effect on surface manifestations, e.g. hot pools, steam vents etc.

All the above items serve to maintain resource sustainability and are thus of significant environmental benefit.

Re-injection should be considered an integral part of any modern, sustainable and environmentally friendly geothermal utilization, both as a method of effluent water disposal and to counteract pressure draw-down by providing artificial water recharge (Stefánsson, 1997). Re-injection is essential for sustainable utilization of virtually closed and limited recharge geothermal systems. Cooling of production wells, which is one of the dangers associated with re-injection, can be minimised through careful testing and research. Tracer testing, combined with comprehensive interpretation, is probably the most important tool for this purpose.

Many different methods have and are still being tried to overcome these technical problems mentioned above such as the use of settling tanks that promote polymerisation of the silica molecules and settling in the tanks prior to injection; injection of the effluent liquid directly from the separators at temperatures in the range of 145–160°C, so called "hot injection", both to avoid contact with atmospheric air and to hinder scaling in the injection system; controlling the pH of the effluent commensurate with reduction in the rate of silica/calcite precipitation using acids and add condensate from the plant to dilute the silica in the brine, to name a few. The danger of production well cooling can be minimised through careful testing and research. Tracer testing, combined with comprehensive interpretation, is probably the most important tool for this purpose. One way to delay the effects of cooling is also to locate the re-injection wells far enough away from the production area, say 2 km. Another way gaining popularity is to inject deep into the reservoir, even where there is small permeability, by pumping at high pressures (60–100 bar).

Surface disposal contravenes the environmental statutes of most countries and the use of settling tanks has ceased mostly because of associated cost and complexity. The most commonly adopted injection methods are the last two, i.e. hot re-injection and chemical pH control ones. The main disadvantage of the hot re-injection technique is the lowered overall thermal efficiency and the consequent greater fluid production (more wells to yield the same power output) required. The main disadvantage of the pH control scheme is the very large acid consumption (cost) and uncertainties regarding its long-term effects.

Hot re-injection is precluded in low-temperature power generation and the most common technique is to make use of the reverse solubility of calcite in water by operating the conversion system at a pressure level above the CO_2 bubble point and only reduce the pressure once the fluid temperature has attained a level low enough to prevent calcite dissipation prior to re-injection.

4.9 Chemical injection system

Chemical injection systems are sometimes applied for production and reinjection wells as wells as the the surface equipment to reduce scaling, corrosion and for ph-control.

Calcite scaling is common in production wells tapping liquid dominated reservoirs of 220-250°C. In order to reduce or prevent the calcite scaling in these wells a scale inhibitor is injected through a capillary tubing down hole. Similar injection is applied with caustic soda to neutralize acid wells to reduce the corrosivity. Acid is used for pH modification in order to arrest the scaling of silica in waste water going to reinjection, for cases where the water is supersaturated. Chemical control of pH by caustic soda and of biofilms is also applied to the cooling water (turbine condenser/cooling towers).

5. POWER PLANT DESIGN PARAMETERS

The most important power plant design parameters are:

- **Resource**
    1. Steam conditions: Optimum turbine inlet steam pressure. Gas (% NCG) in steam.
    2. Size (thickness and areal extent), and long term capacity, and natural recharge.
    3. Temperature and pressure of deep resource fluid.
    4. Chemical composition (liquid and gas phase) of deep fluid.
    5. Geology, stratigraphy, lithology and geothermal reservoir properties (faults, fractures, formation porosity, mineral alteration types and age, type of permeability).
    6. Reservoir permeability.
    7. Thickness of production/injection zones.
    8. Well productivity/injectivity.
    9. Two phase zones.
    10. Reservoir response to production/injection.
    11. Natural state modelling, computer simulation of reservoir, and model predictions.
    12. Reservoir monitoring and management.
- **Accessibility**
    1. Topography of resource area.
    2. Remoteness from population centres.
    3. Closeness to nature parks and environmentally restricted areas.
- **Market**
    1. Size, type and security of market.
    2. Proximity of market.
    3. Accessibility to existing power transmission lines, substations.
- **Permits etc.**
    1. Resource concessions.
    2. Exploration permits.
    3. Drilling permits.
    4. Development permits.
    5. Environmental Impact Assessment.
    6. Building and other permits.
- **Pre and post investment studies, business plan**

All the above parameters are important to the development plan, production and injection well drilling and well design. They are no less important in the selection of power plant type, siting of power station, production and injection well siting arrangement (well spacing, etc.), production and injection well numbers etc. It also plays a key-role in planning development increment size and timing.

Early information of resource fluid liquid and gas phase chemical composition is extremely important since it affects most component design, materials selection, types of components selected etc.

REFERENCES

Axelsson, G., Gudmundsson, Á., Steingrímsson, B., Pálmason, G., Ármannsson, H., Tulinius, H., Flóvenz, Ó.G., Björnsson, S., and Stefánsson, V., 2001: Sustainable production of geothermal energy: suggested definition. *IGA News*, *Quarterly No. 43*, 16 pp. Web: http://www.geothermal-energy.org/publications_and_services/iga_newsletter.html

Axelsson, G., and Stefánsson, V., 2003: Sustainable management of geothermal resources. *Proceedings International Geothermal Conference 2003, Reykjavík,* 9 pp.

Axelsson, G., Stefánsson, V., and Björnsson, G., 2005: Sustainable utilization of geothermal resources for 100–300 years. *Proceedings World Geothermal Congress 2005, Antalya, Turkey*, 8 pp.

Bertani, R., 2005: World geothermal power generation in the period 2001–2005. *Geothermics, 34*, 651–690.

Bertani, R., 2010: World geothermal power generation - 2005–2010. Update Report. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 41 pp.

Stefánsson, V., 1997. Geothermal re-injection experience. *Geothermics, 26*, 99–130.

Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksöz, M.N., Veatch, R.W., 2006: *The Future of geothermal energy. Impact of enhanced geothermal systems (EGS) on the United States in the 21st century*. MIT, Boston, 372 pp. Web: http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf

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GEOTHERMAL UTILIZATION – PRODUCTION OF POWER

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ABSTRACT

This manuscript covers the thermodynamics of power production from a geothermal resource, as well as analysis of the most common cycles and components. A treatment of the economics of geothermal power plants is as well included. This manuscript is intended as background material for the lectures of the author at this Short Course.

1. THERMODYNAMICS OF GEOTHERMAL POWER PRODUCTION

1.1 Energy and power, heat and work

The production of electricity from a geothermal source is about producing work from heat. Electricity production from heat will never be successful unless appropriate respect is paid to the second law of thermodynamics.

Energy is utilized in two forms, as heat and as work. Work moves bodies, changes their form, but heat changes temperature (changes the molecular random kinetic energy). Work is thus the ordered energy, whereas heat is the random "unorganized" energy. Heat and work are totally different products for a power station, but these two energy forms cannot be produced independent of each other. Independent production of heat and work is in a way similar to have cattle producing three hind legs per animal when required.

It is as well appropriate to discuss the relation between power and energy right here in the introduction to this chapter. A power station is built to be able to supply certain maximum power. The source heat supply and the design of the power plant internals are based on this maximum power (Figure 1). On the other hand the income of the power station will be depending on the energy sold, on the integral of produced power with respect to time.

Geothermal installations have normally zero energy cost. The inflow into the well is not charged for. The only cost is the investment cost in equipment and installations to get the fluid to the surface, and to process it appropriately in the power plant in order to obtain the product, be it heat for a direct use application or an electricity producing power plant.

As a consequence of this, a geothermal power plant is a typical base load plant, the bulk portion of the cost is there regardless of how much power the plant is producing. Duration curves and utilization time will be discussed later in this chapter.

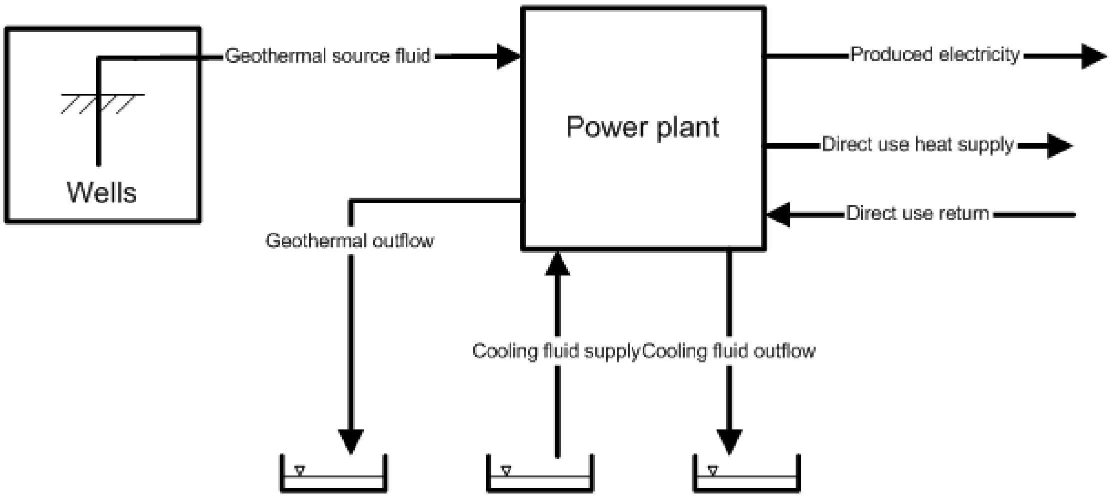

FIGURE 1: Schematic of a geothermal power plant

2. CONVERSION OF HEAT TO WORK

Work can always be changed into heat. Even during the Stone Age, work was used to light fire by friction, by rubbing wood sticks to a hard surface. The same applies today, the electric heater is converting work into heat with 100% efficiency.

Conversion of heat into work is difficult and is limited by the laws of thermodynamics. A part of the heat used has always to be rejected to the surroundings, so there is always an upper limit of the possible work production from a given heat stream.

Textbooks use the Reversible Heat Engine (RHE, Carnot engine) as a reference (Figure 2). RHE is the best engine for producing work from heat, assuming that the engine is operating between two infinitely large heat reservoirs. The reference to the Carnot engine has to be taken with caution, as the real heat reservoirs are usually not infinitely large, and the heat supply or rejection will happen at a variable temperature.

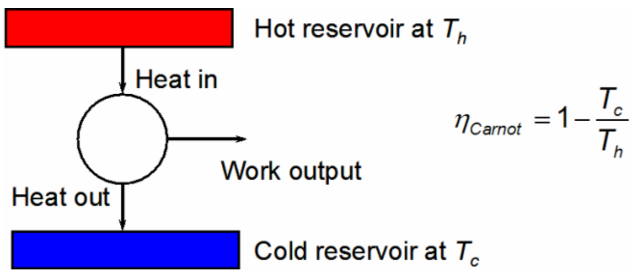

FIGURE 2: The Carnot engine

2.1 Exergy

The second law of thermodynamics demands that a part of the heat input to any heat engine is rejected to the environment. The portion of the input heat, which can be converted into work, is called Exergy (availability, convertible energy). The unconvertible portion is called Anergy. Thus the exergy of any system or flow stream is equal to the maximum work (or electricity) which can be produced from the source. The thermodynamic definition of exergy for a flow stream is:

$$x = h - h_0 - T_0 \left(s - s_0 \right) \tag{1}$$

The zero index refers to the environmental conditions for the subject conversion. The local environment for the power plant defines the available cold heat reservoir, and all the anergy rejected tot the environment will finally be at the environmental conditions.

The exergy of a flow stream is thus the maximum theoretical work which can be produced if the stream is subjected to a process bringing it down to the environmental conditions.

If the stream is a liquid with constant heat capacity, the above equation can be written as:

$$x = c_{liquid}\left[\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right] \tag{2}$$

Economics of power production are conveniently analyzed by using exergy. A power plant has the main purpose of converting heat into work, and therefore the relevant physical variable for cost and economic performance calculation is the exergy rather than the total energy or the heat flow.

2.2 Efficiency definitions

Efficiency is the ratio of input to output, a performance measure for the process. There are many possibilities of defining input and output, but the most standard definition of efficiency is the power plant thermal efficiency.

Figure 3 shows the energy streams for a binary power plant.

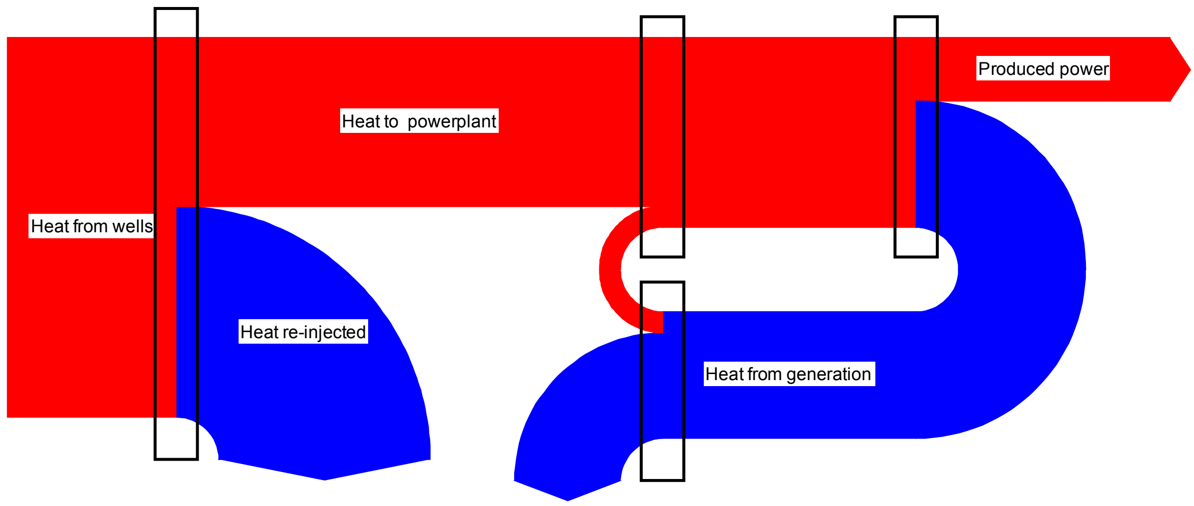

FIGURE 3: Energy streams in a binary power plant

The thermal efficiency is seen as the ratio of produced power to the heat transferred to the power plant. The effectiveness is the ratio of the heat transferred to the power plant to the heat available from the wells. It is obvious that the total power plant efficiency will be the multiple of power plant efficiency and effectiveness.

2.3 Power plant thermal efficiency

The power plant thermal efficiency is the ratio between power produced and the heat flow to the power plant. The power plant thermal efficiency is traditionally defined as:

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}_{in}} \tag{3}$$

The heat input is then the heat input to the power plant, and takes no notice of how much heat is available from the wells. This can be very misleading. The wells make up a great portion of the power plant cost, and the economics of the power plant will be decided by the utilization of the well investment. The Carnot efficiency is as well misleading, it is based on the assumption that the thermal reservoirs are infinitely large, no cooling will occur in the hot reservoir by heat removal, and no heating will be in the cold reservoir by heat addition. Therefore the only relevant performance measure will have to be based on the exergetic efficiency, and due to the importance of the well investment, the effectiveness as well.

Calculating efficiency based on the first law for a cogeneration power plant is in no way easy, because the plant has two products, heat and work. The first law does not provide any equivalence between heat and work, or the value of these products. A cogeneration plant will only be analyzed properly by exergetic analysis.

If the power plant effectiveness is high, the geothermal fluid return temperature is low, and the average temperature of the heat input to the power plant is low. This will lead to lower efficiency, but larger power plant. If the well flow is given, then high effectiveness will lead to a plant with higher power, but lower first law efficiency.

2.4 Example

Assume that an ideal power with 100% isentropic efficiency plant has a source of 120°C and 150 kg/s flow (Figure 4). The cooling water is assumed to enter the power plant at 10°C and leave the plant at 20°C. Let's assume that the first ideal power plant is able to cool the geothermal fluid down to 80°C.

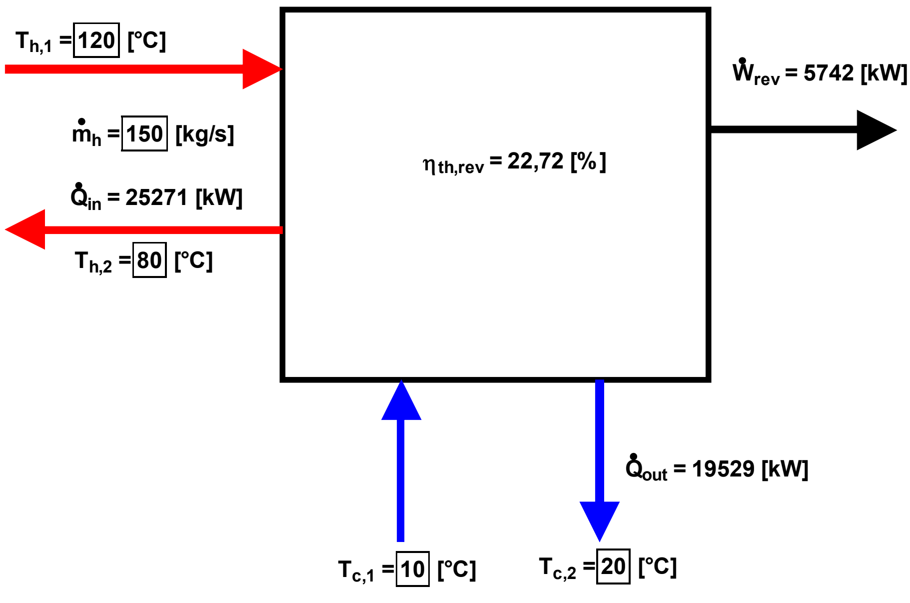

FIGURE 4: A low effectiveness ideal power plant

The obtained power is 5.7 MW, efficiency is 22.7%. What will happen if the effectiveness is doubled, and the geothermal return water temperature is brought down to 40°C?

The efficiency falls down to 18.1%, but the output power is increased to 9.1 MW (Figure 5). It is very obvious that the power plant with lower efficiency, but higher effectiveness is more powerful and will be more economic, at least if the technical design limitations do not hurt too badly.

The general relation between output power and efficiency for this example are given in Figure 6.

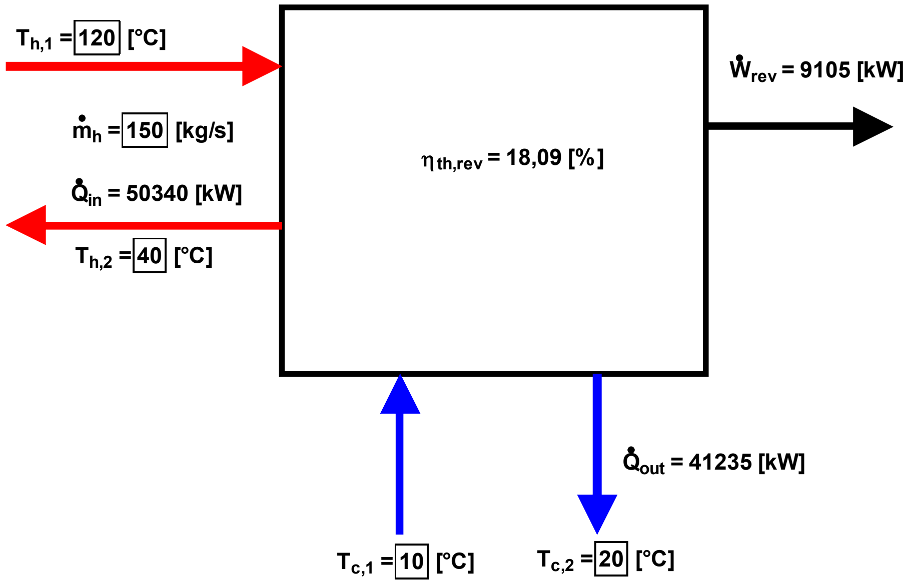

FIGURE 5: A high effectiveness ideal power plant

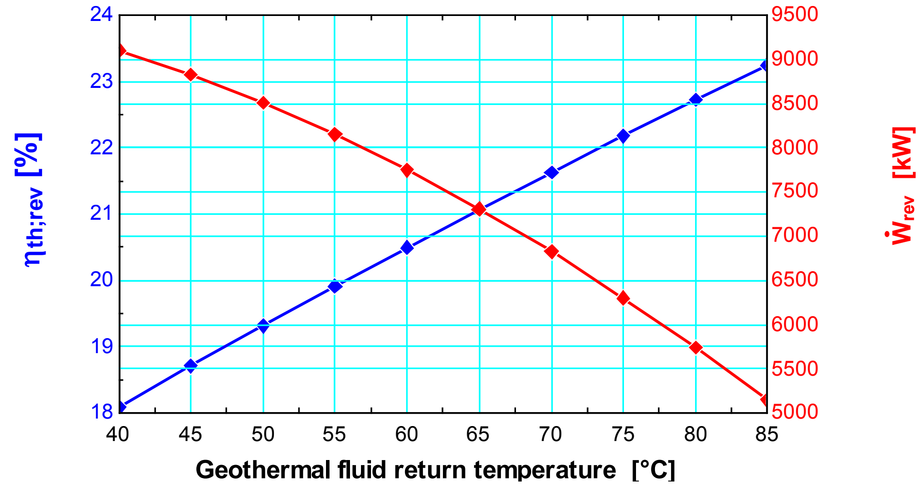

FIGURE 6: Net power and efficiency as a function of re-injection temperature

2.5 Effectiveness

The power plant effectiveness is the ratio between the available energy to the energy input to the power plant. The available energy is found by assuming that the geothermal fluid can be cooled down to the environmental conditions. Effectiveness will be the deciding factor for the possible power plant size, rather than the quality of the power plant.

2.6 Second law efficiency and effectiveness

Exergy is the portion of the energy which can theoretically be converted into work. It is logical to base performance criteria for production of electricity on exergy rather than heat or energy, because then the performance calculation will take into account what can be done, and not incorporate any "perpetuum mobile" in the calculations.

The second law approach makes as well easy to treat cogeneration. Then the exergy stream in the sold heat is treated in the same way as the produced electrical power, having the same exergy unitary cost.

3. ANALYSIS

Efficiency is the ratio of benefit to cost. In order to be able to define efficiency, the inputs (cost) and outputs have to be defined. In a low temperature heat conversion process, two cases regarding the stream are possible, depending on if the heat contained in that stream can be sold to a heat consuming process.

The conversion efficiency is a measure of how much of the available heat is converted into work. It has to be kept in mind that only a part of the heat can be converted into work due to the limitations imposed by the second law of thermodynamics. Exergy, the potential of any system to produce work, is the correct property to consider, when the conversion efficiency is analyzed. Exergy is dependent of the properties of the source as well as the properties of the environment, where the environmental temperature and pressure are the main properties.

The temperature of the entering cooling fluid is taken to be the environmental temperature, the lowest temperature which can be obtained, as well as defining the thermal sink temperature for the Carnot engine efficiency. The environmental pressure is logically the ambient atmospheric pressure

This process can be seen as a non-conserving heat exchange process between the source stream and the cooling fluid stream. Figure 7 is a block diagram of a power plant converting heat into electricity.

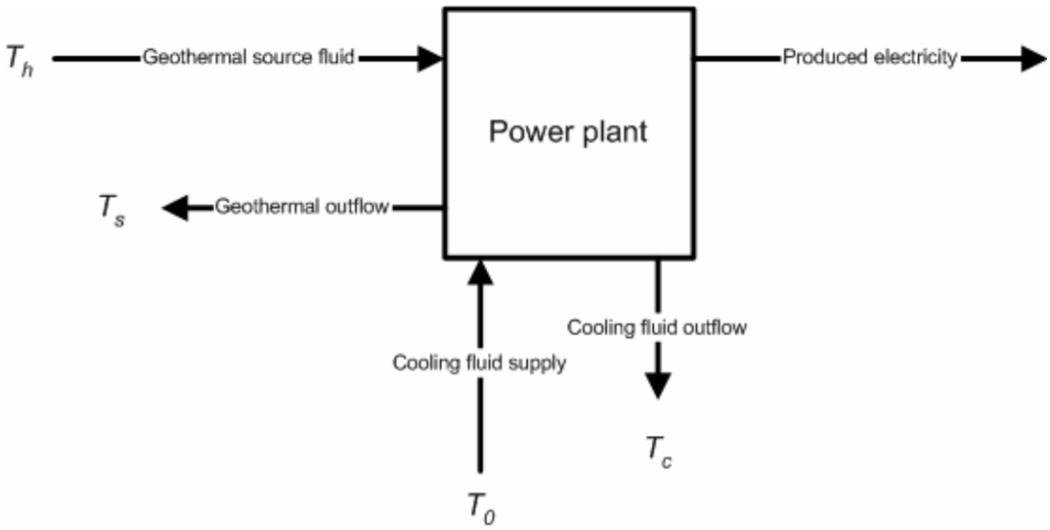

FIGURE 7: Electrical power plant schematic

The variables related to the conversion are as follows:

c_h = Source fluid heat capacity;
m_h = Flow rate of source fluid;
T_h = Source fluid inlet temperature;
T_s = Source fluid outlet temperature;
c_c = Cooling fluid heat capacity;
m_c = Cooling fluid flow rate;
T_c = Cooling fluid outlet temperature; and
T_0 = Cooling fluid inlet temperature (Environmental temperature).

In the following this system will be analyzed in order to gain a better understanding of the conversion of low temperature heat into electricity. It is assumed that the geothermal source fluid is liquid water with constant heat capacity.

The streams in and out of the system have four flow properties: mass, heat capacity, enthalpy and exergy. The mass conservation is obvious, no mixing of the source and cooling streams is assumed. The heat capacity is important for the characteristics of the heat conversion, and will be treated here as a heat capacity flow, the product of fluid heat capacity and flow rate. The product of the enthalpy relative to the environmental temperature and the flow rate defines the heat flow in and out of the system. The exergy will give information on the work producing potential of the system, and is calculated in the same way as the enthalpy. Reference textbooks such as Cengel (2002) give basic information on exergy and its definition, but here the analysis is as well based on Kotas (1985) and Szargut (1988). Thórólfsson (2002), Valdimarsson (2002) and Dorj (2005) apply these methods on specific geothermal applications.

The heat ($\dot{Q}$) and exergy ($\dot{X}$) flows are given by:

$$\dot{Q}_h = c_h \dot{m}_h (T_h - T_0) \tag{4}$$

$$\dot{Q}_s = c_h \dot{m}_h (T_s - T_0) \tag{5}$$

$$\dot{Q}_c = c_c \dot{m}_c (T_c - T_0) \tag{6}$$

$$\dot{X}_h = c_h \dot{m}_h \left[(T_h - T_0) - T_0 \ln\left(\frac{T_h}{T_0}\right) \right] = \dot{Q}_h - c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_0}\right) \tag{7}$$

$$\dot{X}_s = c_h \dot{m}_h \left[(T_s - T_0) - T_0 \ln\left(\frac{T_s}{T_0}\right) \right] = \dot{Q}_s - c_h \dot{m}_h T_0 \ln\left(\frac{T_s}{T_0}\right) \tag{8}$$

$$\dot{X}_c = c_c \dot{m}_c \left[(T_c - T_0) - T_0 \ln\left(\frac{T_c}{T_0}\right) \right] = \dot{Q}_c - c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0}\right) \tag{9}$$

The energy (1. law) and exergy (2. law) balances are:

$$\begin{aligned} \dot{Q}_h - \dot{Q}_s - \dot{Q}_c &= \dot{W} \\ \dot{X}_h - \dot{X}_s - \dot{X}_c &= \dot{W}_{rev} \end{aligned} \tag{10}$$

or:

$$\dot{Q}_h - \dot{Q}_s - \dot{Q}_c - c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_s}\right) + c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0}\right) = \dot{W}_{rev} \tag{11}$$

The energy balance is valid for all processes, ideal and real. The exergy balance gives only information on the reversible work, or the largest amount of work that can be obtained from the power plant.

If the power plant is ideal, then:

$$\dot{W}_{rev} = \dot{W} \quad or \quad -c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_s}\right) + c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0}\right) = 0 \tag{12}$$

Then the heat capacity flow ratio for a reversible power plant is:

$$C_{rev} = \left.\frac{c_c \dot{m}_c}{c_h \dot{m}_h}\right|_{rev} = \frac{\ln\left(\frac{T_h}{T_s}\right)}{\ln\left(\frac{T_c}{T_0}\right)} \tag{13}$$

Assume that electricity is the only output of the power plant. The heat contained in the stream is rejected to the surroundings.

$$\begin{aligned} \text{Product:} \quad & \dot{W} \\ \text{Input:} \quad & \dot{Q}_h \\ \text{Rejected:} \quad & \dot{Q}_s \ and \ \dot{Q}_c \end{aligned}$$

First law efficiency:

$$\eta_{I,E} = \frac{\dot{W}}{\dot{Q}_h} = \frac{\dot{Q}_h - \dot{Q}_s - \dot{Q}_c}{\dot{Q}_h} = \frac{(T_h - T_s) - C(T_c - T_0)}{T_h - T_0} \tag{14}$$

First law maximum efficiency:

$$\eta_{I,\max,E} = \frac{\dot{W}_{rev}}{\dot{Q}_h} = \frac{\dot{X}_h - \dot{X}_s - \dot{X}_c}{\dot{Q}_h} = 1 - \frac{\dot{Q}_s + \dot{Q}_c + c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_s}\right) - c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0}\right)}{\dot{Q}_h}$$

$$= \frac{(T_h - T_s) - T_0 \ln\left(\frac{T_h}{T_s}\right)}{(T_h - T_0)} - C \frac{(T_c - T_0) - T_0 \ln\left(\frac{T_c}{T_0}\right)}{(T_h - T_0)} \tag{15}$$

$$= \frac{\ln\left(\frac{T_c}{T_0}\right)(T_h - T_s) - \ln\left(\frac{T_h}{T_s}\right)(T_c - T_0)}{\ln\left(\frac{T_c}{T_0}\right)(T_h - T_0)}$$

Second law efficiency:

$$\eta_{II,E} = \frac{\dot{W}}{\dot{W}_{rev}} = \frac{\dot{Q}_h - \dot{Q}_s - \dot{Q}_c}{\dot{X}_h - \dot{X}_s - \dot{X}_c} = \frac{\dot{Q}_h - \dot{Q}_s - \dot{Q}_c}{\dot{Q}_h - \dot{Q}_s - \dot{Q}_c - c_h \dot{m}_h T_0 \ln\left(\frac{T_h}{T_s}\right) + c_c \dot{m}_c T_0 \ln\left(\frac{T_c}{T_0}\right)}$$

$$= \frac{(T_h - T_s) - C(T_c - T_0)}{(T_h - T_s) - T_0 \ln\left(\frac{T_h}{T_s}\right) - C\left((T_c - T_0) - T_0 \ln\left(\frac{T_c}{T_0}\right)\right)} \qquad (16)$$

4. POWER PLANT TYPES

The geothermal power plants can be divided into two main groups, steam cycles and binary cycles. Typically the steam cycles are used at higher well enthalpies, and binary cycles for lower enthalpies. The steam cycles allow the fluid to boil, and then the steam is separated from the brine and expanded in a turbine. Usually the brine is rejected to the environment (re-injected), or it is flashed again at a lower pressure. Here the Single Flash (SF) and Double Flash (DF) cycles will be presented.

A binary cycle uses a secondary working fluid in a closed power generation cycle. A heat exchanger is used to transfer heat from the geothermal fluid to the working fluid, and the cooled brine is then rejected to the environment or re-injected. The Organic Rankine Cycle (ORC) and Kalina cycle will be presented.

5. SINGLE FLASH CYCLE

A flow sheet for the SF cycle is shown in Figure 8.

The geothermal fluid enters the well at the source inlet temperature, station 1. Due to the well pressure loss the fluid has started to boil at station 2, when it enters the separator. The brine from the separator is at station 3, and is re-injected at station 4, the geothermal fluid return condition.

The steam from the separator is at station 5, where the steam enters the turbine. The steam is then expanded through the turbine down to station 6, where the condenser pressure prevails.

The condenser shown here is air cooled, with the cooling air entering the condenser at station c1 and leaving at station c2.

The condenser hot well is at station 7. The fluid is re-injected at station 4.

Typically, such a process is displayed on a thermodynamic T-s diagram, where the temperature in the cycle is plotted against the entropy (Figure 9). A T-h diagram is shown in Figure 10.

The condition at station 1 is usually compressed liquid. In vapour dominated fields, such as Lardarello in Italy, the inflow is in the wet region close to the vapour saturation line.

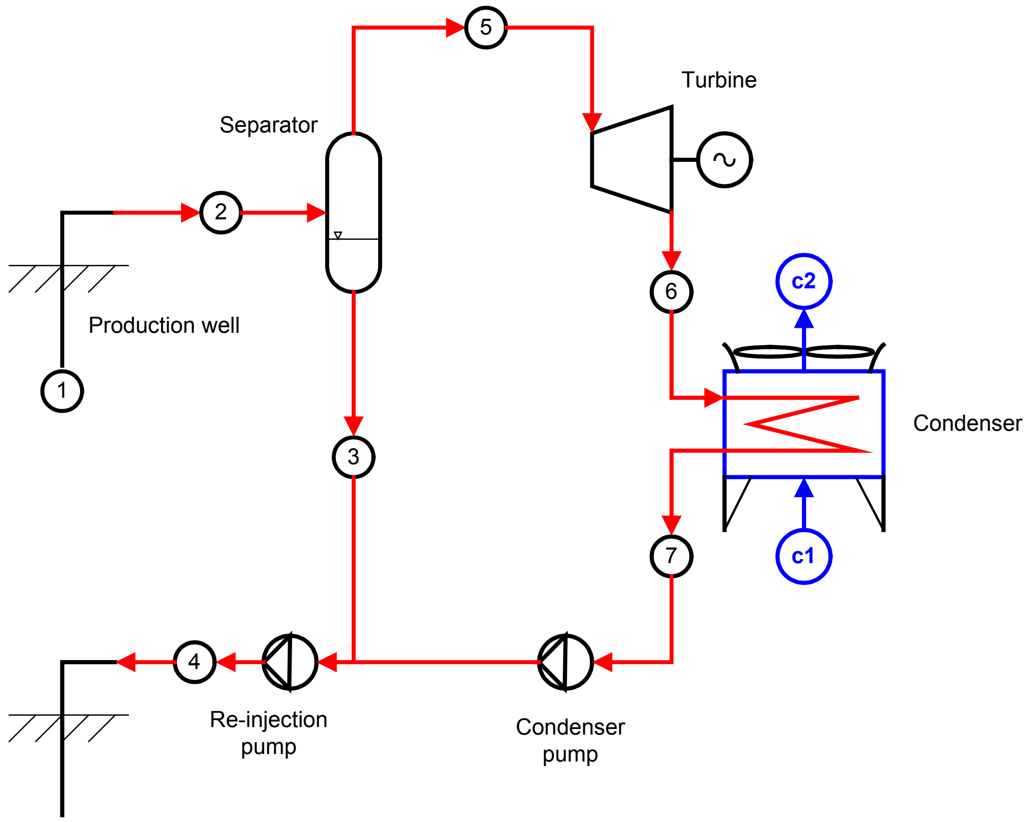

FIGURE 8: Single flash cycle schematic

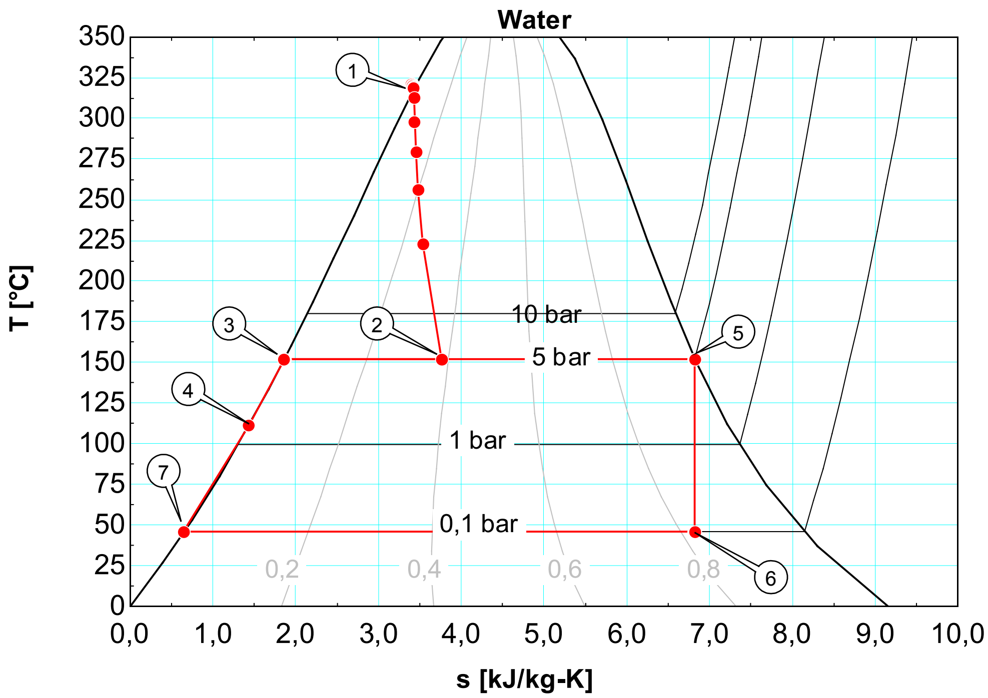

FIGURE 9: T-s diagram of a single flash cycle

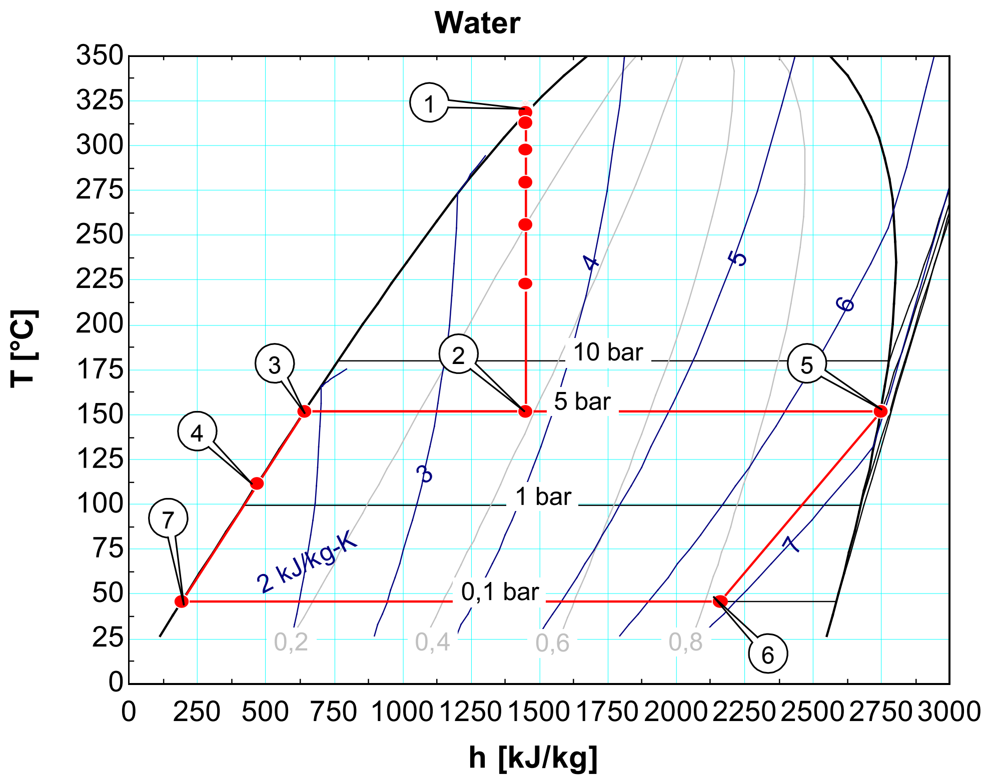

FIGURE 10: T-h diagram of a single flash cycle

6. DOUBLE FLASH CYCLE

A flow sheet for the DF cycle is on Figure 11.

The geothermal fluid enters the well at the source inlet temperature, station 1. Due to the well pressure loss the fluid has started to boil at station 2, when it enters the separator. The brine from the separator is at station 3, and is throttled down to a lower pressure level at station 8. The partly boiled brine is then led to a low pressure separator, where the steam is led to the turbine at station 9. The turbine is designed in such a way, that the pressure difference over the first stages is the same as the pressure difference between the high and low pressure separators. The mass flow in the lower pressure stages of the turbine is then higher than in the high pressure stages, just the opposite of what happens in a traditional fuel fired power plant with a bleed for the feedwater heaters from the turbine.

The brine from the low pressure separator is at station 10, and is then re-injected at station 4, the geothermal fluid return condition.

The steam from the high pressure separator is at station 5, where the steam enters the turbine. The low pressure steam enters the turbine a few stages later, at station 9. The steam is then expanded through the turbine down to station 6, where the condenser pressure prevails.

The condenser shown here is air cooled, with the cooling air entering the condenser at station c1 and leaving at station c2.

The condenser hot well is at station 7. The fluid is re-injected at station 4.

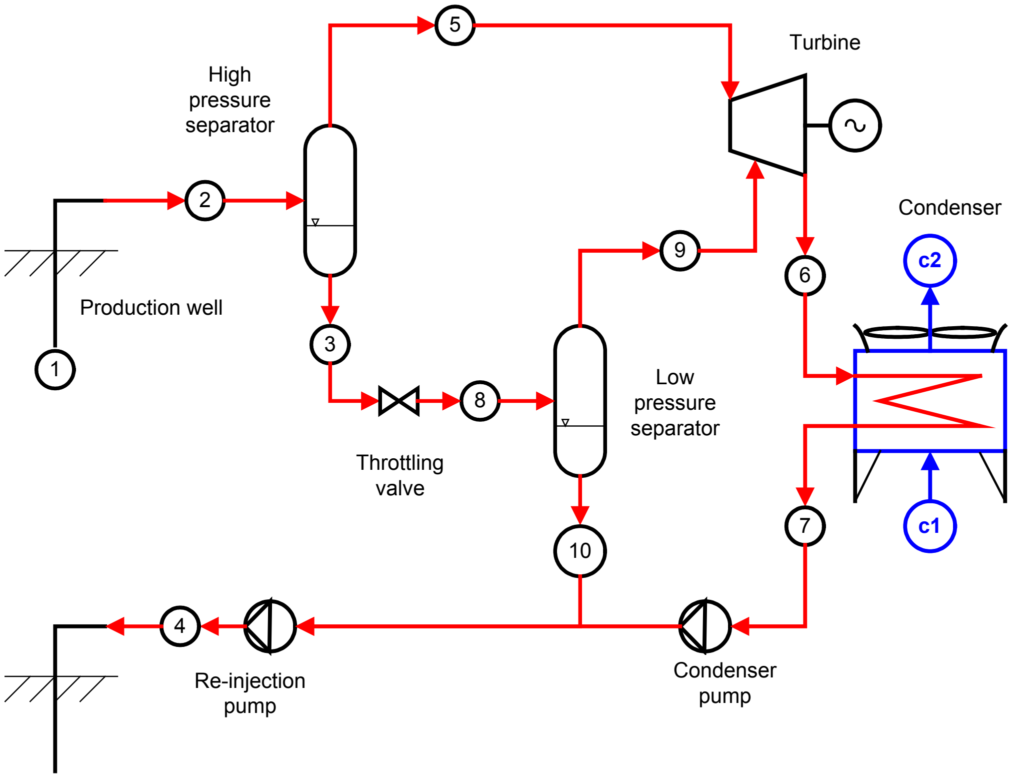

FIGURE 11: Double flash cycle schematic

The double flash cycle is presented in Figure 12 on a T-s diagram and on a T-h diagram on Figure 13.

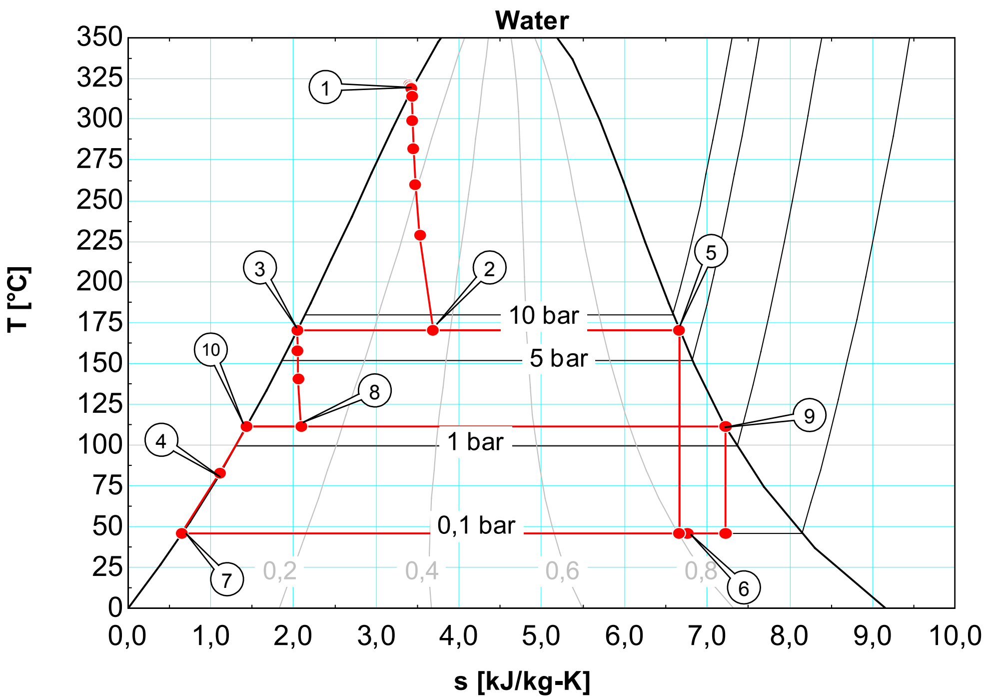

FIGURE 12: T-s diagram of a double flash cycle

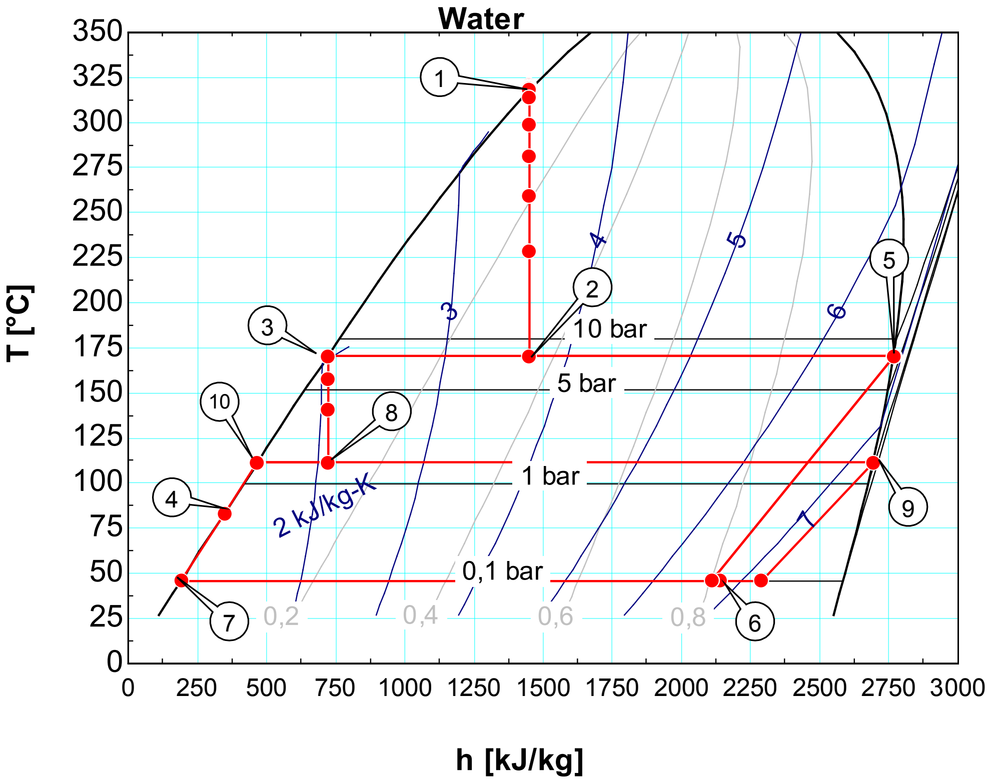

FIGURE 13: T-h diagram of a double flash cycle

7. ORGANIC RANKINE CYCLE (ORC)

A flow sheet for the ORC cycle is on Figure 14.

The geothermal fluid enters the well at the source inlet temperature, station s1. The fluid is frequently liquid water. If the pressure is kept sufficiently high, no non-condensable gases will be separated from the liquid, and a gas extraction system is not necessary. The fluid is then cooled down in the vaporizer, and sent to re-injection at station s2.

Pre-heated (in the recuperator) ORC fluid enters the vaporizer at station 2. The fluid is heated to saturation in the vaporizer, or even with superheat in some cases. The vapour leaves the vaporizer at station 3, and enters the turbine.

The exit vapour from the turbine enters the recuperator at station 4, where the superheat in the steam can be used to pre-heat the condensed fluid prior to vaporizer entry. The now cooled vapour enters the condenser at station 5, where it is condensed down to saturated liquid at station 6.

A circulation pump raises the pressure from the condenser pressure up to the high pressure level in station 1. There the fluid enters the recuperator for pre-heat before vaporizer entry.

The condenser shown here is air cooled, with the cooling air entering the condenser at station c1 and leaving at station c2.

An ORC cycle is presented on Figure 15 on a T-s diagram and on a T-h diagram on Figure 16.

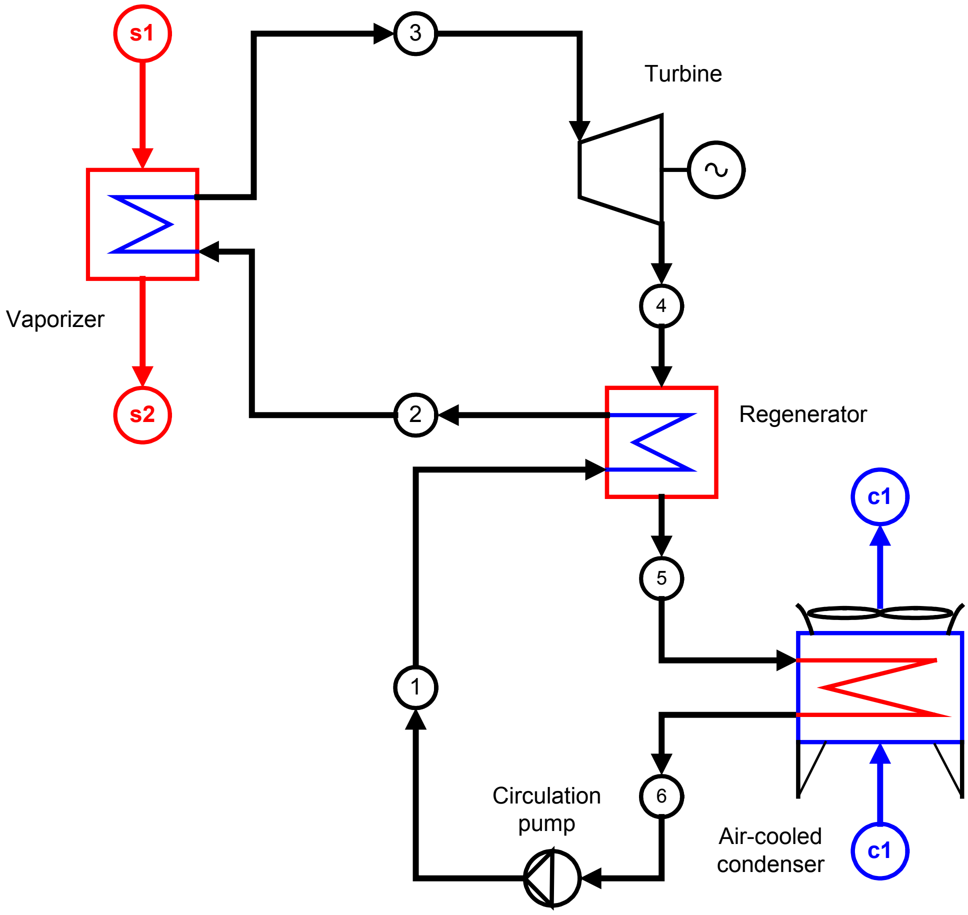

FIGURE 14: Flow diagram for an ORC cycle with recuperation

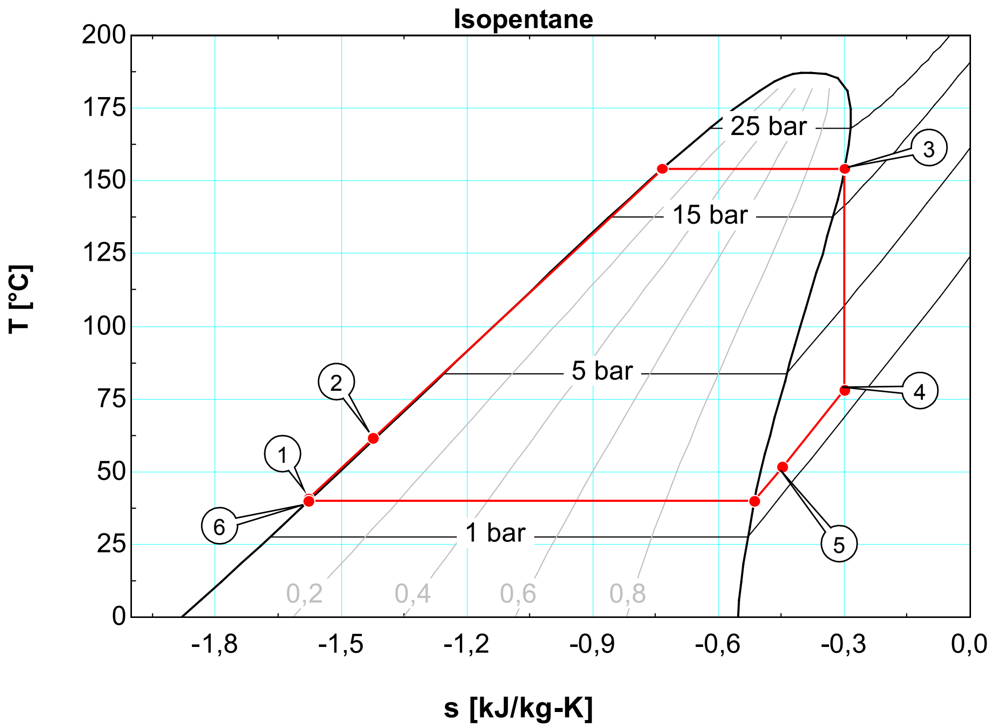

FIGURE 15: T-s diagram of an ORC cycle with recuperation

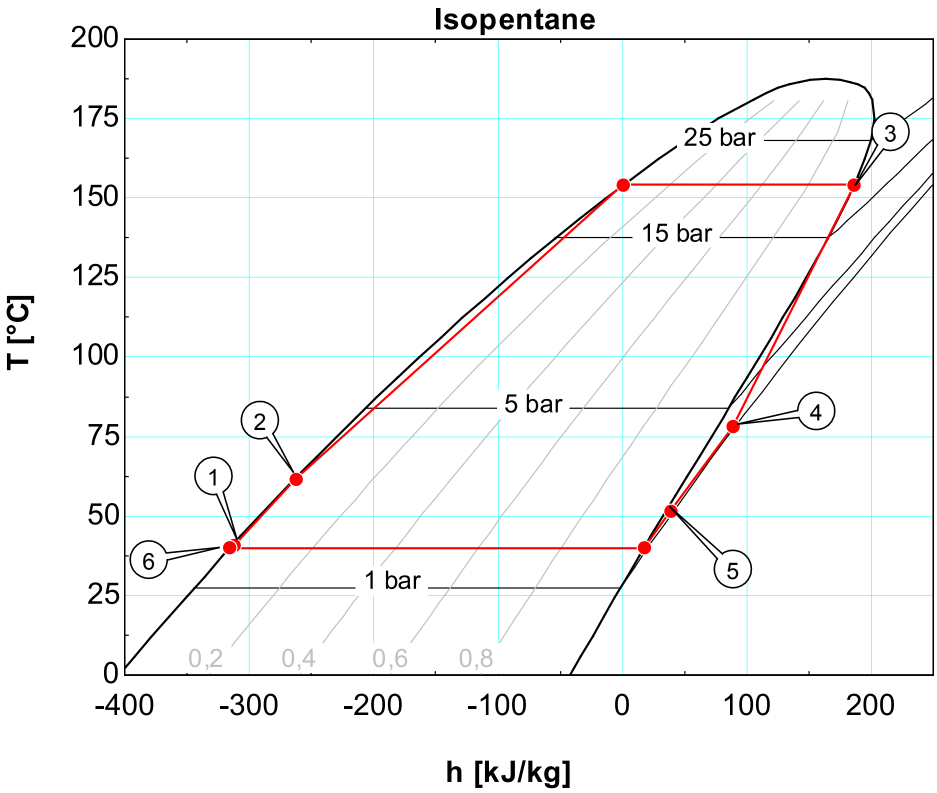

FIGURE 16: T-h diagram of an ORC cycle with recuperation

8. RECUPERATION

Recuperation will increase the power plant efficiency. Then a part of the rejected heat is recovered for input to the power plant. If the plant were run on fuel, this would lead to direct fuel savings.

This is not the case in geothermal power production. There the wells have certain maximum flow rate, and the well cost is usually entirely fixed, has very little if any relation to the flow from the well. The more the fluid from the well can be cooled, the more heat can be input to the power plant.

Recuperation increases the temperature of the working fluid at the vaporizer entry, and leads thus to higher geothermal fluid exit temperature from the vaporizer. The heat removal from the geothermal fluid is thus partly replaced by the recovered heat.

There is frequently a lower temperature limit on the geothermal fluid temperature. This limit may be imposed by chemistry (danger of scaling) or the requirements of a secondary process, such as district heating. If this is the case, Recuperation can help.

Figure 17 shows a calculation of an isopentane ORC cycle, with geothermal fluid temperature of 200°C. It is assumed that the well flow is 1 kg/s, condensation temperature is 40°C. Three curves are calculated, no Recuperation at all, if 50% of the heat available is used for Recuperation and finally if all the available heat is used. The available heat is the heat which can be removed from the turbine exit vapour until the vapour reaches dew point. After that the vapour temperature is the same as the condensation temperature and no recuperation can occur. Note that the following calculation results are based on an ideal ORC cycle.

It can be seen from the diagram, that the point of highest power is moved upwards by ca 20°C by the effect of the regeneration. Recuperation can thus keep the maximum power for geothermal fluid temperatures from ca 65°C to ca 85°C. It has to be kept in mind that a recuperator will be large and expensive, as well as causing pressure drop and associated losses. A cycle without recuperation will be more economical, if the geothermal fluid does not have any temperature limitation. Recuperation will not, repeat not, increase the produced power, even if it increases the efficiency. The increase of efficiency results only from less input of heat from the geothermal fluid. And this heat is normally free of charge.

The thermal efficiency increases when the geothermal return temperature increases (Figure 18). This is in accordance with the second law of thermodynamics, as the average input temperature of the heat increases, and thereby the efficiency.

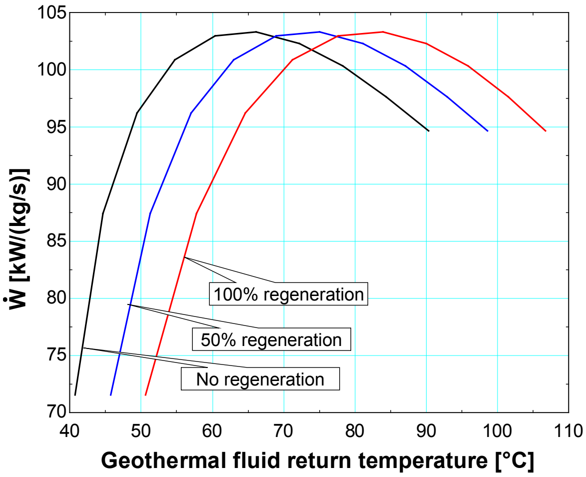

FIGURE 17: Power obtained from 1 kg/s of 200°C geothermal fluid (ideal cycle)

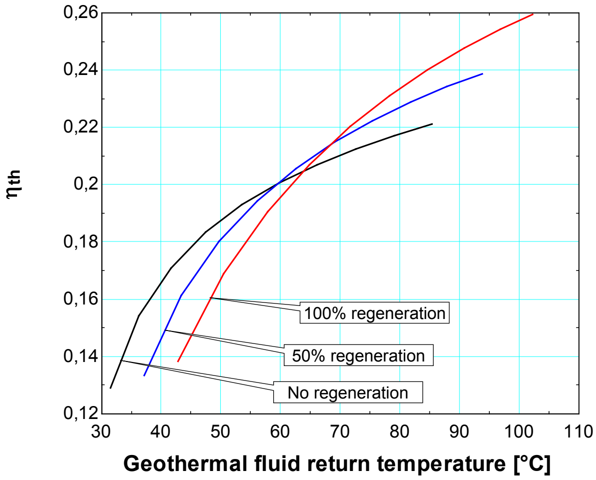

FIGURE 18: Thermal power plant efficiency (ideal cycle)

The power plant effectiveness is independent of the recuperation ratio, if the effectiveness is drawn as a function of the geothermal return temperature. And obviously this is a linear relation of the return temperature (Figure 19).

The total efficiency is found by multiplying the thermal efficiency by the effectiveness, and logically this is the same set of curves as the curves for the power obtained from the geothermal flow at the very beginning (Figure 20).

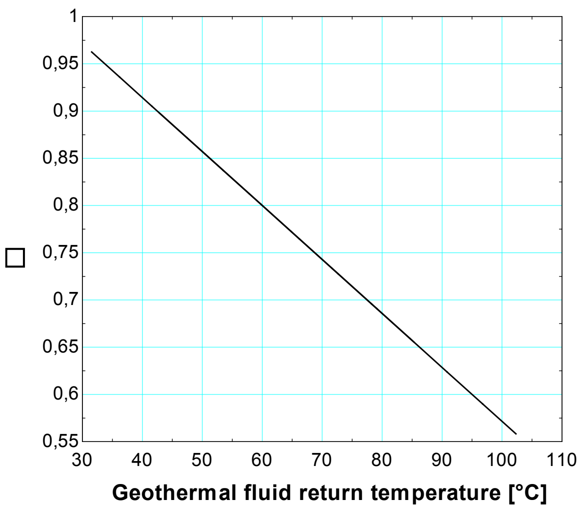

FIGURE 19: Power plant effectiveness (ideal cycle)

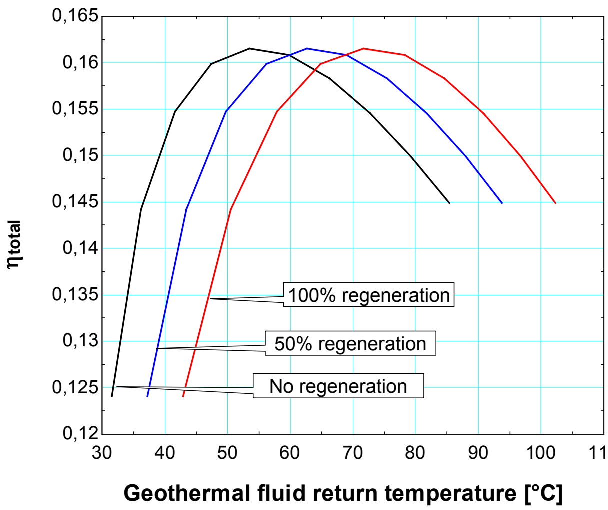

FIGURE 20: Thermal power plant total efficiency (ideal cycle)

The conclusion is simply that recuperation serves only to move the highest power production towards higher geothermal return temperature.

A final note is that a real cycle will show lower efficiency for higher recuperation, so recuperation will always reduce the maximum power available from a given geothermal flow stream. Recuperation will as well increase the plant cost, and has thus to be seen as a measure to preserve power, if a secondary process or geothermal fluid chemistry limits the return fluid temperature.

9. KALINA CYCLE

The Kalina cycle is patented by the inventor, Mr. Alexander Kalina. There are quite a few variations of the cycle.
The Kalina power generation cycle is a modified Clausius-Rankine cycle. The cycle is using a mixture of ammonia and water as a working fluid. The benefit of this mixture is mainly that both vaporization and condensation of the mixture happens at a variable temperature. There is no simple boiling or condensation temperature, rather a boiling temperature range as well as condensation range. This is due to the fact, that the phase change process is a combined process, both the phase change of the substance and absorption/separation of ammonia from water.

9.1 The fluid

A phase diagram for ammonia – water mixture at 30 bar pressure is shown on Figure 21. The lower curve is the so-called bubble curve, when the first vapour bubble is created. This bubble has higher ammonia content than the boiling liquid. As the bubble ammonia content is higher than that of the liquid, the ammonia content in the liquid phase will be reduced. The upper curve is the so-called dew curve, when the last liquid drop evaporates. This drop has considerably lower ammonia content than the vapour.

The boiling process for 50% mixture is indicated on the diagram. The temperature range for the boiling of the mixture at 30 bar is shown on Figure 22. The temperature range from bubble to dew is largest at approximately 67% ammonia concentration, and is then close to 95°C.

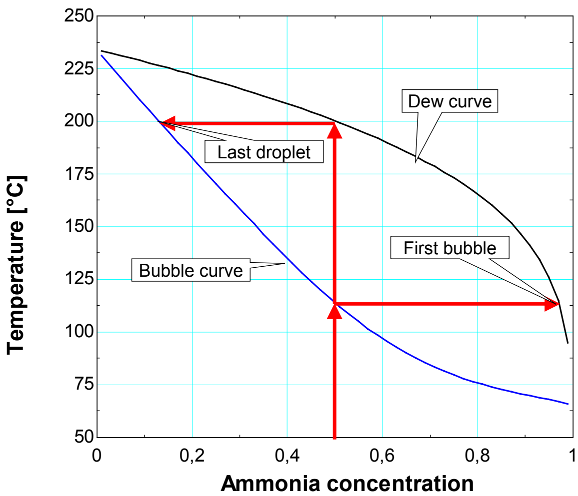

FIGURE 21: Ammonia-water phase diagram at 30 bar pressure

The mixture has thus a finite heat capacity, which is beneficial if the heat source is a liquid with constant or close to constant heat capacity.

The enthalpy of vaporization is as well dependent on the ammonia concentration (Figure 23).

Ammonia-water mixture is technically well known and widely used as a working fluid. Ammonia-water mixtures have been used in absorption refrigeration systems for decades. And ammonia is no newcomer to the technical field, it has been used in chemical and refrigeration processes for very long time. Ammonia is toxic, but the safeguards are well established.

Temperature - enthalpy diagrams for the mixture, at 25%, 75% and 95% ammonia concentration are shown on Figures 24, 25, and 26.

The change in the curve form for boiling at constant pressure is to be noted. For low ammonia concentration, the largest temperature increase is at the beginning of the boiling, for high concentration at the end of the boiling. Intermediate concentration has S-formed boiling curve, and is therefore best suitable for power generation.

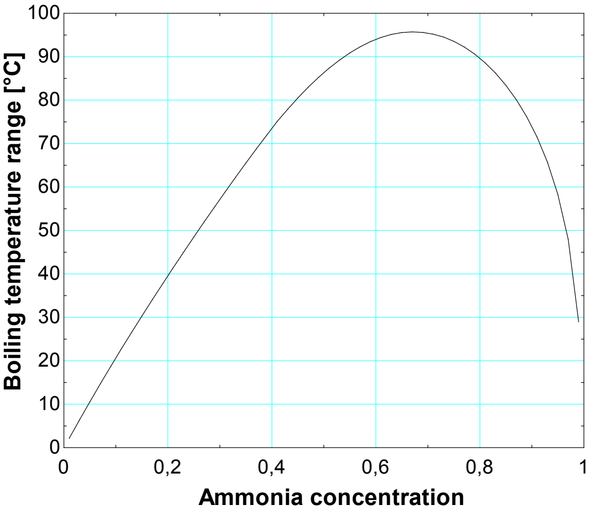

FIGURE 22: Ammonia-water boiling range at 30 bar pressure

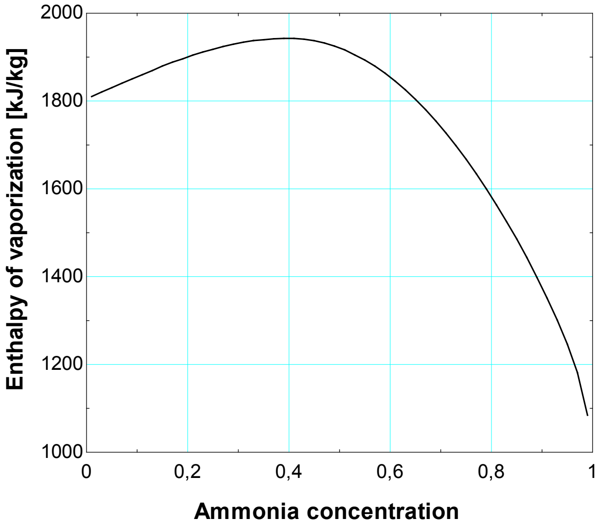

FIGURE 23: Ammonia-water enthalpy of vaporization at 30 bar pressure

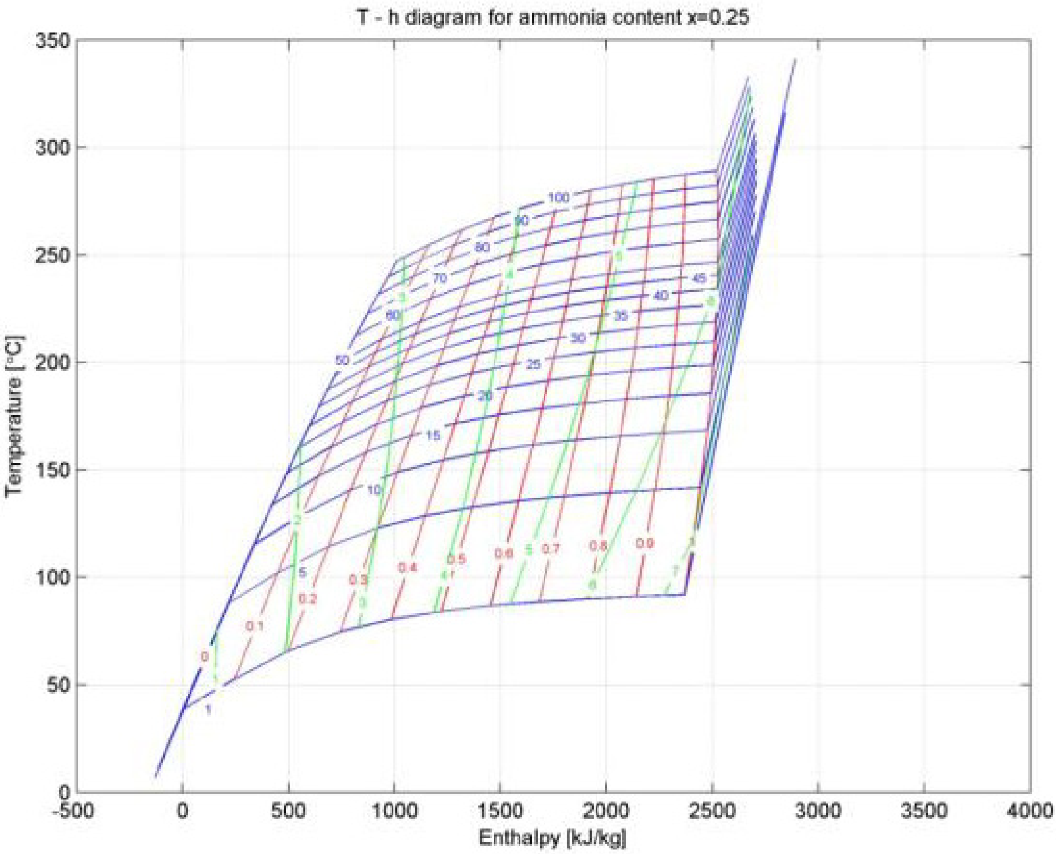

FIGURE 24: T-h diagram for 25% ammonia-water mixture

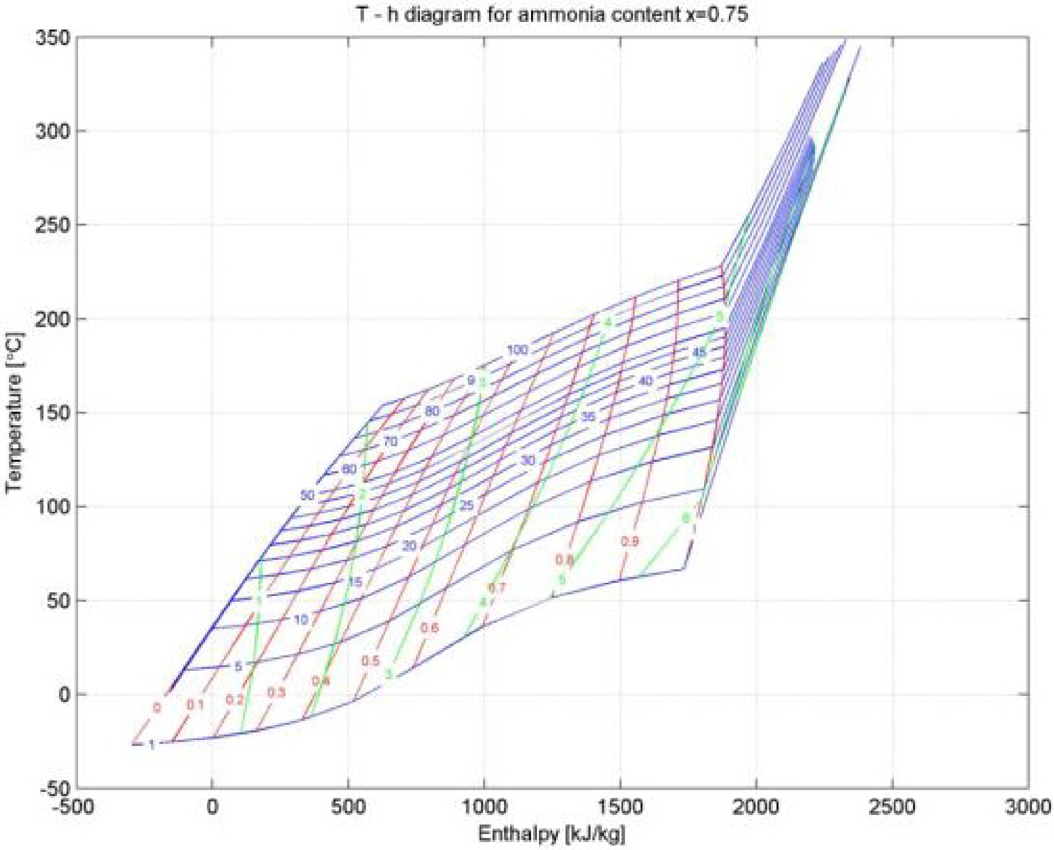

FIGURE 25: T-h diagram for 75% ammonia-water mixture

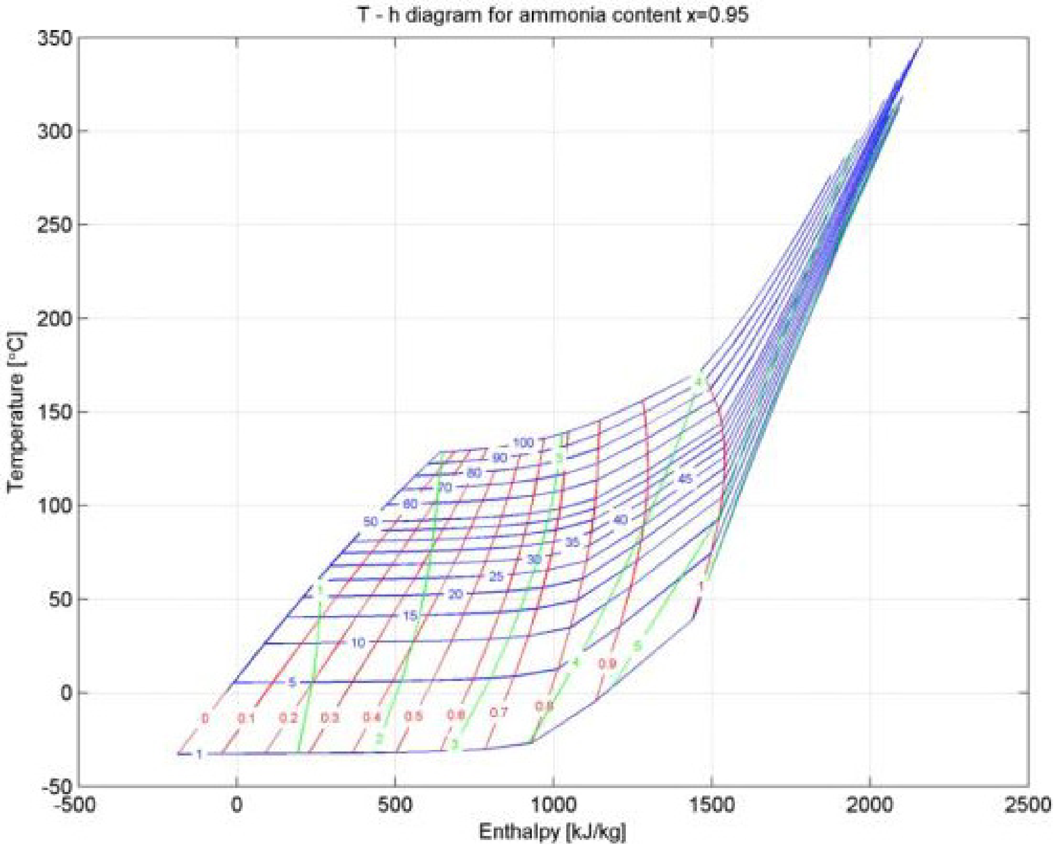

FIGURE 26: T-h diagram for 95% ammonia-water mixture

9.2 The cycle

A flow sheet for the Kalina saturated cycle is shown on Figure 27.

The cycle is "saturated" because there is no superheat in the cycle. The fluid is not boiled entirely in the vaporizer, and the vapour-liquid mixture is then separated afterwards. This is done in order to maximise the vapour temperature at the vaporizer outlet.

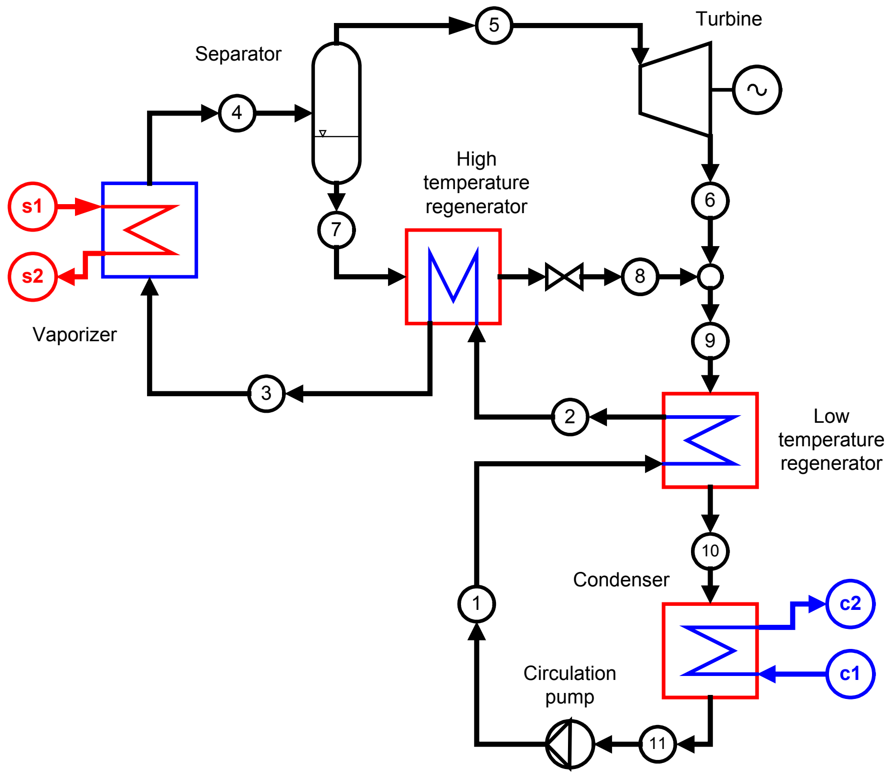

FIGURE 27: Flow diagram of a saturated Kalina cycle

The geothermal fluid enters the well at the source inlet temperature, station s1. The fluid is frequently liquid water. If the pressure is kept sufficiently high, no non-condensable gases will be separated from the liquid, and a gas extraction system is not necessary. The fluid is then cooled down in the vaporizer, and sent to re-injection at station s2.

Pre-heated (in the recuperators) liquid ammonia-water mixture enters the vaporizer at station 3. The fluid is boiled partly in the vaporizer. The liquid-vapour mixture leaves the vaporizer at station 4, and enters the separator.

The separated liquid leaves the separator and enters the high temperature recuperator at station 7. After the high temperature recuperator the liquid is throttled down to the condenser pressure in station 8, and mixed with the turbine exit vapour from station 6.

The ammonia-rich vapour enters the turbine at station 5, and is expanded to the condenser pressure at station 6.

The exit vapour mixed with the throttled liquid (now at the average ammonia concentration) from the high temperature recuperator enters the low temperature recuperator at station 9.

The cooled fluid from the low temperature recuperator enters the condenser at station 10. The fluid gas now started to condense, and the ammonia concentration is not the same in the liquid or vapour phase. An absorption process is going on, where the ammonia rich vapour is absorbed into the leaner liquid, in addition to condensation due to lowering of the mixture temperature. The kinetics of the absorption process determines the rate of absorption, whereas heat transfer and heat capacity controls the condensation process.

Finally all the mixture is in saturated liquid phase in the hot well of the condenser at station 11. The circulation pump raises the fluid pressure up to the higher system pressure level, and the liquid is then preheated in the recuperators in stations 1 through 3.

The condenser shown here is water cooled, with the cooling water entering the condenser at station c1 and leaving at station c2.

9.3 External heat exchange

A mixture of ammonia and water will not boil cleanly, but as well change the chemical composition. The vapour will be more ammonia – rich, whereas the liquid will be leaner for the partially boiled mixture. This can be seen from the phase diagram of ammonia –water mixture presented earlier. Similar variation of the chemical composition will be encountered in the condenser for the partially condensed mixture. This results in a variable temperature during the heat exchange process both in the vaporizer and the condenser. A heat exchanger diagram for a vaporizer is shown on Figure 26. There typical curves have been drawn both for isopentane and 80% ammonia – water mixture.

The temperature difference between the primary and the secondary fluid in the Kalina vaporizer is small compared for the isopentane vaporizer, even for similar or same pinch temperature difference. Entropy is generated whenever heat is transferred over a finite temperature difference, thus is the entropy generation in the Kalina vaporizer less, and thereby the destruction of exergy less. On the other hand the Kalina vaporizer will need larger heat exchange area due to the smaller temperature difference. And the diagram shows well that the logarithmic temperature difference approach for the sizing cannot be used, as the fluid heat capacity is far from being constant.

A similar situation is in the condenser. There ammonia rich vapour is absorbed and condensed, with the associated changes in chemical composition of both liquid and vapour.

A heat exchanger diagram of both isopentane and ammonia – water mixture in a water cooled condenser is shown on Figure 27.

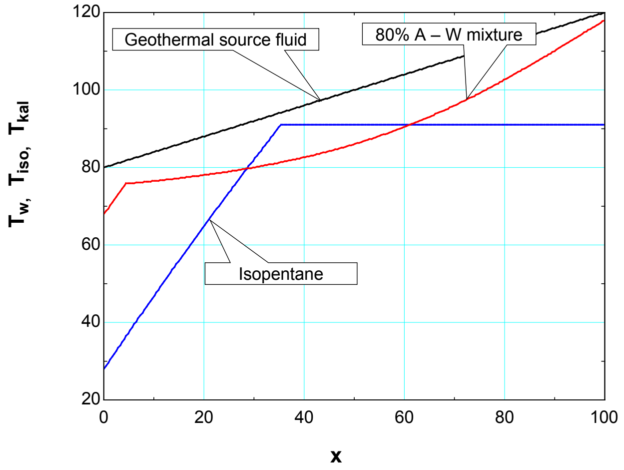

FIGURE 26: Heat exchanger diagram for a vaporizer in a binary power plant, x=100 is at geothermal fluid entry, and x=0 at the outlet

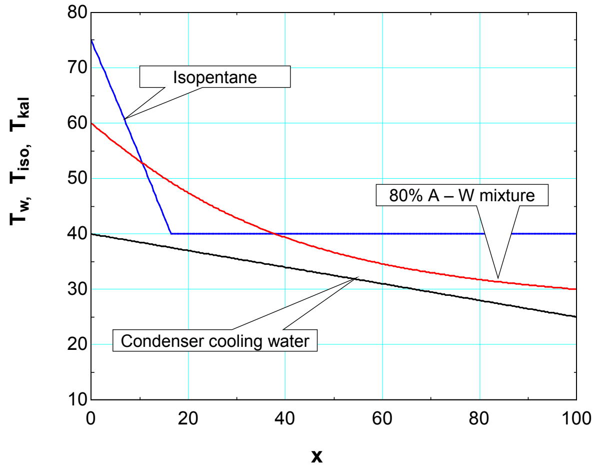

FIGURE 27: Heat exchanger diagram for a condenser in a binary power plant, x=100 is at cooling water entry, and x=0 at the outlet

Both fluids will have the pinch point internally in the condenser, and the ammonia – water mixture will even have the pinch at an unknown point. The isopentane will obviously have the pinch at the fluid dew point, but it cannot be known beforehand at which vapor ratio the pinch for the ammonia – water mixture will be.

9.4 Kalex / New Kalina

A novel cycle has been invented by Mr. Kalina, using ammonia – water mixture as well. Information on this cycle is sparse, and no commercial application is presently known. It seems that Mr. Kalina is employing more pressure stages in the new cycle, resulting in that the mixture concentration in the cycle can be better optimized. That means as well that there are more concentration variations in the cycle. Time will show if the increased complexity of this cycle proves to be worth the claimed increase in efficiency.

10. COMBINED CYCLES

The cycles treated previously are frequently combined. A binary cycle is then used as a bottoming cycle to a flash cycle, increasing the total plant efficiency at the cost of complexity. The flash cycle has the benefit of low investment, and the binary bottoming cycle serves then to increase the efficiency – for substantially increased investment cost.

Samples of two such combinations are shown in Figures 28 and 29.

11. CYCLE COMPARISON

The flash steam cycles require high enthalpy of the geothermal fluid to be feasible. The fluid is separated, which can lead to chemical problems with the brine, when the mineral concentration increases due to the flashing. All non-condensable gas released from the fluid in the flashing process will have to be removed from the condenser (if present) and disposed of in an environmentally sound way. This has limited the use of flash cycles to the high temperature geothermal fields in sparsely populated areas.

The binary cycles have the benefit of having heat exchange only with the geothermal fluid. The geothermal fluid can then be kept under sufficiently high pressure during the heat exchange process to avoid boiling and release of non-condensable gases. The fluid can then be re-injected back into the reservoir, containing all minerals and dissolved gases.

By appropriate selection of working fluid, the geothermal fluid can be economically cooled further down then what is possible with the flash cycles. This will increase the power plant effectiveness at the cost of efficiency, as previously said. But at the end an optimum value for the plant return temperature of the geothermal fluid emerge, and this temperature will give the highest power plant output for a given flow stream from the wells.

The binary cycles have the disadvantage of having a secondary working fluid, often expensive, toxic and flammable. This leads to expensive safety measures required for the power plant.

When the geothermal fluid temperature is medium to low, the ORC cycle becomes more economical than the flash cycles. If the fluid temperature is below say 180°C it is likely that an ORC cycle will be more economical than a flash cycle. This is as well valid for higher temperatures if the gas content in the fluid is high.

The ORC cycle gives normally high power plant effectiveness. The cycle can be modified by adjusting the level of recuperation to suit the secondary process requirements (such as bottoming district heating system) or chemical limitations regarding the plant geothermal fluid return temperature. When recuperation is used, the plant efficiency increases and the plant effectiveness is reduced, as discussed before.

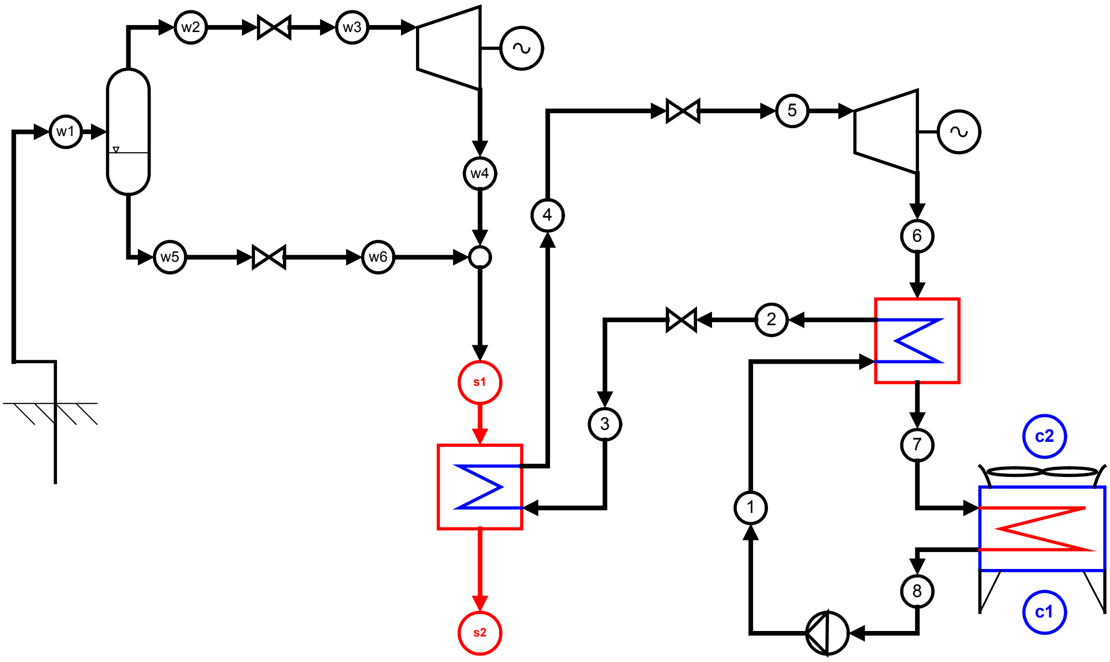

FIGURE 28: A single flash back pressure cycle combined with an ORC cycle

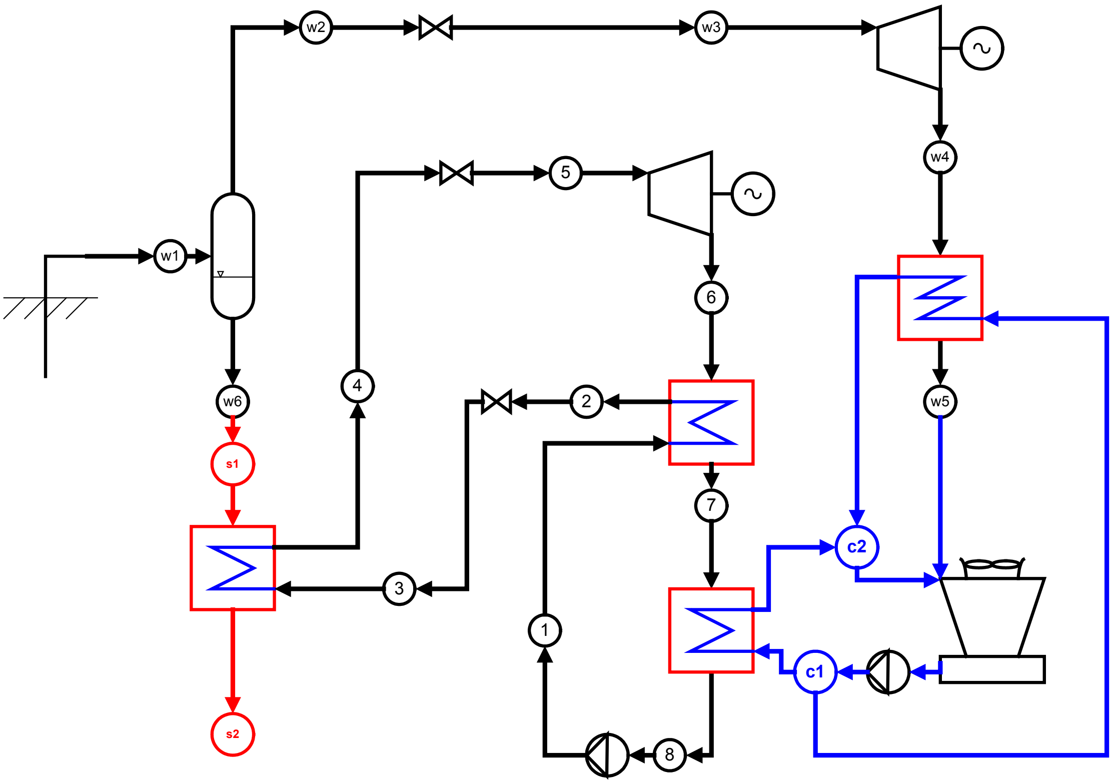

FIGURE 29: A single flash condensing cycle combined with an ORC cycle

Another advantage of the ORC cycle is that it can be easily adapted to fluid with partial steam. The constant vaporizer boiling temperature has then to fit with the condensation temperature of the partial steam in the geothermal fluid.

When the geothermal fluid temperatures get lower than say 150-160° the Kalina cycle seems normally to be superior to the ORC cycle. Kalina is better fit for situations where the geothermal fluid is only liquid water, due to the variable temperature of the vaporizer boiling and separation process in the ammonia – water mixture.

Other technical differences between these two binary cycles are that the pressure level of the Kalina cycle is higher than for a corresponding ORC cycle.

The turbine cost in the ORC cycle is thus higher, due to high volume flow in the turbine at lower pressure. On the other hand, then all equipment in the Kalina cycle will have a higher pressure class than in the ORC cycle. The piping dimensions will be larger in the ORC cycle due to higher volume flow.

There does not seem to be any major difference in requirements of the piping/equipment material for these two cycles, with the exception of the turbine. Turbine corrosion has been encountered in the Kalina cycle, leading to the use of titanium as material for the turbine rotor.

Fluid safety measures are similar, as the ORC cycle uses commonly flammable working fluids. The precautions needed due to the flammability seem to be at the same order of magnitude as the requirements due to the toxicity of ammonia.

The technical complexity of the two cycles is at the same order of magnitude. The complexity is highly dependent on the level of recuperation used in the cycle, and therefore a comparison of the cycle complexity has to be made with caution. Obviously a non-recuperated ORC cycle is a lot less complex than a highly recuperated Kalina cycle with two temperature levels of recuperation. But this is not a fair comparison.

At the time of writing this text, the only geothermal Kalina plant is at Husavik, Iceland. A second plant is being built at Unterhaching in Bavaria, Germany. Presently the limited use of the Kalina cycle may be its biggest disadvantage, but this will most probably change during the coming years. ORC cycles are widespread and have been in use for decades.

12. POWER PLANT COMPONENTS

This chapter treats the main equations and short discussion of the main power plant components. The most relevant items related to geothermal engineering are as well discussed shortly.

12.1 Well and separator

A simplified model of the well and separator is presented on Figure 30. Station 1 is the undisturbed geothermal reservoir. The main thermal parameter for the reservoir with regard to the power plant design is the field enthalpy, or energy content of the fluid. Station 2 is the entry of the steam – water separator, station 3 is the steam outlet from the separator and station 4 is the brine outlet of the separator.

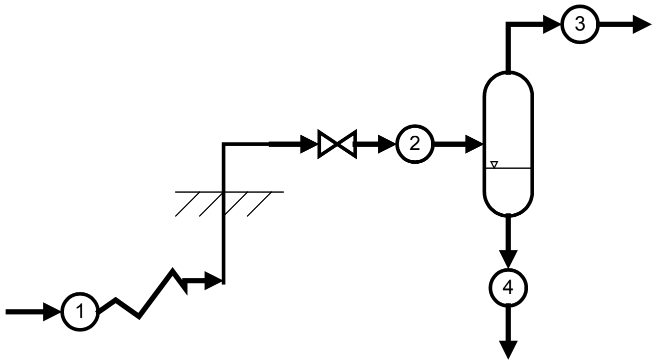

FIGURE 30: Schematic of a separator

The wells have certain productivity, i.e. there is a relation between the wellhead pressure and the flow from the well.

The productivity is individual from well to well, and this relation is further complicated by the fact that the well may not be artesian, that is a well pump is required to harvest fluid from the well. Generally this relation can be presented as:

$$\dot{m}_1 = f(p_2) \tag{17}$$

where the function takes the presence of a well pump into account, as well the field characteristic.

The flow up the well and in the geothermal primary system can usually be treated as isenthalpic, the is that the heat loss in the well and the piping is neglected. No fluid loss is assumed, leading to:

$$\dot{m}_2 = \dot{m}_1 \tag{18}$$

$$h_2 = h_1 \tag{19}$$

The throttling in the well and primary system results most frequently in that the fluid starts to boil, which results in that the temperature is a direct function of the separator pressure (Station 2). If the well is non-artesian and a well pump is used, the pressure may be kept sufficiently high to avoid boiling, in which case a separator is not needed at all and the source fluid is liquid in the sub-cooled region at all times.

If boiling occurs and a separator is employed, the relation between temperature and pressure is:

$$T_2 = T_{sat}(p_2) \tag{20}$$

defined by the thermodynamic properties of steam and water.

The steam fraction is then defined by the energy balance over the separator. The heat flow in the incoming mixture of steam and water (from the well) equals the sum of the energy flows in the steam and the brine from the separator. The mass flow of steam from the separator will thus be:

$$\dot{m}_3 = \dot{m}_2 \frac{h_2 - h_4}{h_3 - h_4} \tag{21}$$

The separator is working in the (thermodynamic) wet area, containing a mixture of seam and water in equilibrium. All temperatures in the separator will thus be equal, assuming that there are no significant pressure losses or pressure differences within the separator.

$$T_3 = T_2 = T_4 = T_{sat}(p_2) \tag{22}$$

The enthalpy of the steam outgoing stream from the separator is thus the enthalpy of saturated steam at the separator pressure.

$$h_3 = h_g(p_2) \tag{23}$$

Mass balance holds over the separator, the sum of steam mass flow and brine mass flow equals the mass flow of the mixture from the wells towards the separator.

$$\dot{m}_4 = \dot{m}_2 - \dot{m}_3 \tag{24}$$

The selection of separator pressure is very critical for the power plant. If the wellhead pressure is low, boiling may occur in the formation around the well, which may lead to scaling within the cracks and narrow flow passages in the formation. This will lead to short well life.

Higher separator pressure means that better steam is available for the turbine (higher enthalpy), but the amount will be less, dictated by the separator energy balance as well as less well productivity due to higher wellhead pressure. This may as well influence the separation of non-condensable gases from the geothermal fluid.

The selection of the separator pressure is thus an optimization process, economical, thermodynamic and geothermal.

12.2 Vaporizer

The vaporizer is the first component of an ORC or a Kalina power plant (Figure 31). Station s1 is the entry of the geothermal fluid to the vaporizer, and station s2 is the outlet. Station 1 is the entry of the power plant working fluid (liquid) to the vaporizer, and station 2 is the outlet of the working fluid vapour or mixture towards the turbine.

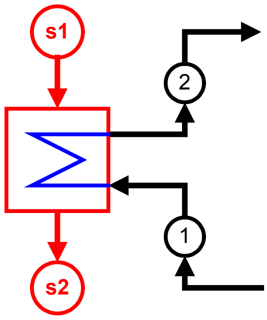

FIGURE 31: ORC vaporizer schematic

Obviously the heat removed from the source fluid has to equal the heat added to the working fluid.

$$\dot{m}_s \left(h_{s1} - h_{s2}\right) = \dot{m}_{working\ fluid} \left(h_2 - h_1\right) \tag{25}$$

The fluid condition at station 2 is determined by the cycle and the turbine requirements, for an ORC cycle this would be saturated or slightly superheated, for most Kalina cycles it would be in the wet region, with vapour fraction at 50-100%.

The vaporizer is nothing but a heat exchanger between the hot source fluid and the cold working fluid of the cycle. It has to be observed that the temperature of the hot fluid is higher than the one of the cold fluid throughout the vaporizer. As well it must be kept in mind that the relation between the enthalpy and the temperature is highly non-linear, requiring that the vaporizer is divided into appropriate sections for the calculation.

The source fluid outlet temperature is critical as regards scaling. This temperature must be kept sufficiently high to avoid scaling on the source fluid side of the exchanger. Cleaning of the source fluid side may be necessary, so the vaporizer design must take this into account. Any geothermal fluid may be corrosive, so an appropriate material has to be used for the vaporizer.

12.3 Turbine

The turbine converts a part of the vapour enthalpy to shaft work, and then electricity in the generator. Station 1 is the vapour inlet to the turbine, and station 2 is the turbine exit (Figure 32).

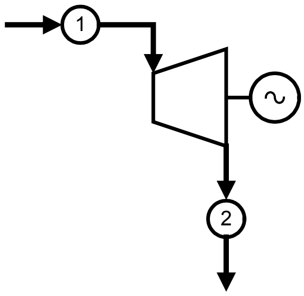

FIGURE 32: Turbine schematic

The ideal turbine is isentropic, having no second law losses. In this case the entropy of the incoming vapour equals the entropy in the exhaust steam. The corresponding enthalpy change (reduction) of the vapour is the largest enthalpy change possible. The isentropic exit enthalpy is then the enthalpy at the same entropy as in the inlet and at the exit pressure, which is roughly the same as prevails in the condenser.

$$h_{2,s} = h(s_1, p_2) \tag{26}$$

The turbine isentropic efficiency is given by the turbine manufacturer. This efficiency is the ratio between the real enthalpy change through the turbine to the largest possible (isentropic) enthalpy change. The real turbine exit enthalpy can then be calculated:

$$h_2 = h_1 - \eta_{is}(h_1 - h_{2,s}) \tag{27}$$

The work output of the turbine is then the real enthalpy change multiplied by the working fluid mass flow through the turbine.

$$\dot{W} = \dot{m}(h_1 - h_2) \tag{28}$$

The expansion through the turbine may result in that the exit vapor is in the wet region, or that a fraction of the mass flow is liquid. This can be very harmful for the turbine, resulting in erosion and blade damage.

The Kalina cycle uses a mixture of ammonia and water, so that the droplets created in the turbine are electrically conductive. It is the meaning of the writer that this conductivity is the reason for the corrosion encountered in the turbine in Husavik, Iceland. This corrosion has been avoided by the usage of non-magnetic titanium for the turbine rotor.

Many of the working fluids for the ORC cycle are retrograde, which means in this context that the exit vapour is superheated. The heat removal in the condenser will then partly be "de-superheat", heat transfer out of the vapour at temperature higher than the final condensing temperature.

Ammonia-water mixture is not retrograde, but as the condensation will occur at a variable temperature, the heat removal process is very similar to that of the retrograde fluids.

12.4 Recuperator

The recuperator is a heat exchanger between the hot exit vapour from the turbine and the condenser. It is a de-superheater in the ORC cycle, transferring heat from the turbine exit vapour to the condensate from the condenser.

Station 1 is the turbine exit vapour, station 2 is the recuperator outlet towards the condenser, station 3 is the inlet of the condensate from the condenser, and station 4 is the pre-heated feed to the vaporizer (Figure 33).

The heat removed from the turbine exhaust vapour is equal the heat added to condensate:

$$\dot{m}(h_1 - h_2) = \dot{m}(h_4 - h_3) \tag{29}$$

The mass flow is the same on both sides of the recuperator. The hot fluid from the turbine is on the hot side, will be condensed in the condenser and then pumped right away through the cold side of the recuperator towards the vaporizer.

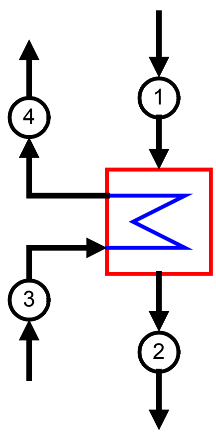

FIGURE 33: Recuperator schematic

It has to be observed that the temperature of the hot fluid is higher than the one of the cold fluid throughout the recuperator. The fluid behaviour is usually close to linear, so it is normally not necessary to divide the recuperator into sections.

The effect of recuperation on the cycle has been treated earlier in this text.

12.5 Condenser

The condenser may be either water or air cooled. The calculations for the condenser are roughly the same in both cases, as the cooling fluid (air or water) is very close to linear. Station 1 is the working fluid coming from the recuperator (or turbine in the case of a non-recuperated cycle), shown in Figure 34. Station 2 is the condensed fluid, normally saturated liquid with little or no sub-cooling. Station c1 is the entry of the cooling fluid, station c2 the outlet.

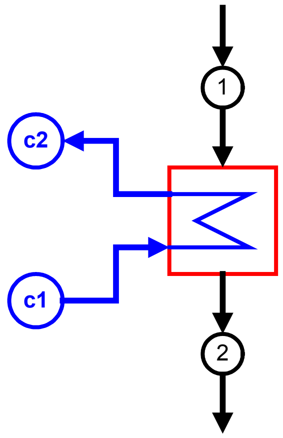

FIGURE 34: Condenser schematic

The condenser is nothing but a heat exchanger between the hot vapour from the recuperator/turbine and the cooling working fluid of the cycle. It has to be observed that the temperature of the hot fluid is higher than the one of the cold fluid throughout the condenser. As well it must be kept in mind that the relation between the enthalpy and the temperature is non-linear, requiring that the vaporizer is divided into appropriate sections for the calculation. This is especially valid for Kalina cycles, in the ORC cycle there is only a property change at the dew point, where de-superheat ends and condensation begins.

13. THERMOECONOMICS

Thermoeconomics analyze the power generation economics from the exergetic viewpoint. A thorough treatment of thermoeconomics is found in Bejan et al (1996) and El-Sayed (2003).

Thermoeconomics deal with the value of the energy within a plant, where heat and work conversion finds place. The analysis is based on exergy flows, and breaks the plant up into individual components, where each component can be analyzed separately.

Each component will have one or more exergy input (feed) streams, and one or more output (product) exergy streams. A feed stream is either input to the plant, or is a product of a previous component. An output stream is either a product from the plant or a feed to the next component in the chain.

Exergy loss due to irreversibilities will occur in all components of the power plant. This is the so-called exergy destruction, and the stream is termed exergy destruction stream for the subject component. In some components there will be a rejected exergy stream, which is of no further use in the process. This is the exergy loss, and exergy loss stream for the subject component. Figure 35 is a schematic which shows this relationship better.

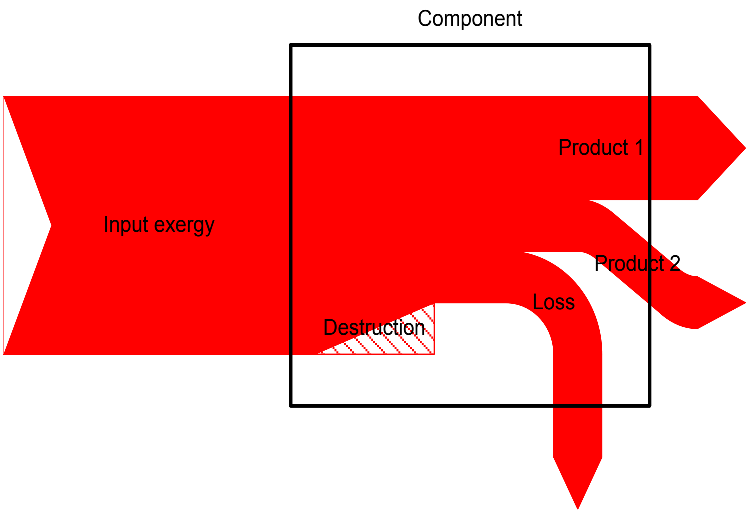

FIGURE 35: Component exergy streams

Anergy is assumed to have no value, as well as all exergy loss streams and destruction streams. The unitary exergy cost is calculated for each point in the energy conversion process, and cost streams are used to gain an overview over the economics of the power generation process. Each component will have three types of cost flows associated, the input exergy cost flow, the component investment cost flow, and the product exergy cost flow. A cost balance, equating the product cost flows (all having the same unitary exergy cost) to the sum of the input exergy cost flows and the component investment cost flow.

The component has to be paid for and maintained. The associated cost is fixed, and is not dependent on the magnitude of the exergy streams entering and leaving the component. The investment cost flow is calculated as:

$$\dot{Z} = \dot{Z}_{CI} + \dot{Z}_{OM} \tag{30}$$

Where $\dot{}$ = Dot above character denotes time derivative (rate) (1/s, 1/h);
CI = Capital and investment (index);
OM = Operation and maintenance (index); and
Z = Fixed cost ($).

The unitary exergy cost is important for the study of the component performance. Each kilowatthour of exergy entering and leaving the component carries cost (or has value), which can be compared to the cost of electricity. The exergy stream is then a product of the unitary exergy cost and the exergy flow:

$$\begin{aligned} \dot{C}_i &= c_i \dot{X}_i = c_i \left(\dot{m}_i x_i \right) \\ \dot{C}_e &= c_e \dot{X}_e = c_e \left(\dot{m}_e x_e \right) \\ \dot{C}_w &= c_w \dot{W} \\ \dot{C}_q &= c_q \dot{X}_q \end{aligned} \tag{31}$$

where $\dot{}$ = Dot above character denotes time derivative (rate) (1/s, 1/h);
e = Product, output, exit (index);
C = Cost, value ($);
c = Untiary (specific) cost, value ($/kWh);
i = Feed, input (index);
m = Mass (kg);
q = Heat (index);
W = Work (kJ, kWh);
w = Work or power (index);
X = Exergy (kJ, kWh); and
x = Specific exergy (kJ/kg).

The Sankey diagram shown in Figure 36 describes cost flow for a sample component graphically.

There is no such thing as a free lunch. The cost flow of the products must be equal to the sum of all incoming cost flows, both those connected with exergy as well as the investment cost flow. This balance is written as:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{32}$$

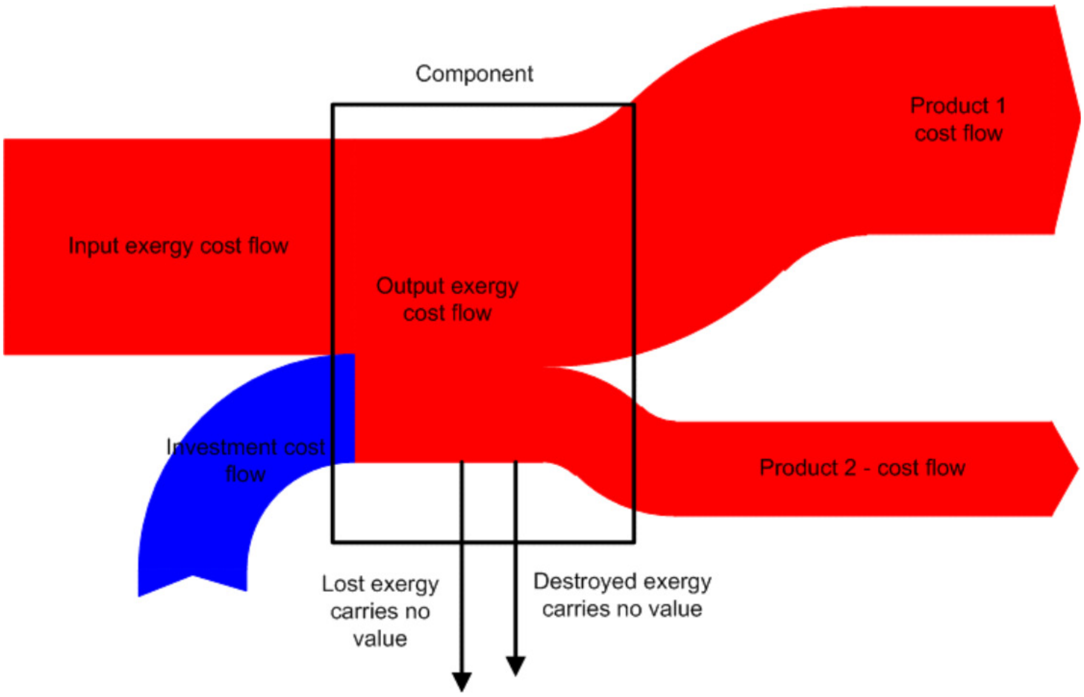

FIGURE 36: Component cost (value) streams

where	$\cdot$	= Dot above character denotes time derivative (rate) (1/s, 1/h);
	C	= Cost, value ($);
	e	= Product, output, exit (index);
	i	= Feed, input (index);
	k	= Number of component;
	q	= Heat (index);
	w	= Work or power (index); and
	Z	= Investment cost ($).

It is traditional in thermodynamics to consider heat flow as input and work flow as output. That is the reason for entering the heat cost flow as input and the work (power) cost flow as output.

The product cost flow can now be solved from this equation, assuming that all previous components in the chain have already been solved.

Equation 32 is now modified to include unitary cost values:

$$\sum_e \left(c_e \dot{X}_e\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{X}_{q,k} + \sum_i \left(c_i \dot{X}_i\right)_k + \dot{Z}_k \qquad (33)$$

where	$\cdot$	= Dot above character denotes time derivative (rate) (1/s, 1/h);
	C	= Cost, value ($);
	c	= Unitary (specific) cost, value ($/kWh);
	e	= Product, output, exit (index);
	i	= Feed, input (index);
	k	= Number of component;
	q	= Heat (index);
	W	= Work (kJ, kWh);
	w	= Work or power (index);
	X	= Exergy (kJ, kWh); and
	Z	= Investment cost ($).

Thermoeconomic optimization will not be treated further here, but this discipline has very powerful tools, enabling the designer to keep consistent economic quality in all components in the power production chain.

14. FEASIBILITY AND ECONOMICS

Thermoeconomy is a very powerful tool to optimize individual plant components. One of the main benefits is that the thermoeconomic tools enable us to deign with consistent quality and performance for all of the installed components.

This is a different question to the question if the plant is a good idea at all. A feasibility study should reveal that. In order to make a useable feasibility study, two main estimates have to be done:

a) Estimation of income; and
b) Estimation of power plant cost

The income estimate cannot be done unless having a good process model at hand, taking into account the climatic conditions over the year, properties of the wells and geothermal fluid, as well as a thorough model of the plant internals.

Such a model will then be able to yield estimates for the power produced by the generator, the power consumed by parasitic components such as circulation pumps and cooling tower and of course thermodynamic process data for the power plant cycle.

The estimation of cost for the plant involves estimating the size of individual components and their price, in addition to installation and secondary cost. It is worth to keep in mind that roads, buildings, fire protection, environmental protection components, control systems, and even lockers and showers for the employees are also a part of the power plant cost.

All this is small compared to the cost invested in the geothermal field, purchase or lease of land, concession fees, field research, and finally drilling of wells. In far too many cases this is considered sunk cost, and is not taken into the account when designing the power plant, with the result that the plant is optimal, assuming that all cost outside the plant is sunk and paid by space aliens.

The cost estimate considering all the cost will yield a larger power plant, suboptimal if only the plant is considered, but giving a higher income and therefore a contribution to the amortization of the field cost.
Renewable energy projects have typically very low variable cost if any at all. The plant has to be built and paid for in the beginning, and will after that produce power without much additional cost. Usually total cost will not be reduced if the plant is run on reduced power.

The value of the parasitic power is sometimes complicating the calculations. The price of produced green energy from the power plant may be substantially higher than the market price on the grid due to green subventions. One possible way of simplifying this is to calculate a net present value for every kilowatt of parasitic power and simply add that to the plant investment cost.

14.1 The mathematics

The three equations of engineering have to be fulfilled, always, everywhere:

a) Conservation of mass;
b) Conservation of momentum; and
c) Conservation of energy.

The only way to make an estimation of the power produced and thus the income is to make a mathematical model of the power plant. The thermodynamic properties of the geothermal fluid and the plant working fluid have to be incorporated, and the model has to be built on the laws of thermodynamics. They are not subject to negotiation, they are absolute.

The plant is then described in a large set of non-linear equations, which have to be solved. A mathematical environment called Engineering Equation Solver (EES) has been used by the author for this purpose. EES has thermodynamic properties of most of the relevant fluids built in, and is already an equation solver, as the name implies.

Heavyweight software such as Aspen or Simulis is of course capable of such modelling, but is expensive and requires much training in order to be an effective tool. Matlab is a standard numerical environment today, but lacks thermodynamic properties. It is possible to integrate Matlab with properties programs made by the US National Institute of Standards (NIST), but this integration is not commercially available and requires in-depth knowledge of programming. Matlab is polished, tried and tested and has a huge user base. But Matlab is also a notorious “hard to learn, easy to use” program.

14.2 Degrees of freedom for the plant design

A binary power plant has around 25-30 design parameters for the thermal design. Some of these parameters have values, which do not change much from case to case. Others are critical optimization parameters. All these parameters are dependent on the plant surroundings, the field parameters, and the market parameters. It is therefore absolutely critical to determine the plant input parameters correctly. The selection of all other parameter values is dependent on that.

The score function for the plant operation is also critical. A common misunderstanding is to take some more or less well founded efficiency value and use that as the only criterion to determine if the plant is good or bad. A power plant is built to produce power as cost effectively as possible. Therefore it is a lot more sensible to base the power plant design on some specific power plant cost in $/kW, ensuring that both the cost model and the power plant model is reflecting the reality as closely as possible.

Geothermal power production is simply a chain of components or processes from the inflow into the well all the way over to the power plant transformer station. The objective is to convert as much of the exergy found in the well inflow to sellable power, electricity or heat. And as typical with any chain, it will never be stronger than the weakest link. The power plant cold end and the associated cooling fluid supply is a part of this chain.

The 25-30 design parameters that have to be selected define an optimization space with a dimension which is one higher that the number of parameters.. The optimization process has therefore a huge number of degrees of freedom, and there are not many general universally usable solutions available, which can give satisfactory performance.

There is no way around a careful design and selection of all these design parameters.

15. GEOTHERMAL FIELD AND WELLS

The well is one of the most expensive part of the power production system. The well will have production dependent on the wellhead pressure. The maximum flow will occur with wellhead pressure zero, and zero flow will yield the well closure pressure, which is again the maximum wellhead pressure. The well characteristic curve will be a deciding factor in the selection of the separator pressure in the flash plants for higher enthalpy fields. Lower separator pressure, higher well flow, higher steam ratio from the separator, but lower quality steam. The lower the wellhead pressure, the lower in the well the boiling of the fluid will start, and finally boiling will occur in the formation, usually with horrible results. Scaling may occur in the formation, destroying the well.

The field enthalpy is a major criterion for the power plant design, and will more or less determine which power plant type can be used. The fluid chemistry is another decisive factor. Scaling behaviour of the fluid usually demands a certain minimum geothermal fluid temperature to be held throughout the entire power plant. Corrosion may require certain materials or the use of additives. Non-condensable gas in the fluid may require gas extraction system with the associated parasitic loss.

Therefore the power plant designer is bound by the fluid enthalpy and chemistry for his selection of the design parameters. To disregard the comments of the geochemist is a sure way to failure.
From the viewpoint of thermoeconomics, the inflow to the well is free of charge, but when the fluid has reached the surface the exergy stream from the well has to carry the field development, drilling and well construction investment cost.

16. EXAMPLE OF COST CALCULATION

Assume that the field development and well cost amounts to 5,000,000 € for each well. Two production wells are drilled and one re-injection well. The well production is 150 kg/s, and the well is low enthalpy, producing only liquid water. The environment is taken at 10°C, 1 bar pressure. Yearly capital cost and operation and maintenance are taken as 10% of investment. Utilization time is assumed 8,000 hours per year.

Under these assumptions the well exergy flow can be calculated as well as the unitary exergy cost (Figure 37).

These results show, that a substantial part of the final cost of electricity is already defined by the well. If we could buy an ideal lossless power plant at zero price, this would be the final cost of electricity.

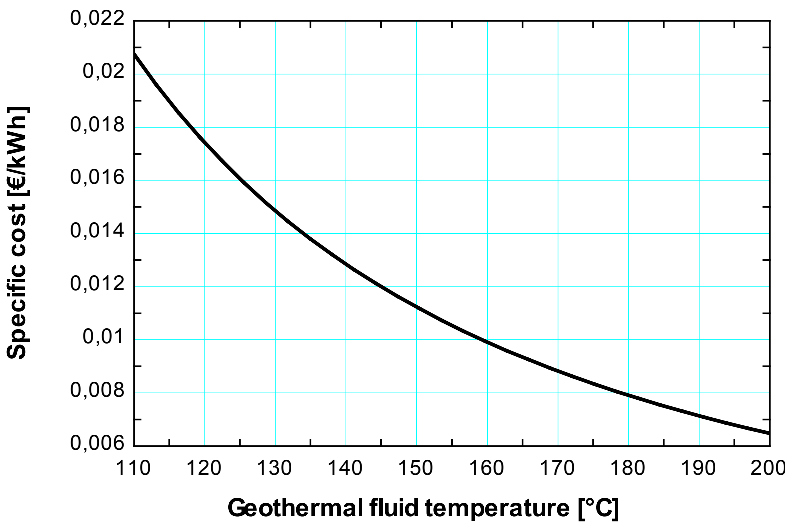

FIGURE 37: Unitary well exergy cost

REFERENCES

Bejan, A., Tsatsaronis, G., and Moran, M., 1996: Thermal design and optimization, J. Wiley, New York, NY, United States, 560 pp.

Cengel, Y.A., and Boles, M.A., 2002: *Thermodynamics: An engineering approach* (4th edition). McGraw-Hill, 1056 pp.

Dorj, P., 2005: *Thermoeconomic analysis of a new geothermal utilization CHP plant in Tsetserleg, Mongolia*. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 2, 74 pp. Web: http://www.os.is/gogn/unu-gtp-report/UNU-GTP-2005-02.pdf

El-Sayed, Y. M., 2003: Thermoeconomics of energy conversions. Pergamon Press, 276 pp.

Kotas, T. J., 1985: *The exergy method of thermal plant analysis*. Butterworths, Academic Press, London, 296 pp.

Szargut, J., Morris, D.R., Steward, F.R., 1988: *Exergy analysis of thermal, chemical, and metallurgical processes*. Springer-Verlag, Berlin, 400 pp.

Thórólfsson, G., 2002: *Bestun á nýtingu lághita jarðvarma til raforkuframleiðslu (Optimization of low temperature heat utilization for production of electricity)*. University of Iceland, Dept. of Mechancial Engineering, MSc thesis, 71 pp.

Valdimarsson, P., 2002: Cogeneration of district heating water and electricity from a low temperature geothermal source. *Proceedings of the 8th International Symposium on District Heating and Cooling, NEFP and the International Energy Agency, Trondheim, Norway*.

The following textbooks cover the material in this paper in more depth:

DiPippo, R., 2008: *Geothermal power plants: Principles, applications, case studies and environmental impact* (2nd edition). Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, 493 pp.

Popovski, K., Andritsos, N., Fytikas, M., Sanner, B., Ungemach, P., and Valdimarsson, P., 2010: *Geothermal energy*. MAGA Macedonian Geothermal Association, Skopje, Republic of Macedonia.

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

GEOTHERMAL BINARY CYCLE POWER PLANTS – PRINCIPLES, OPERATION AND MAINTENANCE: A CASE STUDY FROM EL SALVADOR

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ABSTRACT

Binary cycle power plants play an important role in generating electricity from low geothermal temperature resources. This paper describes the thermodynamic model of a binary cycle power plant and its components by modelling a basic binary cycle, as well as binary cycles with a recuperator for different turbine inlet pressure. An analysis is made on how the addition of a recuperator in the cycle shifts the maximum point of turbine work output, serves to increase the turbine work output for a given reinjection temperature, and helps when the reinjection temperature is limited by the geothermal water chemistry. The maintenance of binary cycle power plants is highly influenced by different factors, such as the nature of the geothermal fluid used in the primary loop, the nature of the working fluid, the technology and location of the plant, and climate and weather. At the same time, this paper presents the operation and maintenance in the Berlin binary cycle power plants in El Salvador.

1. INTRODUCTION

Geothermal energy has often been associated with the movements of tectonic plate boundaries. El Salvador, a small country in Central America with an area of 21,040 km^2 and a population of 6.2 million, is located in the pacific coast of Central America along the "Pacific Ring of Fire" where the Cocos and the Caribbean plates interact. The volcanic activity and seismicity associated with these plate movements are important for the geothermal potential in the country.

El Salvador was the first Central American country to exploit geothermal resources. Electricity generation using geothermal energy started in 1975. The development has reached a total capacity of 204.2 MW.

In El Salvador, the geothermal resource management, exploitation and production of geothermal energy are developed by LaGeo S.A de C.V and the installed capacity is distributed mainly in two geothermal fields: 95 MW in Ahuachapán geothermal field and 109.2 MW in Berlin geothermal field. Figure 1 shows the location of El Salvador in Central America together with its geothermal fields.

Geothermal systems are classified by temperature, enthalpy and physical state among others. According to the temperature classifications, the geothermal heat varies from below 150°C to above 200°C, and can be a mixture of steam and water, or mainly steam or mainly water. The temperature of the geothermal reservoir defines the type of technology required to exploit the available heat and the utilization of the geothermal resource.

As mentioned earlier, El Salvador has two geothermal fields and both are classified as high-temperature geothermal fields, with Ahuachapán having reservoir temperatures between 230 – 250°C and Berlin with a temperature of 300°C. Generally, the high temperature fields are mainly exploited for generation of electricity as is the case in El Salvador. The technology that has been utilized for exploiting Ahuachapán geothermal fields consists of two single flash condensing turbines and one double flash condensing turbine, while Berlin geothermal field utilizes three flash condensing turbines and one binary cycle power plant.

FIGURE 1: Location of El Salvador in Central America and its geothermal fields

The project for increasing the capacity of the Berlin power plant started in 2005. The power plant now has an increased capacity with the addition of a 44 MW condensing unit and a 9.2 MW binary unit. For the added binary power unit, the temperature used is 180°C and is obtained from the separated water of the production wells. The total installed capacity of El Salvador is forecasted to be about 290 MW by 2015 (Bertani, 2012).

Electricity generation from geothermal energy made a modest start in 1904 at Larderello in the Tuscany region of north-western Italy with an experimental 10 kW-generator (Lund, 2004). Since then, the interest in developing and exploiting geothermal resources began around the world, and today electricity from geothermal energy is considered to be one of the sources of renewable energy worldwide. It has grown to 10,898 MW in 24 countries, producing an estimated 67,246 GWh/yr. The development of the worldwide geothermal power production can be seen in Figure 2.

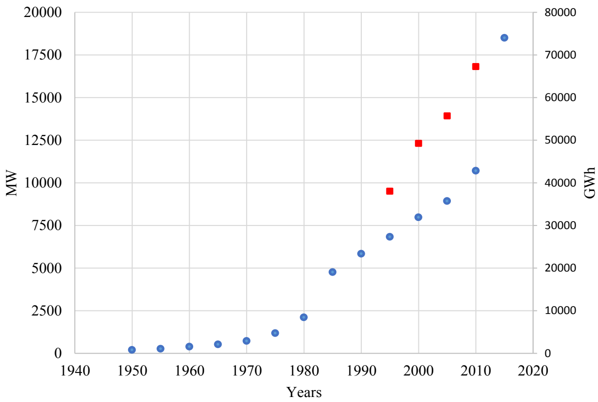

FIGURE 2: Development of worldwide geothermal power production (Bertani, 2012)

The number of geothermal countries is expected to increase from 24 in 2010 to 46 in 2015. Binary power plant technology plays a very important role in the modern geothermal electricity market (Bertani, 2012). The first geothermal binary power plant was put into operation at Paratunka near the city of Petropavlovsk on Russia's Kamchatka peninsula, in 1967, commissioning a 670 kW power plant. It ran successfully for many years, proving the concept of binary plants of today. Nowadays, binary plants are the most widely used type of geothermal power plant with 162 units in operation in May 2007, generating 373 MW of power in 17 countries. They constitute 32% of all geothermal units in operation but generate only 4% of the total installed power. Thus, the average power rating per unit is small, only 2.3 MW/unit, but units with ratings of 7–10 MW are coming into use with advanced cycle design (DiPippo, 2007).

El Salvador has played a major role in the worldwide development of binary power plants, with the first installed binary power plant in the country located in the Berlin geothermal field. In this first unit, the

Organic Rankine Cycle has been used to generate electricity using Isopentane as a working fluid. The binary power plant was designed to utilize remnant heat from the geothermal water (waste brine) to evaporate the Isopentane. This unit is currently producing electricity, however, there has been operational challenges causing tripping of equipment and even resulting to unit shut-downs. Since the unit started running, maintenance and overhaul measures have been developed, and some modification executed on the equipment ensuring continuous operation of the plant at maximum capacity and efficiency. LaGeo has had experience with this technology and is still in the learning process. However, it has been a great first step for the development of electricity production using geothermal water in El Salvador.

2. BASIC BINARY CYCLE

The concept of the binary cycle power plant, known as an Organic Rankine Cycle (ORC), is a modification of the Rankine cycle where the working fluid, instead of water, is an organic fluid having a low boiling point and high vapour pressure compared with the steam water, along all state points that comprise the thermodynamic cycle.

The geothermal binary cycle power plant is formed by two cycles. The primary cycle that contains the geothermal fluid and the secondary cycle in which the organic working fluid is enclosed. The primary cycle starts from the production wells and ends in the re-injection wells. In the primary cycle, the temperature and the desired flow rates of geothermal fluid are determined by the reservoir´s field properties. The geothermal fluid can either be water or steam. When the geothermal fluid is geothermal water or brine, it is kept at a pressure above its flash point at fluid temperature along the primary cycle, to avoid flashing of geothermal fluid in the heat exchangers. The geothermal fluid temperature at the end of the primary cycle is not allowed to drop to the silica scaling point.

The main components of a basic geothermal binary cycle power plant are the preheater, evaporator, turbine, condenser, and working fluid pump. The schematic diagram in Figure 3 shows the main components of the cycle. The basic thermodynamic process of binary cycles is the Rankine cycle, where the working fluid vapour reaches the superheated condition in the evaporator condenses into the condenser. The simple method to describe a binary power cycle is to follow the T-S diagram shown in Figure 4. The thermodynamic states of the working fluid in the secondary cycle are also shown on the P-H diagram in Figure 5. Such diagrams help in understanding the thermodynamic cycle and different states of the working fluid.

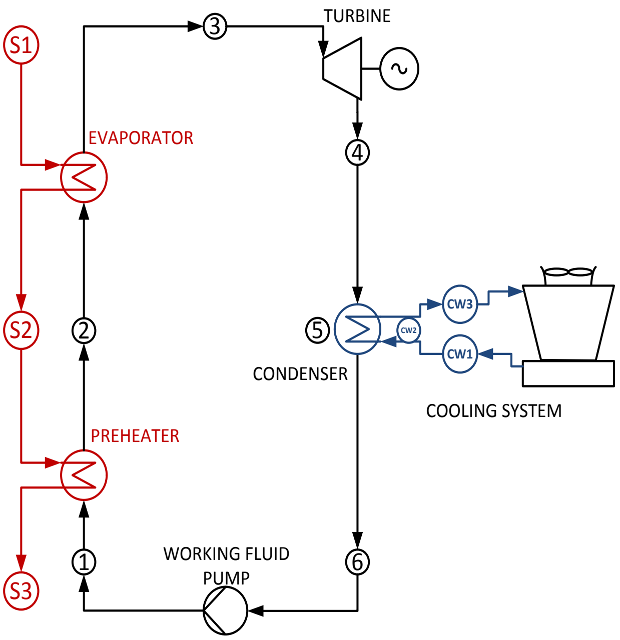

FIGURE 3: Schematic diagram of the basic binary power cycle

The binary cycle (Figure 3) consists of the following four processes:

6 – 1	Isentropic compression in the working fluid pump;
1 – 2 – 3	Constant pressure heat addition in preheater and evaporator;
3 – 4	Isentropic expansion in a turbine; and
4 – 5 – 6	Constant pressure heat rejection in a condenser.

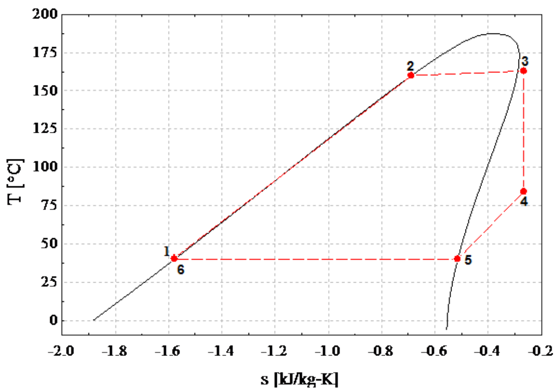

FIGURE 4: T-S diagram for a binary cycle using Isopentane as a working fluid

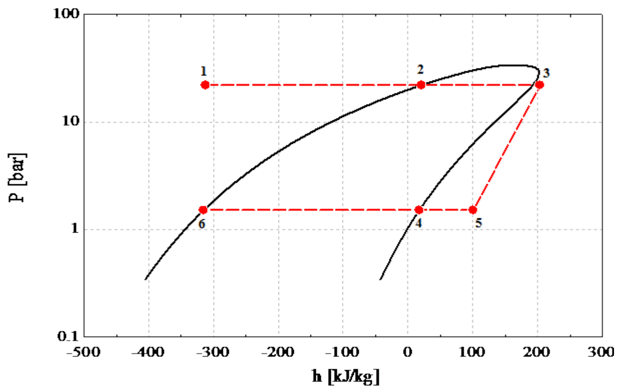

FIGURE 5: P-H diagram for a binary cycle using Isopentane as a working fluid

It is important to note that the area under process 1-2-3 represents the heat transferred to the working fluid in the preheater and evaporator, and the area under process curve 4-5-6 represents the heat rejected in the condenser. The difference between these two areas is the network produced during the cycle (the area enclosed by the cycle curve).

The binary cycle power plants can be cooled by water or air; these methods of cooling are called wet and air cooling systems. In areas where water is valuable, not easily accessible, or conserved, dry cooling systems are used.

3. BINARY CYCLE WITH RECUPERATOR

The binary cycle can be modified with the incorporation of the recuperator. The recuperator is another heat exchanger and represents additional equipment in the binary cycle power plant. The incorporation of a recuperator is shown in Figure 6. The figure shows the position of the components in the cycle. The recuperator increases the temperature of the working fluid at the preheater entry (point 2) and thus leads to the re-injection of the geothermal fluid from the preheater at higher temperature (point S3).

Point S3 is the outlet of the geothermal fluid from the preheater. This point has design temperature limits imposed by the risk of scaling or the requirements of a secondary process.

Figures 7 and 8 show the simulation results for a basic binary cycle and a binary cycle with a recuperator for different reinjection temperatures. This simulation for both cycles was done using Isopentane and n-Pentane as a working fluid with an inlet temperature of the geothermal fluid of 180°C. For the calculations, 221 kg/s of geothermal fluid and a condensing temperature of 40°C as are assumed. The calculation is based on an ideal binary cycle.

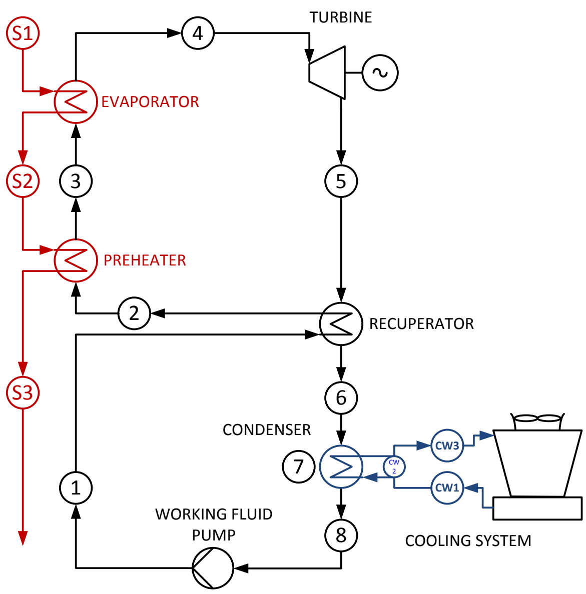

FIGURE 6: Schematic diagram of the binary power cycle with a recuperator

The addition of a recuperator causes no change in the maximum turbine work output of the binary cycle as shown in Figure 7 and 8. The recuperation process does not increase the turbine work output, but the efficiency increases as a result of less input of heat from the geothermal fluid (Valdimarsson, 2011). The addition of a recuperator however, causes shift in the maximum point of turbine work output of the cycle with respect to reinjection temperature.

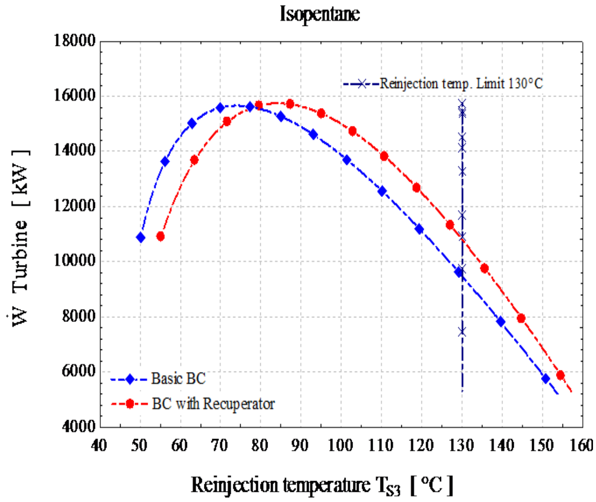

FIGURE 7: Variation of turbine work output with reinjection temperature for Isopentane

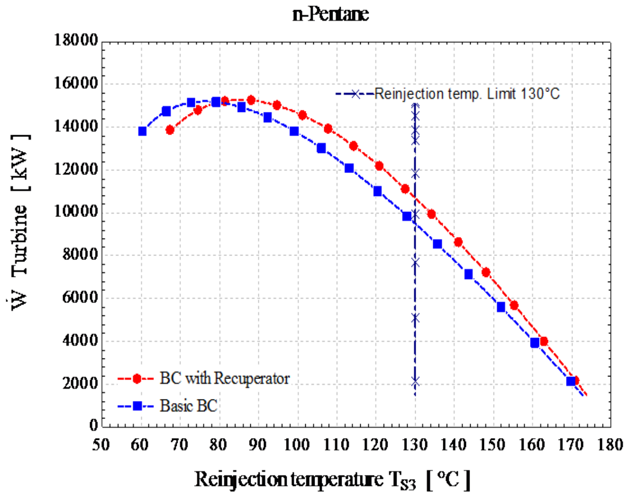

FIGURE 8: Variation of turbine work output with reinjection temperature for n-Pentane

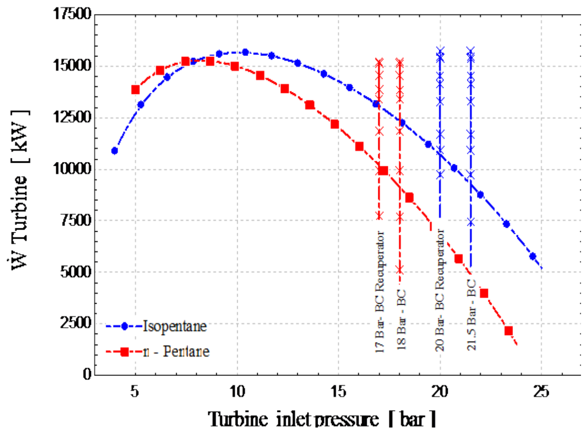

FIGURE 9: Turbine work output against turbine inlet pressure for Isopentane and n-Pentane at same reinjection temperature (T_{53}=130°C)

When the reinjection temperature is limited by the chemistry of the geothermal water, adding a recuperator serves to increase the turbine work output for a given reinjection temperature. Figures 7 and 8 show that the turbine work output is increased by 15% at 130°C reinjection temperature. Figure 9 shows the value of pressure that fits for 130°C when Isopentane and n-Pentane are used in a basic binary cycle and binary cycle with a recuperator.

Figures 10 and 11 show the simulation results of a basic binary cycle and a binary cycle with a recuperator for different turbine inlet temperatures. The simulation uses the same parameters and assumptions as for the previous simulation and at a constant reinjection temperature of 130°C. When the reinjection temperature is constant in both simulations, this condition leads to simulate the same amount of available heat that can be exchanged in the preheater and the evaporator.

The result for these simulations shows that for Isopentane and n-Pentane as working fluids in a binary cycle with a recuperator, the turbine work output increases according to the design inlet pressure for the turbine.

The recuperator will be large and expensive and will cause pressure drops in the system, as well as associated losses. The basic binary cycle will be economical if the geothermal fluid does not have reinjection temperature limits (Valdimarsson, 2011).

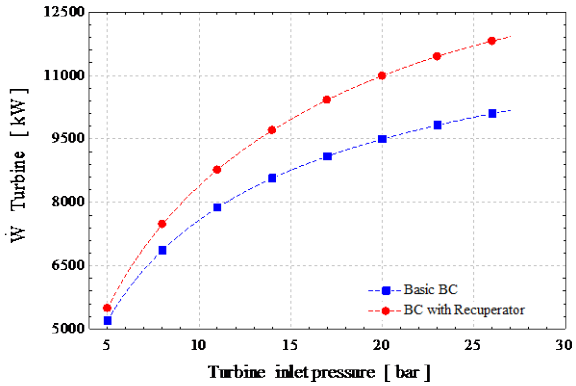

FIGURE 10: Variation of turbine work output with turbine inlet pressure for Isopentane

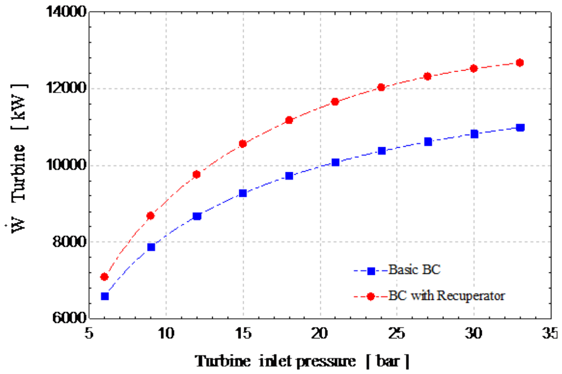

FIGURE 11: Variation of turbine work output with turbine inlet pressure n-Pentane

4. CASE STUDY: BERLÍN BINARY POWER PLANT

The Berlín binary cycle power plant is located at Berlin, Usulután in El Salvador, at wellpad TR-9, and is known as Unit 4. The Berlín geothermal field has four power plant units; the development history is summarized in Table 1. The Berlín binary cycle started its construction in 2005 and was commissioned in 2007. The goals of this binary power plant are to generate electricity based on geothermal energy to supply the demand of the country, increase the efficiency of the Berlín geothermal field and contribute to the local sustainable development. The binary cycle power plant technology is used for first time in El Salvador.

In Berlin, the amount of additional power that could be generated from the separated water in a binary unit depends on how much heat can be removed from the separated water before scaling becomes a problem. The geothermal water from Berlin liquid dominant reservoir has about 1% of total dissolved solid (TDS) with appreciable amounts of calcium and boron (100 to 200 ppm). When the water is separated in cyclone separators at 10 bars and 185°C, the water contains 800 ppm of silica and for this condition, the separated water has a silica saturation index (SSI) of 0.95 %. Additionally, when the separated water is cooled the SSI increases, for example SSI: 1 at 180 °C and SSI: 2.2 at 100°C (at 2.2 silica is oversaturated). A research was conducted to minimize scaling potential in the re-injection system, and the result recommends 130°C as a lowest temperature value, implementing acid dosing to maintain the pH between 5.5 to 6.0 (SKM, 2004).

TABLE 1: Berlin geothermal field development in El Salvador (Guidos and Burgos, 2012)

Phase	Building years	Technology	Units	MWe/Unit
Well head units	1992	Back pressure steam turbine	2	5 * Out of operation
Unit 1 & 2	1999	Condensing steam turbine	2	28
Unit 3	2005	Condensing steam turbine	1	44
Unit 4	2007	Isopentane binary cycle unit	1	9.2

Geothermal wells in the Berlin geothermal field produce two phase fluids, geothermal water and steam. The steam is used to feed the turbines in the power plant and the geothermal water is re-injected in the wells downstream of the production wells and power plant. The binary cycle power plant in Berlín is designed to remove an internal energy from the geothermal water that has a temperature of 180°C to generate electricity. The geothermal water used in this unit comes from wells TR4/5 and TR2/9, where steam is used to generate electricity in Units 1 and 2. The Berlin binary cycle power plant is a good example of a bottoming power plant.

The organic Rankine cycle is utilized to generate electricity and this binary power plant uses Isopentane as its working fluid. The gross power output is 9.2 MWe and its own energy consumption for the circulation pumps, cooling water pumps, cooling tower fans, and other electrical and auxiliary equipment is taken from the same generation. Therefore, the net power production delivered to the grid is 7.8 MWe.

In Berlin binary cycle power plant, the process is divided into three loops. The first loop is the geothermal water circulation, heat resource. The second loop is the working fluid process, and the third loop is the cooling water circulation.

In the first loop of this binary power plant, the heat source is coming from two reinjection systems, one pipeline collects the geothermal water from wells TR-2 and TR-9, and the system is called TR2/9. Another pipeline collects the geothermal water from the wells TR4 and TR5 and the system is called TR4/5. Figure 12 shows the process diagram for the first loop. The system TR4/5 carries 221 kg/s of hot water at 22 bars, while the system TR2/9 carries 79 kg/s at 11 bars. The geothermal water exchanges heat with the working fluid in the preheater and the evaporator. This exchange takes place in both systems and the vapour of the working fluid leaves the evaporators at 22 bars. The geothermal water is then cooled down from 180 to 140°C before being re-injected.

The second loop is the Isopentane process cycle. The amount of working fluid used in Berlin power plant is 123.3 kg/s. Table 2 shows the changes along the loop and the parameters of the working fluid under design conditions.

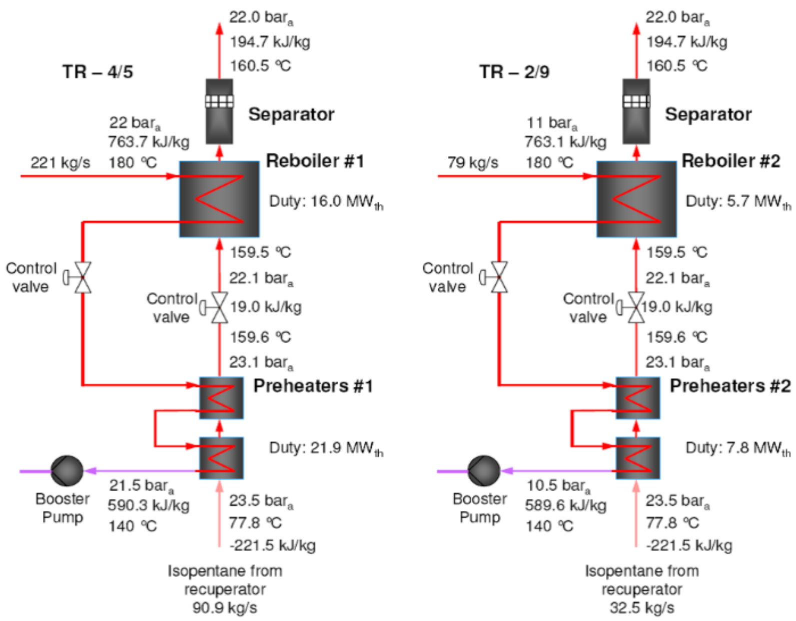

FIGURE 12: Preheaters, evaporators and the first loop process diagram (ENEX, 2007)

The third loop corresponds to the cooling water cycle; the flow of water in this cycle is 1,013 kg/s. In this loop, the water removes the heat from the working fluid through the condenser, which is a shell and tube heat exchanger type. The water interchanges the removed heat with the atmosphere in the cooling tower. A set of pumps is used to circulate the water from the condenser to the cooling tower. Due to evaporation during heat exchange, blow down and drift, constant make-up water is needed. The make-up pumps deliver 20.3 kg/s of condensate water from the pond of condensation units.

In the Berlin binary cycle, the turbine-gearbox-generator is mounted on a structural steel skid. In the turbine, the working fluid expands from the inlet to the outlet pressure in two steps: The first step takes place in the inlet guide vanes (IGV) (variable nozzles) and the final step takes place in the radial wheel or rotor (Figure 13). The turbine converts the kinetic energy into mechanical work, transmitted by the shaft to the generator via a gear box (GE-Energy, 2013). The turbine case is sealed at the shaft by a dry face mechanical seal. Nitrogen and air are injected as a sealing and cooler fluid. The mechanical seal has an internal division in the labyrinth seal, i.e. front labyrinth (working fluid) and back labyrinth (lubrication oil) sides. The nitrogen goes through the front labyrinth side and is mixed with the vapour, to ensure that the working fluid is retained in the turbine. The mix of air and purge nitrogen goes through the back labyrinth side of the mechanical seal and flows toward the vent cavity, so this mix removes any heat generated in the mechanical seal and ensures that the lubrication oil mist does not migrate to the expander process. The gearbox is connected to the turbine through a power shaft and connected to the generator through a low speed coupling. This gearbox reduces the turbine shaft speed from 6490 to 1800 rpm. The generator is a brushless excitation type ABB unit with a horizontally mounted rotor and air to water closed circuit cooling. It produces a current of 13.8 kV and 60 Hz.

TABLE 2: Design condition for the working fluid at each step along the process in the cycle

Working fluid phase change	**Parameters**		
Evaporation	Temperature	159.5	°C
Expansion	Turbine inlet pressure	22	bar
	Turbine outlet pressure	1.85	bar
	Turbine inlet temp.	160.5	°C
	Turbine outlet temp.	92.9	°C
Cooling	Recuperator outlet temp.	52.6	°C
Condensation	Condenser pressure	1.8	bar
	Condenser outlet temp.	44.8	°C
Compression	Pump discharge press.	23.78	bar
	Pump discharge temp.	46.1	°C
Heating in recuperator	Temperature	77.7	°C
Heating in preheater	Temperature	159.5	°C

The heat exchanger in the Berlin binary cycle is used to transfer heat between different fluids. Figure 14 shows the arrangement of all shell and tube heat exchanger in this plant. Basically, the heat exchanger transfers heat from the geothermal water to the working fluid in the preheater and evaporator; between the exhaust vapour and liquid working fluid in the recuperator; and from the working fluid to the cooling water in the condenser. The working fluid in the process flows in the shell side in this equipment.

The cooling tower has the main function to remove the heat from the water used in the condenser. The cooling tower acts as a final heat sink in the process by delivering this heat into the environment. This cooling tower is a counter flow type and has two fans that draw air upward against the flow of water dropping from the top. Operating under design conditions, the tower can handle a flow of up to 4,122 m^3/hr. The water from the condenser to the cooling tower is pumped by centrifugal pumps that are designed as a single stage, double suction and a horizontal split volute type.

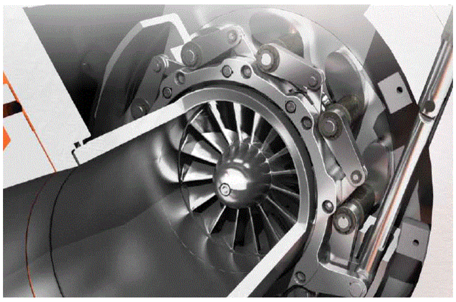

FIGURE 13: Inlet guide vanes (IGV) and radial wheel of turbine (GE-Energy, 2013)

The working fluid pumps are vertical, centrifugal and multistage types. The pumps are equipped with a mechanical seal, with a cartridge design that allows the seal to be changed without having to take the pumps parts. The mechanical seal is flushed by an American Petroleum Institute (API) plan. The API helps to select the type and control for mechanical seal applications. For working fluid pumps in the Berlin binary unit, the temperature at the seal should be maximally 10°C above the pumped working fluid temperature. The working fluid pumps are driven by a three phase electrical motor.

As mentioned above, the mechanical seal used in the turbine casing works with nitrogen in the working fluid side and both fluids exist as a mix in the outlet of the turbine. To remove the non-condensable nitrogen from the working fluid, a nitrogen extraction system is installed in the condenser, where the working fluid liquefies and the nitrogen remains in the gas phase which is ejected to the atmosphere from a gas separator.

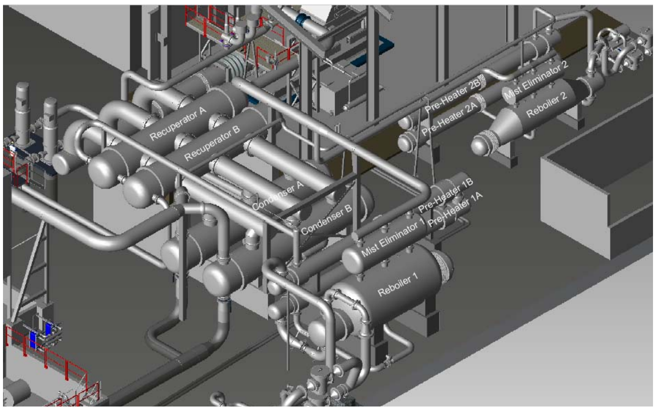

FIGURE 14: Shell and tube heat exchanger in the Berlin binary plant (ENEX, 2007)

The units have auxiliary systems, which allow automatic control and monitoring the Berlin binary cycle. These are the nitrogen generator system, pneumatic, ventilation, fire protection, inhibitor, auxiliary cooling water for generator-gearbox-turbine set, lubrication, instrument and control systems.

The operation is totally automatic, locally and remotely monitored. Figure 15 shows the actual screen for the process that is used by the operator to monitor the cycle. According to the operation manual for the binary unit (ENEX), these units have the following operation procedures: preconditions for start-up, turbine start-up, turbine warm start, normal operation, normal shutdown, turbine trip, and trip of the working fluid cycle. For operation of the Berlin binary plant, there is only one operator in shifts. The operator in shift is responsible for monitoring all the parameters of the unit, fixing troubleshooting and executing start-ups and shutdowns procedures. The operator works in 8 hour shifts.

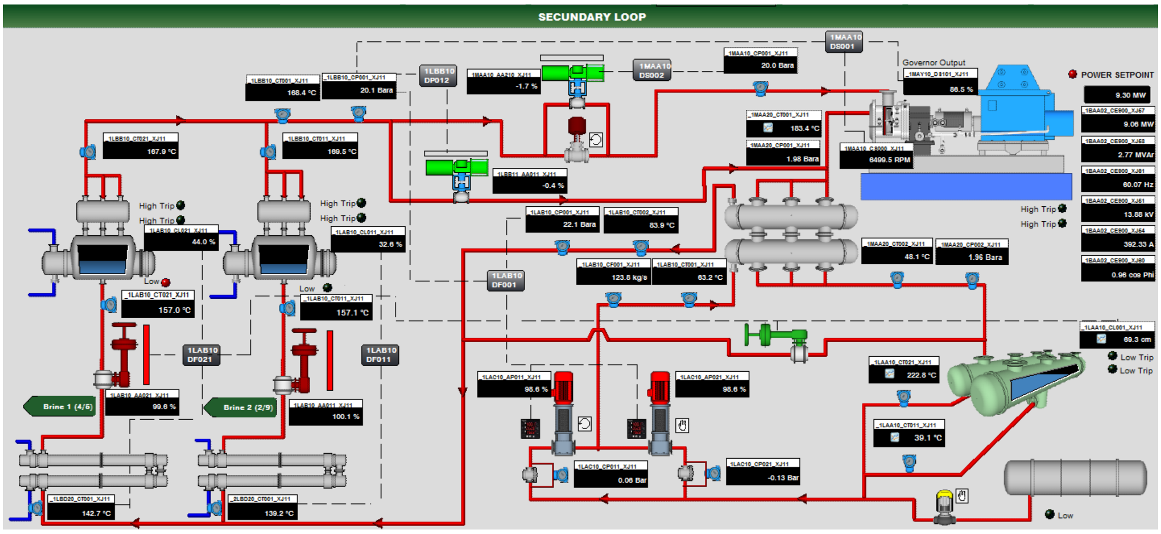

FIGURE 15: Screen of the second loop in the Berlin binary power plant

5. BINARY CYCLE MAINTENANCE WORK AND EXPERIENCES

The maintenance of a binary cycle power plant includes a series of activities carried out on each component of the binary plant in order to ensure its continuous performance. The maintenance of the binary cycle power plants is highly influenced by different factors, such as the nature of the geothermal fluid used in the primary loop, the nature of the working fluid, the technology and location of the plant, climate and weather. In order to operate a binary cycle power plant as a base load unit, a perfect maintenance programme is a challenge to ensure high availability and reliability. Corrosion and scaling are the most common problems in binary power plants.

To develop the maintenance activities, it is required to have a maintenance management programme to help in coordination, control, planning, implementing and monitoring the necessary activities required in each component of the binary plant. There are variety of maintenance programme and methods dealing with the following basic maintenance strategies: corrective, preventive, predictive and proactive maintenance. The best maintenance programme analyses and applies the correct combination strategies for each component of the whole power plant. Also, nowadays software are available that can help manage these activities, like Dynamic Maintenance Management (DMM) used in the Svartsengi power plant and Maximo software used in the Berlin power plant. These software have been designed to manage assets and help to automate all aspects of maintenance. These software have the following common functions: machinery history, preventive maintenance schedules, work orders, condition monitoring, condition based flagging, time accounting, fault reports, safety improvements, expense tracking, procurements, trending and performance reports (DMM, 2013; Projetech, 2013).

In this report, the basic maintenance strategies are summarized, the major mechanical maintenance activities carried on turbine, heat exchangers, pumps and cooling towers of the binary cycle power plants are described. The report also describes certain experiences from Berlin binary cycle power plants during their operation and maintenance.

As mentioned above, the basic maintenance strategies are corrective, preventive, predictive and proactive maintenance. Corrective maintenance strategy proposes to run the machinery until it fails. This strategy seems to be economic because the manpower requirements and their costs are minimal. However, when the machinery fails unexpectedly, it is necessary to schedule manpower at the site in emergency shifts, have a complete stock of spare parts available in a warehouse, and make a contract with a specialist in case of emergency. The shut down time depends on the magnitude of the failure. In addition, an unexpected failure can be an unsafe condition or environment, to personnel and facilities. All these factors need to be considered for a corrective maintenance strategy since failure cannot be predicted and for which the cost will be high.

Preventive maintenance consists of scheduling maintenance activities aimed to prevent failures and breakdowns in the machinery. The main goal of this strategy is to prevent the failure before it occurs. The preventive maintenance activities consists in equipment check, lubrication, oil changes, leaks, tightening of bolts, mechanical adjustments, partial or complete overhauls, etc. At the same time, the operating hours according to the manufacturer’s recommendations are scheduled to change worn parts before they really fail. This strategy has the advantage that during maintenance, the workers can identify if the machinery needs further maintenance, and also they can record the deteriorations in the machinery and suggest a time for the next maintenance. The associated costs for this technique are related to the long availability and service life of the machinery. The strategy helps in controlling the shut down time period of the machinery. The disadvantage of this strategy includes unnecessary maintenance, incidental damage to components and the risk of unexpected failure still prevails. Preventive maintenance includes the predictive strategy maintenance.

Predictive maintenance strategy mainly focuses on measuring the operating conditions of the machinery and evaluates if the machinery is working under certain standard conditions. Logging of measurements is done over time, and strategies are recommended to take corrective measures when the measurements go beyond standard operating limits. This strategy requires new tools, software and specialized technicians to obtain and analyse the data, as well, to predict when the machinery must be repaired. Vibration monitoring condition is the most common technique to monitor operation conditions (for example, the continuous monitoring systems installed on the bearing pedestals on the set turbine-gearbox-generator). However, the vibration technique is limited to monitor mechanical conditions, therefore, other monitoring and diagnostic techniques that can be useful to maintain reliability and efficiency of the machinery include: acoustic analysis, motor analysis technique, thermography, tribology, process parameter monitoring, visual inspections, and other non-destructive testing techniques.

Proactive maintenance focuses its work on reducing the failure recurrence or unexpected failure, determining the root cause of previously occurred failures (Asaye, 2009).

In binary cycle power plants, besides the different maintenance practices that are summarized above, major overhauls are carried out according to the manufacturer's recommendations. The common major overhaul period for a binary cycle power plant is between 40,000 to 48,000 hours. The development of the principal mechanical maintenance activities during the major overhauls of the main equipment, the experiences of maintenance, development in Svartsengi and Berlin binary cycles power plant, are mentioned below:

5.1 Turbine

The turbine is the main component in the binary cycles. For this component, the maintenance activities are as follows:

- Disassembling the turbine wheel and nozzles ring;
- Checking the condition of the turbine wheel and nozzles ring;
- Checking the condition of the turbine mechanical seal, o-rings and bearings;
- Checking and cleaning the oil tank filter and change the oil;
- Checking the gearbox; and
- Performing non-destructive testing, such as liquid penetrant, magnetic particles and ultrasonic.

The objectives during the major overhaul are to look for wear, cracks and damage in the movement parts, furthermore some critical parts should be replaced according to the manufacturer's recommendations.

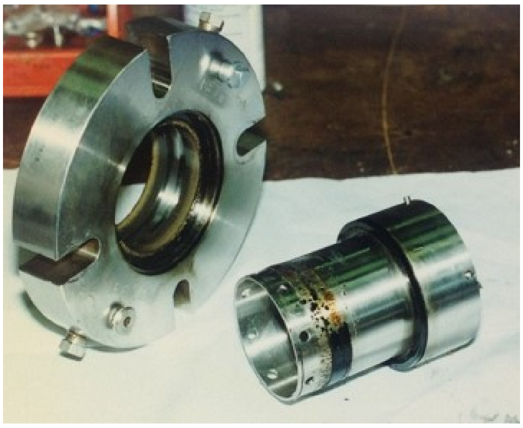

FIGURE 16: Shell and tube heat exchanger in the Berlin binary plant (ENEX, 2007)

Since the start of its operation, the major corrective maintenance activity in the Svartsengi binary power plant, was associated with the mechanical seal. The mechanical seal showed failures in the seal faces caused by the wrong type of lubrication oil. Nowadays, the mechanical seal is working well and the failure is eliminated by lubricating the mechanical seal with high thermal resistance oil. Figure 16 shows the mechanical seal damages.

In the Berlin binary cycle power plant, the mechanical seal is of the dry face seal type and this type of seal has a disadvantage. The disadvantage is the requirement for injection of seal gas during operation and even during shutdown time. This is required to dissipate heat generated by the dry face seal and to avoid contact of the seal faces with the lubricating oil and oil mist on one side and working fluid on the other side. Figure 17 shows the mechanical seal damage. When the mechanical seal is damaged, the amount of seal gas flowing to the working fluid side increases the discharge pressure and decreases the turbine work output, because of the presence of incondensable seal gas flowing in the process.

In the Berlin binary cycle power plant, the nozzle ring of the turbine was changed because of erosion and jamming problem. The change included a new design for the nozzle ring.

5.2 Heat exchangers

The heat exchangers are the components where the geothermal fluid, the working fluid and the cooling fluid interact. The major maintenance work in the heat exchanger is cleaning the heat exchanger area, depending on the process conditions. As it is known, the geothermal fluid flows through the tubes, the major problem found in the heat exchanger is associated with the chemistry of the fluid, i.e. scaling problems. The working fluid side theoretically doesn't require a cleaning process. The cleaning process can be carried out with pressurized water and chemical cleaning. A recommended practice is to run a pressure test to verify the seal of the heat exchanger, to avoid contamination of the working fluid.

FIGURE 17: Mechanical seal contaminated and damaged (The Berlin binary power plant)

In Svartsengi, the geothermal fluid used in the binary power plant is steam, and there have been no major problems. While, in Berlin binary cycle power plant, geothermal water is used in the primary loop, and scaling problems associated with the chemistry of the fluid are present. In Berlin, chemical and pressurized water cleaning process is used during the maintenance work. The pressure test is done in the Berlin binary cycle, to ensure tightness of the heat exchanger. During this test, when leakage is identified in the tubes, they are blocked in order to avoid contamination of the working fluid with the geothermal fluid.

5.3 Working fluid pumps

The working fluid pumps are the component that feed the working fluid in the binary cycles. For this component the maintenances activities are as follows:

- Checking the intermediate bearing sleeves and bushing against wear;
- Checking the shaft and impellers;
- Checking the causing wear ring and the impeller wear ring against any wear;
- Checking the parts against corrosion and erosion;
- Carefully checking the coupling against any wear;
- Checking the bearing cage against any wear;
- Checking the run out of the shaft;
- Checking condition of pump mechanical seal and o-rings;
- Changing oil; and
- Checking the coupling alignment.

In the Svartsengi binary power plant, the major overhaul is carried out for the working fluid pumps after every 40,000 hours and during this work the shaft, sleeves, bushing, wear ring, bearing, mechanical seal, and shaft are replaced. The pump is equipped with a single mechanical seal and the cartridge design allows the mechanical seal to be changed without taking it apart.

In Berlin binary cycle power plant, the working fluid pumps have the same overhaul schedule as in Svartsengi. The mechanical seal in Berlin binary cycle power plants has been changed from single to double seal type. The advantage of the double mechanical seal is that it eliminates leakage of working fluid into the atmosphere and the working fluid losses are eliminated during a failure of the seal. The cartridge design allows changing the mechanical seal without taking it apart.

5.4 Cooling systems

The main function of cooling systems is to condense the working fluid and dissipate the removed heat to the environment. The condensers in Svartsengi are water and air coolers and the maintenance activity is to clean the heat exchanger areas and check the seal in the system. In the Svartsengi power plant, the air cooled condensers have a leakage, which is stopped by installing a short sleeve inside each tube at the end of the header box. These sleeves are installed using hydraulic tube expansion technology. The sleeves are expanded for tight contact with the parent tube in the header box. Figure 18 shows the air condenser, the leakage zone and the sleeves that are used to seal the condenser.

FIGURE 18: Air condensers and the leakage zone

The Berlin binary cycle has a wet cooling system, and the mechanical maintenance work is carried out on the circulating water pumps, gear box and fans. For these components, the maintenance activities are as follows:

- Checking the intermediate bearing and bushing against wear;
- Checking the shaft and impellers;
- Checking the parts against corrosion and erosion;
- Carefully checking the coupling against any wear;
- Checking condition of pump mechanical seal and o-rings;
- Checking the coupling alignment;
- Checking the gears against any wear;
- Checking the fan blades; and
- Changing the gearbox oil.

In the Berlin binary cycle power plant, the circulation water pumps were changed, after corrosion problems were found. The construction material of these pumps was changed from cast iron to stainless steel, and also the material of the stuffing box was changed to a mechanical seal. The corrosion was caused by the chemistry of the condenser water which was used as the cooling fluid.

REFERENCES

Asaye, A.M., 2009: *Evaluation of maintenance management through benchmarking in geothermal power plants.* University of Iceland, MSc thesis, UNU-GTP, Iceland, report 3, 60 pp.

Bertani, R., 2012: Geothermal power generation in the world 2005 – 2010 update report. *Geothermics, 41,* 1-29.

DiPippo, R., 2007: *Geothermal power plants: Principles, applications, case studies and environmental impact* (2nd edition). Butterworth Heineman, Elsevier, Kidlington, UK, 493 pp.

DMM, 2013: *DMM Software.* Dynamic Maintenance Management. Website: www.dmm.is

ENEX, 2007: *Binary plant Berlin, operation and instruction manual*. ENEX, manual prepared for LaGeo S.A. de C.V.

GE-Energy, 2013: *Turboexpander-generators. Products & Services – Turboexpander.* General Electrics Energy. Website: www.ge-energy.com.

Guidos, J., and Burgos, J., 2012: Geothermal activity and development in El Salvador – Producing and developing. *Presented at "Short Course on Geothermal Development and Geothermal Wells", LaGeo, Santa Tecla, El Salvador*, 12 pp. Website: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-14-07.pdf

Lund, J.W., 2004: 100 years of geothermal power production. *GHC Bulletin, 25-3*, 11-19. Web: http://geoheat.oit.edu/bulletin/bull25-3/art2.pdf

Projetech, 2013: *Maximo asset management by IBM.* Website: www.projetech.com

Valdimarsson, P., 2011: Geothermal power plant cycles and main components. *Paper presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador*, 24 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-12-35.pdf

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

GEOTHERMAL ENERGY: CURRENT SITUATION IN COSTA RICA

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ABSTRACT

The Instituto Costarricense de Electricidad (ICE) leverages commercial high enthalpy geothermal resources for power generation with a total installed capacity of 204 MWe; distributed from the Miravalles Geothermal Field, consisting of three flash technology plants, a backpressure unit and a bottoming binary technology; and the Las Pailas Geothermal Field unit I, using mixed cycle binary technology. Both fields are equivalent to 7% of the total power capacity installed in Costa Rica and generate nearly 15% of the total energy produced in the national electric system.

In addition, Las Pailas Geothermal Field unit II that is in the development phase with a projected capacity of 55 MWe and the Borinquen Geothermal Field that is in the feasibility phase with a 110 MWe generation capacity.

ICE works with two plants that use binary technology which gives us the experience needed for the eventual use of medium and low enthalpy. At moment the low enthalpy is exploited for the purposes of eco-tourism.

1. INTRODUCTION

Costa Rica has significant unexploited resources for power generation, however, the national electrical sector has a matrix where more than 90% of production comes from alternative energy: hydroelectric, geothermal and wind.

The renewable source support the thermal generation when it suffers due to climate variations and changes. The strategy aims to intensify the use of alternative energies diversifying the matrix and reducing the use of fossil fuels, which involve higher costs and increase the environmental impact (Mainieri, 2010).

In Figure 1, it is observed that geothermal energy represents 7% of the total installed capacity and 15% generated; staying as the second most important source of electricity generation.

2. HIGH, MEDIUM AND LOW ENTHALPY GEOTHERMAL RESOURCES IN COSTA RICA

The important conditions for high enthalpy resources in the country allow the geothermal exploitation to focus on these types of deposits, using plants with flash technologies and binary systems. The

Miravalles Geothermal Fields and Las Pailas I are in the production stage, Las Pailas II is in the development stage and Borinquen is in the feasibility phase. Figure 2 shows the general geothermal zoning determined from superficial explorations and projections.

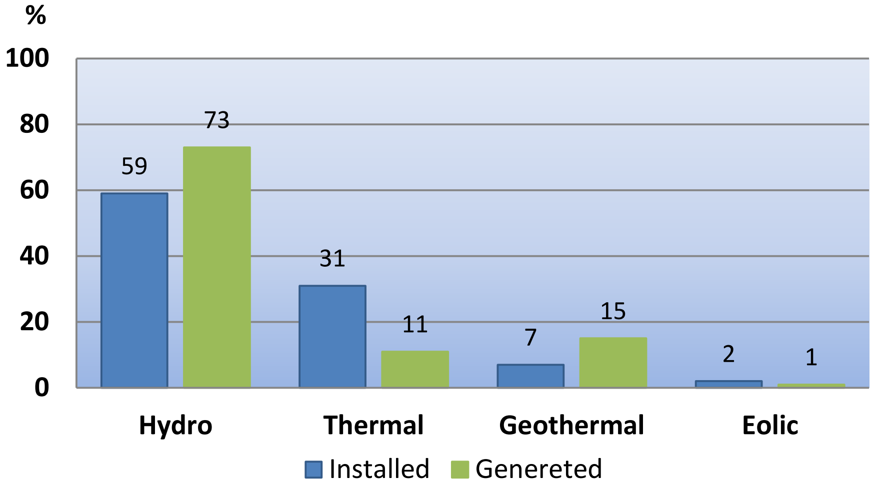

FIGURE 1: Average installed electrical capacity vs. generated in Costa Rica, data collected from Instituto Costarricense de Electricidad, 2013.

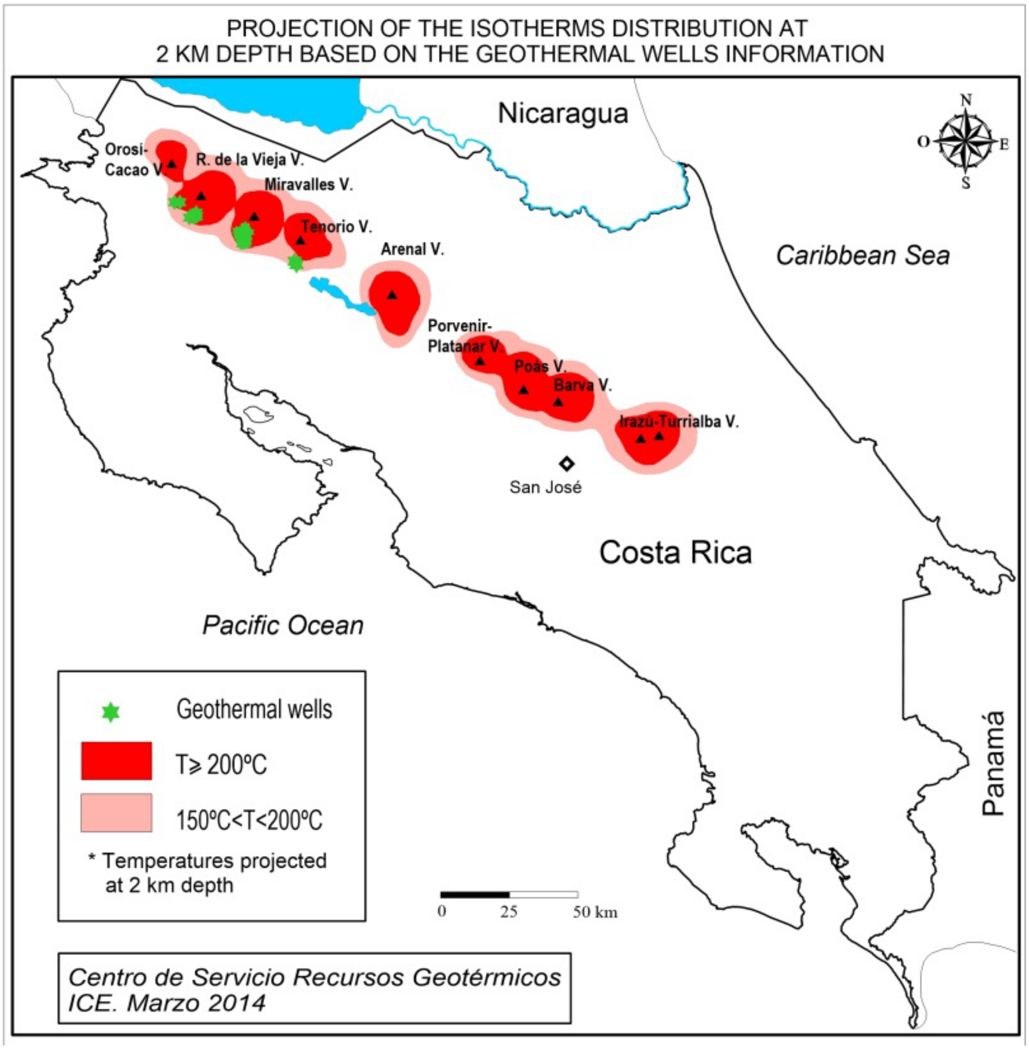

FIGURE 2: Geothermal zoning and sites of interest in Costa Rica

In the areas of exploitation aquifers have been found with temperatures between 150–180°C and even lower, however they are isolated to prevent thermal contamination toward aquifers with higher temperatures. Studies have not been done to estimate the value of the exploitation of these due to the focus on power generation from high enthalpy resources, because it needs less infrastructure and lower costs.

Although there is no exploitation of medium enthalpy there are 2 plants that work with binary technology which gives us the experience to know the characteristics of the process if it is implemented in the future. Currently, low enthalpy is used in the development of thermal pools in different areas of the country, benefiting from the growth of ecotourism.

3. MIRAVALLES GEOTERMAL FIELD (MGF)

Located in the southern flank of the Miravalles volcano, this field came into operation with the first unit in 1994 and the last in 2003. It is composed of five units with a total installed capacity that reaches 162 MWe distributed in the following form: unit I and II with 55 MWe each, unit III 29 MWe, unit V 18 MWe and the backpressure unit is 5 MWe.

The reservoir has a liquid dominance with an average temperature of 240°C, enthalpy between 980 and 1150 kJ/kg (Vargas, 2013a), and is divided according to the chemistry of fluids: pH neutral, acidic-sulfated and neutral-bicarbonated (Mainieri, 2010).

In total 56 wells have been drilled: 30 for production, 11 for injection and 15 for monitoring (Castro and Chavarría, 2014). Of the production wells, 26 generate fluids with a neutral pH and the remaining 4 with an acidic pH (Figure 3). This field is unique in the world in that it produces electricity using acidic wells, which is a great achievement for the country because of the high cost invested in its drilling.

The plan is to increase the installed capacity of MGF by 2016 with deep wells to the east and southeast sectors of the field.

3.1 Units I, II and III

Unit I came into operation in March 1994, and was the first plant installed by ICE and Unit II was started in August 1998. These use flash technology, and each have a generation capacity of 55 MWe. However, its design allows working with an overload, so the real generation is 60 MWe.

The units require about 420 tons of steam per hour for normal operation. The production wells feed the satellites with biphasic fluid that have the function to separate the steam from the liquid, supplying steam to the plant and sending liquid to the injection wells.

The construction of Unit II was designed to be interconnected with Unit I, while the steam to be used by both units arrives at independent collectors, which in turn are interconnected to each other. The operation of the Unit III began in 2000, a new separation unit was built for it and is independent of the other two units. By 2014 these units will be implemented in a non-condensable gas extraction system to make better use of wells with significant gas content.

3.2 Unit V

This unit is the first binary cycle plant installed. The system of production in this type of plant consists of a cycle of heat exchange. Using residual geothermal fluid that comes out of units I, II and III with a temperature of about 160°C, this is known as a bottoming binary process. Before being reinjected, it is passed through heat exchangers, which in turn evaporate pentane that drives the turbine. The outgoing fluid heat exchangers is at a temperature of approximately 130°C, and continues its path to the wells for reinjection. The use of pentane has as the benefit of cleaning the turbine, moving impurities which can be stored.

The design of the plant is environmentally friendly in that it does not have atmospheric emissions except water vapor and CO_2 coming from the cooling towers, and only a small loss of pentane (about 0.0001% of the circulation flow rate), (Moya and DiPippo, 2006).

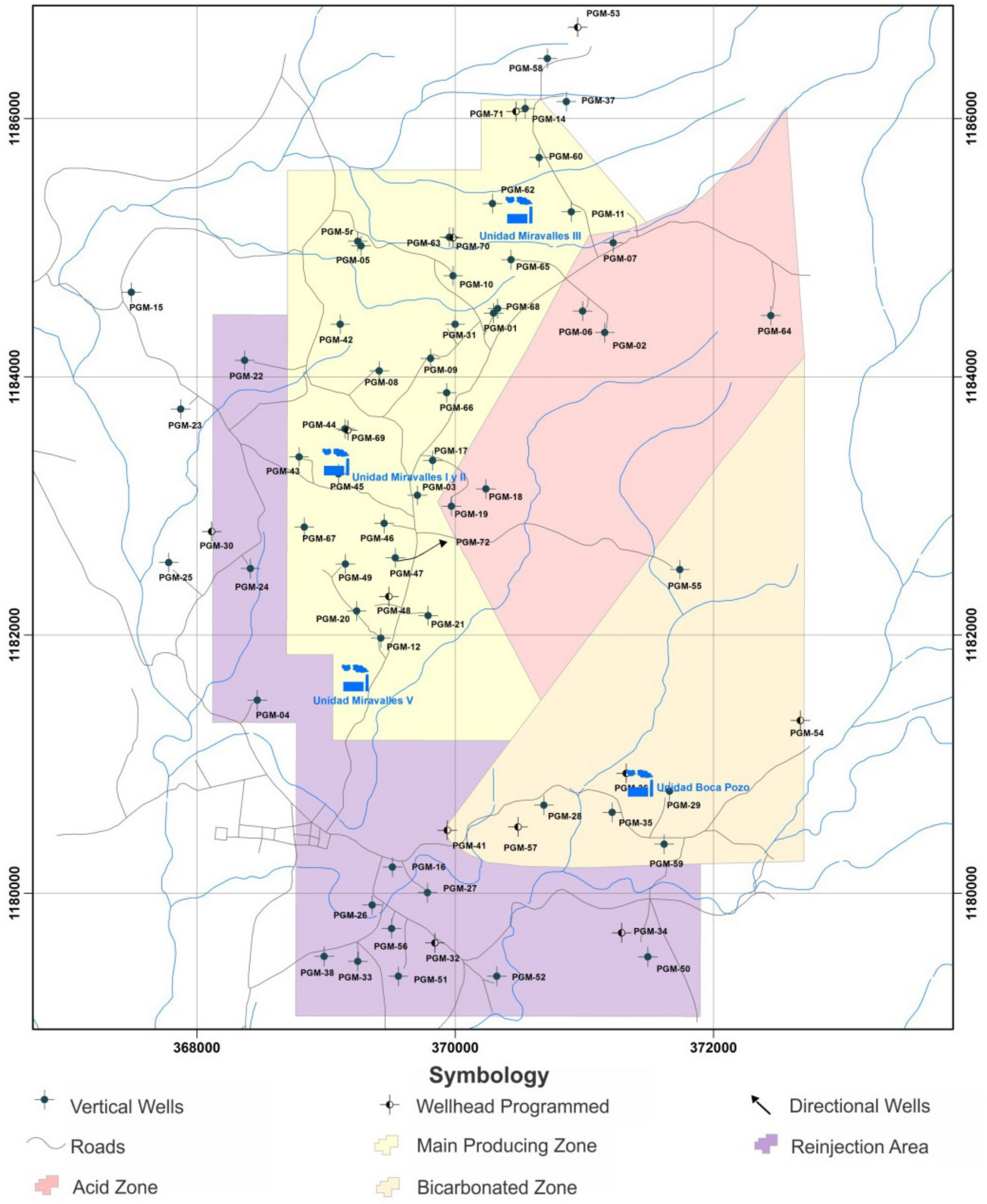

FIGURE 3: Location of wells and chemical zoning within Miravalles Geothermal Field

The bottoming cycle involves some limitations in the operations and logistics of reinjection in the entire Miravalles field, because if the temperature of the output fluid is less than 130°C it would result in greater cooling in the reservoir, which should be compensated for with reinjection in far away places, resulting in a decrease in the pressure of the system.

3.3 Backpressure unit

In November 1994, a backpressure unit was also installed which is fed by a single well (PGM-29) and provided with a single separator with automated control. The PGM-29 presents different conditions from the rest of the geothermal reservoir; the non-condensable gases are higher than the average value in the rest of the field.

4. LAS PAILAS GEOTHERMAL FIELD (LPGF)

4.1 Unit 1

LPGF is located on the southern flank of the volcano Rincon de la Vieja. It is a binary power plant that came into operation in July 2011. It generates 42 MWe and provides 36 MWe to the system. The production system, like Miravalles Unit V, operates with a cycle of heat exchange with pentane as the working gas, however this plant has a higher generation capacity. It directly uses two-phase fluid with a total mass flow of 460 kg/s from the production wells (Moya and DiPippo, 2012). Before entering into the plant, the fluid is separated into brine and steam with a flow of 350 kg/s and 88 kg/s respectively to a temperature of 159°C and 6 bar absolute. The brine passes to the pentane preheater and the steam is directed to the heat exchanger to evaporate the pentane. After the process, the liquid is reinjected at a temperature of 140°C and the outgoing vapor is condensed at 45°C.

LPGF is not visually invasive because of its proximity to the Rincon de la Vieja National Park, its design is environmentally friendly, with no emissions except water vapor and CO_2, outgoing from the cooling towers and only a small loss of pentane.

The binary-type power cycle for high temperatures implies some limitations, since it requires use of the energy generated in its consumption. For Las Pailas this corresponds to approximately 6 MWe (14%), which is used in: the transfer of pentane, cooling towers and injection pumps. Additionally, the brine reinjection creates complications causing more wear on the mechanical pump seals.

Currently there are a total of 16 wells in this field: nine to production, five of injection and seven of monitoring. The aquifers in the area have a composition sodium-chlorinated of neutral pH, high salinity and low gases; average temperatures of 250°C and enthalpies between 979-1295 kJ/ kg (Vargas, 2013b).

4.2 Unit 2

Unit 2 is located on the south-southeast of Rincon de la Vieja volcano flanks, east of Las Pailas I. This unit will use flash steam technology and is projected to generate 55 MWe. The production stage for this unit is planned for 2018.

At the moment, there are four production wells and one injection well, this year the drilling of production and injection wells continues. Aquifers in the area have a composition of neutral sodium-chlorinated, high salinity and low gases similar at Las Pailas I and temperatures ranging from 215-255°C (Figure 4).

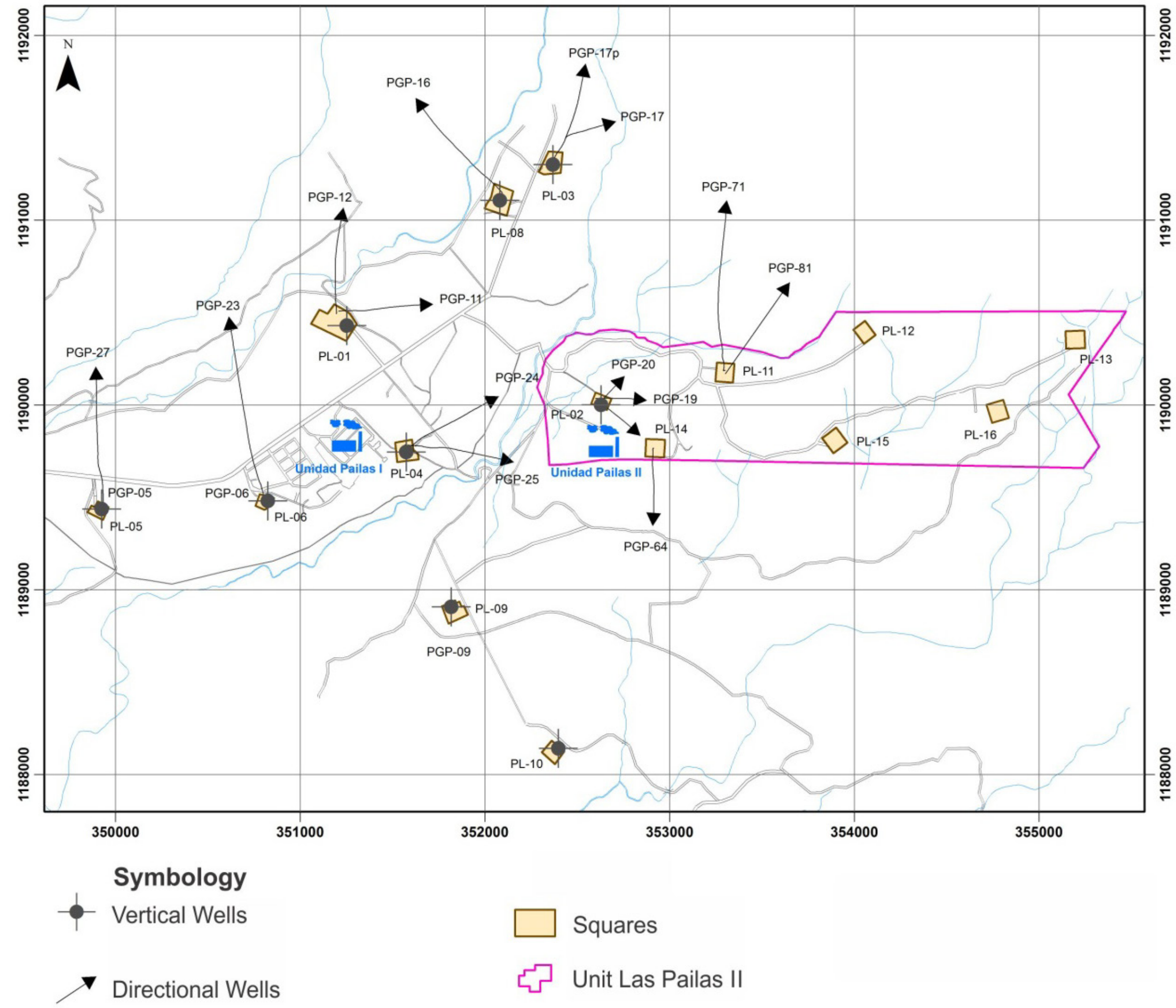

FIGURE 4: Location of wells for units I and II, Las Pailas Geothermal Field

5. BORINQUEN GEOTHERMAL FIELD (BGF)

BGF is located on the southwestern flank of the Rincon de la Vieja volcano. This field has a projection of 110 MWe total power generation and its development stage is planned for 2018.

4 wells have been perforated: three for production and one for injection. These wells are currently used for monitoring the thermohydraulic conditions and possible production. There are also studies on the distribution of the thermal anomaly, its relation to the structural patterns and fluid motion. The aquifers present high salinity, composition sodium-chlorinated, neutral pH, with a low gases and temperatures ranging between 230–240°C (Arias, 2014).

6. OTHER EXPLORATIONS

At present the C.S.R.G is developing the following geothermal exploration work:

Arenal-Poco Sol: The sector of interest is located 12 km south of the Arenal volcano, and is called the Poco Sol sector and is located in the margins of the Peñas Blancas river. For this area, reconnaissance was carried out in the beginning of 2011 covering an area of 690 km^2, with much of the area studied by means of remote sensing. Due to the favorable geological characteristics present in the sector it is now in an advanced pre-feasibility phase, for which a geochemical study was performed, geological-structural mapping, recommendation of sites for perforating geothermal gradient wells and geophysical surveys (Rodríguez, 2002).

North of the Rincón de la Vieja volcano: In the beginning of 2009 the study of geothermal recognition (covering an area of 130 $km^{2)}$ was concluded, including surface geological features and geochemical surveys of thermal and cold creeks.

North of the Tenorio volcano: This area has been in the recognition stage since 2008 by geochemical sampling of emerging springs.

REFERENCES

Arias, J., 2014: Informe Geoquímico de la prueba de producción del PGB-05. Informe técnico interno del Equipo de Geoquímica, Geociencias - C.S.R.G, UEN-PySA, ICE, 4 pp.

Castro, S., and Chavarria, L., 2014: Informe de la evolución de los parámetros termo-hidraúlicos y geoquímicos de los pozos de Miravalles durante el período 1994-2013. Informe interno - C.S.R.G, UEN-PySA, ICE, 56 pp.

Instituto Costarricense de Electricidad, 2013: Generación y Demanda. Informe Anual - Centro Nacional de Control y Energía, 22 pp.

Mainieri, A., 2010: Costa Rica country update report. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 6 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0115.pdf

Moya, P., and DiPippo, R., 2006: Miravalles Unit 5: Planning and design. *GRC Transactions, 30*, 761-766. Web: http://pubs.geothermal-library.org/lib/grc/1025126.pdf

Moya, P., and DiPippo, R., 2012: Las Pailas 35 MW (net) binary power plant, Rincón de la Vieja, Guanacaste, Costa Rica. *GRC Transactions, 36*, 1155-1164. Web: http://pubs.geothermal-library.org/ lib/grc/1030378.pdf

Rodríguez, A., 2002: Informe del levantamiento geoquímico del área geotérmica Poco Sol. Informe interno - C.S.R.G, UEN-PySA, ICE, 22 pp.

Vargas, A., 2013a: Informe de avance de producción del pozo PGM-11. Informe técnico interno del Equipo de Estudios Termohidráulicos, Geociencias - C.S.R.G, UEN-PySA, ICE, 6 pp.

Vargas, A., 2013b: Informe preliminar de producción del pozo PGP-12. Informe técnico interno del Equipo de Estudios Termohidráulicos, Geociencias - C.S.R.G, UEN-PySA, ICE, 7 pp.

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GEOTHERMAL TRAINING PROGRAMME

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EXPERIENCE WITH LOW ENTHALPY GEOTHERMAL PROJECTS IN MEXICO

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ABSTRACT

In Mexico, Comision Federal de Electricidad (CFE) has identified several low enthalpy sites related with thermal water, at shallow depths. Some of those geothermal prospects are located far away from the electrical national grid. In some cases, the population solves their electricity needs by internal combustion engines with a very high operating cost, but there is the possibility of using those low enthalpy sites for rural electrification. By the other hand, there is a high potential of energy recovery from the brine or separated water in the back pressure and condensation units already installed in the four geothermal fields in operation in Mexico. CFE has developed some projects oriented to use both, the energy contained in the thermal waters with off-grid binary cycle power plants and also using the residual brine in the existing geothermal fields to increase the contribution to the distribution network. In this paper, the experiences acquired installing and operating four binary plants of 300 kW each is presented as well as the experience taken from two 1.5 MW air-cooled binary plants using the residual brine from Los Azufres wells.

1. INTRODUCTION

Mexico has numerous low temperature resources around the country. In many states it is possible to find thermal waters used for touristic purposes.

Most of those low temperature resources are related to the Mexican Volcanic Belt and to the tectonic activity in the Baja California Peninsula. Also, in some cases these resources are located in isolated places where it is possible to use them to produce electricity on a very low scale with binary cycle power plants. The acquisition of four binary power plants of 300 kW each, corresponds to a pilot project to test the binary cycle technology in remote sites taking advantage of the hot water as an energy source.

To take advantage of low temperature water it is necessary to drill shallow wells, with the advantage of lower cost compare with those in a depth resource The capacity of the power plants could be as low as around 100 to 300 kW. This is the size of energy units needed by these remote communities.

Also CFE identified possible energy recovery from the brine or separated water in back pressure and condensation units already installed making an improvement to increase the installed capacity and make the most of the energy obtained from geothermal steam, this is the case of the 1.5 MW units at Los Azufres.

Binary cycle power plants are a proven technology worldwide to generate electricity from the geothermal brine or separated water. Most of the binary projects are related to low or moderate enthalpy. In Mexico, these plants were used temporarily as pilot projects in order to promote their application in subsequent projects (Figure 1) and also as a demonstration of their feasibility for rural electrification in remote areas away from distribution network. On the basis of experimental, the 300kW units were not part of the national electricity generation system and did not affect the program and development of this sector, differently from the 1.5 MW that were integrate to Los Azufres grid.

The characteristics of this type of projects are as follow.

- High Availability factor;
- High load factor;
- Non polluting units; and
- High reliability.

FIGURE 1: Binary cycle power plant locations as demonstrative projects in Mexico

2. GEOTHERMAL BINARY CYCLE PLANTS 300 KW

In the year 1998 CFE acquired four binary cycle power plants with capacity of 300 kW each to the company ORMAT, having the aim of exploring the generation on a small scale in rural or isolated areas where it is present thermal manifestations.

Seven sites were explored with thermal manifestations presenting attractive conditions for the installation of these pilot plants, performing perforations between 200m and 700 m deep. But the only one site that presents favourable conditions for the installation of these units was Maguarichic, Chihuahua.

Therefore, due to the budgetary and environmental constraints, it was decided to move three of the four units to the geothermal fields of Cerro Prieto, Las Tres Virgenes and Los Humeros in order to continue testing binary cycle power plants with geothermal brine (González, 2008).

The units were installed with the following objectives:

- Cerro Prieto: the unit was installed in order to experiment with the injection of scale inhibitors for the brine and see the results in the heat exchangers looking to tap a larger scale project using the residual energy. Finally were tested and injected several types of scale inhibitors without achieving considerably that reduces the inlay exchangers.

- Las Tres Virgenes: the unit was fed with geothermal brine produced by the LV-1 well supplying electric power to the pumping station for two years (2000-2002) the generation had to be suspended due to the production decline of mentioned well.

- Los Humeros: the unit was installed in the field in order to take advantage of the residual energy of the brine produced by the H-1 well and test a pond that would act as a cooling tower. Due to production decline in the production of brine from the mentioned well and the presence of leaks in the pond, lead to the suspension of the test.

- Maguarichic, Chihuahua: Pilot for rural electrification.

In this paper it is discussed particularly the Maguarichic project, due to the fact that it was the only off-grid binary cycle power plant used to community electrification and also was the one with the most extended operation.

2.1 Maguarichic project

The Maguarichic geothermal zone is located 11.5 km south westerly from Cuauhtemoc, Chihuahua. It is possible to reach the zone taking the highway Chihuahua-San Juanito and then driving by the secondary road San Juanito-Maguarichic. The zone is located in the Sierra Madre Occidental, in the area known as Sierra Tarahumara.

The geothermal manifestations in Maguarichic are constituted by superficial hot springs and some fumaroles which temperatures ranging from 60°C to 90°C. This zone is 5 miles away from Maguarichic Village. Maguarichic was at that time a small village of around 380 inhabitants.

Before the project that community was supplied with electrical power by a diesel generator that runs approximately 4 to 5 hours/day, mainly because of the fuel high cost. The rest of the time the community lacks of electrical energy supply.

2.1.1 General description of the project

In this zone, the project can be divided into three main parts:

- Drilling the production and injection wells;
- Manufacturing of generation power units; and
- Installation of the Generation unit.

2.1.2 Wells for water supply

The idea of electricity generation using low temperature water involves finding geothermal production of a maximum depth to 500 m, to reduce the well cost. Therefore, after geological, geochemical and geophysical surveys, CFE decided to drill a slim hole into the geothermal reservoir. Well PL-1 was drilled using a self-contained rig, finishing a 3.5" diameter hole to a depth of 49 m. The well produced water at 120°C. With this information and temperature and pressure logs, CFE decided to drill a second well, with a 9 5/8" casing to 35 m and slotted liner to 300 m. Well PL-2's target was to gain even higher temperature and more production. PL-2 well did not offer higher temperature than the measured in the PL-1 well, but produced 35 tons per hour (t/h) of hot water. With this positive result, CFE decided to install one of its small ORMAT geothermal power plants near the village of Maguarichic, at a total cost of approximately $1.3 million (US). Federal, state and municipal funds financed the project, and the community provided in kind services (Sánchez-Velasco et al., 2003).

The requirement of water to operate the pilot binary unit in full load ranges approximately from 70 to 100 tons/hour. Due to the pressure and temperature conditions of shallower well drilled to supply the mentioned flow rate, it was necessary to install down hole pumps of 8" diameter.

For this project two wells were drilled but only PL-2 well, were used to supply water to the pilot binary cycle power plant.

2.1.3 Power unit

As mentioned before, the units were binary cycle, with a capacity of 300 kW using geothermal water at temperatures from 120°C to 170°C. This unit were going to operate without connection to any electrical system, so they had to be able to follow load variations in an automatically way. They need to do that rapidly, to assure a high quality of electrical service for the Maguarichic community.

The units were conceived as a modular type. All its parts, like the preheater, evaporator, turbine generator, lubrication system and control system are located on a platform with approximate dimensions of 3m x 8m. The condenser and the organic fluid storage tank integrate, the second module installed above the powerhouse.

The turbo generator will operate with an organic fluid (isopentane) and has to be equipped with all necessary systems to operate in a continuous and safe way. Starting, operation and stopping mode had to be automatic.

To control load variation it was necessary to have a regulatory system integrated by:

A by-pass system totally automatic to divert the organic fluid to the condenser, before passing through the turbine, to assure the control of load variation.

- The preheater and evaporator of tube type, was built in a single piece;
- The cooling system was closed type with condenser cooled by air and water; and
- Units sent energy at 480 Volts to an elevating substation, where voltage had to be increased to 34.5 kV and to 23 kV.

2.1.4 Unit installation

Because these binary power units were designed in a modular configuration, their construction and installation required a minimum of time, a period of 2 months was taken for the construction in a factory and 1 month for installation.

Maguarichic unit was operating and supplying electric power to the community from 2001 to early 2008 (7 years) since was installed.

3. GEOTHERMAL BINARY CYCLE PLANTS 1.5 MW

Back in 1997, CFE due to an agreement between the Energy Ministers of Israel and Mexico, decided to buy two units of 1.5 MW each to gain experience using this technology, it was decided to install them in Los Azufres to exploit low enthalpy water wells.

After some problems at the initial start-up of the plans, a lot of experiences were obtained in 17 years of operation, showing that binary cycle power plants are technically and economically viable in Mexico.

Binary cycle plants in the Los Azufres geothermal field are known as unit 11 and unit 12.

3.1 General description of the project

Two 1.5 MW ORMAT Energy Converter (OEC) units were installed in two separate locations in Los Azufres Geothermal Field, at an altitude of 9,500 ft (2,900 m above sea level).

The goals for the installation of this power plant were the use of otherwise wasted geothermal brine.
In this zone, the project can be divided into two main parts:

- Manufacturing of generation power units
- Generation unit installation.

3.1.1 Power units

Generally, the production of the geothermal wells at Los Azufres consists of liquid and a mix of steam and gas. This two phase flow is led from the wellhead to a flash separator which separates the liquid (brine) from the saturated steam and the non-condensable gases (NCG). The steam flows from the separator to the existing steam turbine.

The brine flows from the separator to the OEC vaporizer where it heats and evaporates the organic fluid and from the vaporizer to the preheater. The exhausted brine was discharged from the outlet of the preheater through a discharge line directed to a silencer.

The brine has an inlet temperature of 347°F (175°C) and a flow of 517 gpm (141,000 kg/hr) for each of the two locations.

The organic working fluid (isopentane) is fed from the vaporizer to the turbines. After expanding in the turbine, it flowed to the air-cooled condenser and from there via a feed pump back to the preheater.

Each binary module generates 1.5 MW gross, 0.25 MW is used for condenser cooling fans and pentane pump.

To generate 1.5 MW is required 155 t/h of hot water at 175 °C which is cooled to 110 ° C in the heat exchanger.

3.1.2 Unit Installation

The binary cycle power plants were supplied by ORMAT but owned by CFE. All power plant engineering and construction, including installation, well pumping and electrical connections were locally designed and executed by CFE and other Mexican companies.

The first unit was installed next to the back pressure unit 10 of 5MW, to take advantage of the separated water from this unit (160 t/h) while the steam was used in it. The electrical energy from the binary cycle went to the same transformer of the 5 MW unit.

The second unit was installed in the AZ-22 well to get 120 t/h combined with 30 t/h more which produces well AZ-55, the purpose of this binary cycle plant was to test as an independent unit with its own substation.

Those units were commissioned in 1992 and were uninstalling in 2009 (17 years) due to several problems, one of them was that the binary cycle power plant was connected to the system of steam duct of a 50MW condensing unit, when the binary cycle stopped for any problems losses of pressure in the separator and the steam of the principal steam line was discharged by the water line of this highly affected the generation of the condensing unit *(*Gerencia de Proyectos Geotermoeléctricos, 2009*)*.

By the other hand, recurring problems arose with the seal of the turbine unit binary cycle and it was not possible to get support from the manufacturer for repair so the units had to be out of operation for long periods increasing operating costs thereof, which exceeded the benefits to generate electric power with those units (Gerencia de Proyectos Geotermoeléctricos, 2009).

4. NEW PROJECT

Derived from the results of the units at Los Azufres and taking into account the large residual brine separated from the steam of the production wells at Las Tres Virgenes geothermal field, a 1.7 MW binary cycle project is intended to be installing. As mentioned the project is located in Las Tres Virgenes geothermal field, located in the northern part of Baja California Sur State, 32 km northwest of the town of Santa Rosalia, at an elevation of about 720 meters above sea level (Figure 2).

Binary cycle project aims to take advantage of the energy of the separated brine produced by four geothermal wells dedicated to provide steam to the condensing units in operation at this geothermal field, The aim of this project is to contribute to the demand for electricity in the Santa Rosalia system, increasing the share of clean electrical energy and reducing the environmental impact of the energy sector.

The specific objectives are:

- Installing a binary cycle power plant of 1.7 MW net capacity, to increase the installed capacity at Las Tres Virgenes geothermal field; and
- Leverage the residual energy contained in the waste water (brine).

With this project, the system will have a net increase in the capacity of 1.7 MW, without requiring new wells, which represents a technical and economical way of improving the energy efficiency in this isolated system of Mexico.

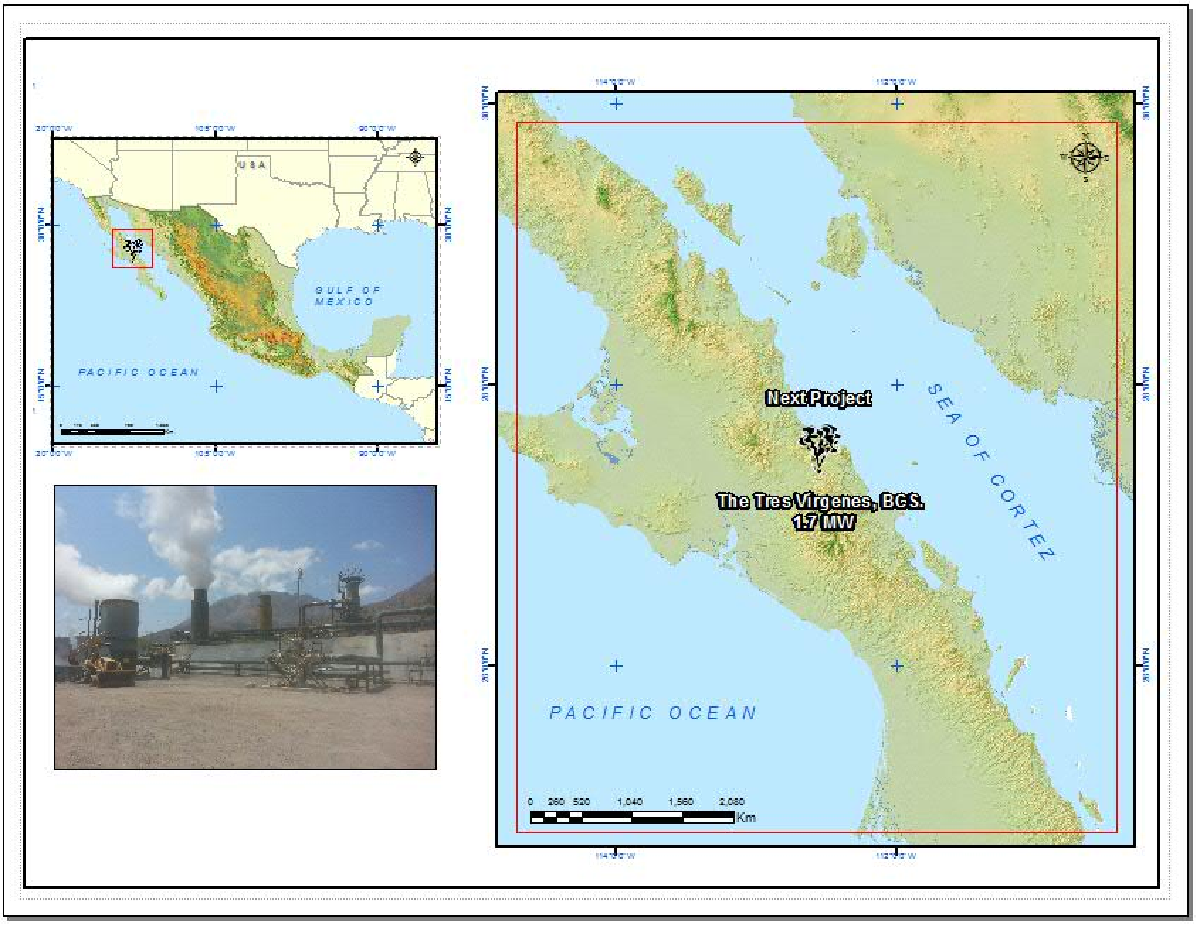

FIGURE2: Localization of the 1.7 MW binary cycle project at Las Tres Virgenes

4. CONCLUSIONS

There are in Mexico several zones with superficial temperatures between 26°C and 90°C in which small binary cycle power plants can be installed, to supply electricity for small and isolated communities. In many of those geothermal zones, the CFE has done geological and geochemical pre-feasibility studies. Results show that it is possible to find low temperature resources at shallow depths (maximum of 500m).

The first projects of this type were conducted by CFE in an isolated zone at the Northern State of Chihuahua: Maguarichic with an impact in the community increasing the productivity and lifestyle of this people.

A large amount of geothermal energy is available from low and moderate enthalpy geothermal sources in Mexico, Central and South America as well as many parts of the world.

The feasibility of binary cycles power plants using the residual brine in the existing geothermal fields to increase the contribution to the distribution network

Increase the electrical capacity of geothermal fields, without requiring new wells, which represents a technical and economical way of improving the energy efficiency.

Interest is high in the use of these proven binary cycle power plants to provide electrical generation in applications in Mexico for a variety of goals, including enhancing central power plants as well as providing power to remote areas.

Among non-fossil alternative energy sources as separated water or geothermal brine provide one of the most attractive means of generating electricity.

The experience accumulated over the past years shows that the binary system has now been developed into a well proven technology. The binary plants units have accumulated operating hours in actual field operation, thus demonstrating the reliability, availability and inherent long life of binary geothermal power systems in Mexico.

REFERENCES

Gerencia de Proyectos Geotermoeléctricos, 2009: *Desincorporación de unidades de ciclo binario en el C.G. Los Azufres, Michoacan.* Comisión Federal de Electricidad, Mexico, 9 pp.

González, R.M., 2008: *Proyecto unidades experimentales de 300 kW.* Comisión Federal de Electricidad, Mexico, 2 pp.

Sánchez-Velasco, R., López-Díaz, M., Mendoza, H., and Tello-Hinojosa, R., 2003: *New CFE geothermal village power plant in Mexico bestows local residents with prosperity - and children with ice cream.* Comisión Federal de Electricidad, Mexico, 4 pp.

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PIPING DESIGN FOR GEOTHERMAL PROJECTS

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ABSTRACT

The best piping configuration is the least expensive over a long term basis. This requires the consideration of installation cost, pressure loss effect on production, stress level concern, fatigue failure, support and anchor effects, stability, easy maintenance, parallel expansion capacity and others. The expansion loops most commonly used in cross-country pipelines are L bends, Z bends, conventional 90° elbows and V bends.

The principal design codes used for piping design are the ANSI/ASME B31.1 (Code for Power Piping) and ANSI/ASME B31.3 (Code for Process Piping), ASTM A53 B, ASTM A106 B and API 5L carbon steel pipes are the ones used for geothermal fields. The allowable stress is S_E=88 MPa for ERW pipes and S_E=103 MPa for seamless pipes, S_A=155 MPa for operation loads, kS_h=124 MPa for earthquake loads and 258 MPa for combined sustained loads and stress range.

Pipe pressure design for the separation station and steam lines is 1.5 MPa, and for brine line ranges from 1.5 to 4 MPa. Pipe diameters are generally 250 to 1219 mm for nominal pipe sizes. The two-phase line can be in the range of 50 to 150 meters, the steam lines from 2000 to 3000 meters and for the brine up to 6000 meters long.

The total cost of pipe installation can be US$ 600 to US$ 1,200 per meter of pipe. Pipe configuration needs to be cost conscious; if the design can use under 10% of excess pipe to get from point to point in a straight line distance, then it is excellent from a piping material and pressure loss point of view.

1. INTRODUCTION

The basic concept of a geothermal piping design is to safely and economically transport steam, brine, or two-phase flow to the destination with acceptable pressure loss (Jung, 1997). The piping associated with geothermal power plants can be divided into the piping inside the power plant and the piping in the steam field.

Piping in the steam field consists of pipelines connecting the production wells to the separation station and those that run cross-country from the separation station to the power plant, and lastly to re-injection wells. The cross-country pipelines run on top of ridges, up and down steep hill slopes, cross roads, and across areas threatened by earthquakes, wind, rain and landslides. The geothermal piping system has to be flexible enough to allow thermal expansion but also stiff enough to withstand the seismic and operational load actions.

The steam field model used is a wet field as the piping encountered in this model covers most, if not all the possible types of fluids and piping that could be expected in any geothermal system.

The wet steam field system consists of:

1. Two-phase flow piping which collects the fluid from several wellheads and sends them to the separator;
2. The separator vessel;
3. The steam pipelines which take the steam from the separator to the power plant;
4. The brine pipelines which take the separated brine from the vessel to a wellpad where the fluid is reinjected into several wells; and
5. Miscellaneous cross-country piping includes the instrumental air lines, the water-supply line and also the condensate line.

Two aspects of the design process of geothermal piping systems that must be considered are the process of preparing the design and the deliverables.

The scope of this paper will be in the piping for the steam field and the process of preparing the design divided into the following main categories: design criteria, production process flow diagram, define control philosophy, separator location, route selection, dimension design, pressure design, load design, design codes and pipe stress analysis.

2. DESIGN CRITERIA AND DELIVERABLES

The design process consists of the establishment of the design criteria for the piping system. For a proper piping design, it is essential that the client and the contractor agree on a design basis, process, and mechanical, civil and electrical control and instrumentation.

Table 1 presents a design criteria guideline for an existing or a new piping system. The electrical control and instrumentation criteria have been considered in this paper as part of the power plant design. Appendix 1 presents the control and instrumentation philosophy for a separation station in the Berlín geothermal field.

Before proceeding with the design of the pipelines, some restrictions or assumptions about the characteristics of the production wells, reinjection wells, and power plant location need to be considered. The output characteristics, mass flow rates, well head pressure, temperature and chemistry of the wells enable the selection of optimum production values, which will be considered for the entire life of the project.

The transportation of the steam from the separation station to the power plant will take place with some heat loss, condensation and tapping due to pressure losses and the imperfect thermal insulation. To determine the size and diameter of pipe and the insulation thickness, the general working equation for an open and steady system is, (DiPippo, 2008):

$$\dot{Q} - \dot{W}_s = -\sum_{i=1}^{n} \dot{m}_i (h_i + 0.5V_i^2 + gz_i) \qquad (1)$$

where $\dot{Q}$ = Rate of heat transfer between the system and the surroundings (+ into the system);

$\dot{W}_s$ = Rate of work transfer (power) between the system and the surroundings (+ out of the system);

i = Index that runs over all inlets and outlets of the system;
n = Total number of inlets and outlets;
$\dot{m}_i$ = Mass flow rate crossing each inlet or outlet;
h_i = Specific enthalpy of the fluid at each inlet or outlet;
V_i = Velocity of the fluid at each inlet or outlet;
z_i = Elevation of each inlet or outlet; and
g = Local gravitational acceleration.

And the conservation of mass requires that:

$$\sum_{i=1}^{n} \dot{m}_i = 0 \tag{2}$$

TABLE 1: Design criteria

General	**Process**	**Mechanical**	**Civil/Structural**
Design life	Steamfield layout	Design Parameters – Process conditions – design Loads	Design codes and procedures
Meteorological & other local data	Economic analysis	Design codes and procedures	Project layout
Environmental requirements	Piping criteria *pressure drop* *line sizing* *pipe routing* *design pressure*	Piping systems design	Access
Operating and maintenance criteria	Draining & venting philosophy	Pipes	General Civil construction
Cost minimisation	Silica deposition	Valves	Thermal Ponds
Avoiding uphill two-phase flow	Insulation	Fittings	Retaining walls
	Control valve types	Vessels	Foundation design
	Pressure relief devices	Mechanical Equipment	Structural design loads
	Pumps	Other components	Pipe supports & anchors
	System isolation philosophy	Constructability and maintainability	Structures
	Instrument air - source & materials		Concrete design
	Sampling & testing requirements		Steel design

For a given power capacity, the size of the steam pipe can be determined by calculating the pressure drop, heat loss and the electric power output, given by the equations in Table 2.

TABLE 2: Equations for calculating the pressure drop, heat loss and the electric power output of steam pipes

Item	Description	Equation
1	Bernoulli Equation	$\frac{P_1}{\gamma}+\frac{V_1^2}{2g}+z_1=\frac{P_2}{\gamma}+\frac{V_2^2}{2g}+z_2+h_L$ (3)
2	Friction Losses in pipe and fittings	$h_L = h_{LPipe} + h_{LFittings}$ (4)
3	Darcy-Weisbach Equation (pipe friction)	$h_{LPipe}=\frac{\lambda L V^2}{D2g}$ (5) $h_{LFittings}=\frac{\sum K_{Fittings}V^2}{2g}$ (6)
4	Electric output	$MW = \overset{*}{m}(h_1 - h_2)\eta_t\eta_g$ (7)

where
P = Pressure;
V = Velocity of fluid;
γ = Specific weight (ρg);
ρ = Density;
g = Gravity;
z = Height;
λ = Pipe friction coefficient;
L = Length of pipe;
D = Inner diameter of pipe;
K = Resistance coefficient for fittings;
h_L = Pressure drop;
h_1 = Enthalpy at inlet turbine conditions;
h_2 = Enthalpy at outlet turbine conditions; and
$\eta_{t,g}$ = Turbine and generator efficiency.

The deliverables that make up and document the design will consist of the conceptual design drawings, specifications, bill of materials, pad general arrangements, reports, piping layout, cross country drawings, etc.. For the process design, the deliverables consist of the Process Flow Diagram (PFD), Process & Instrumentation Diagram (P&ID) and the Line, Valve, Instrument and Equipment list. For the mechanical, civil and electrical design, the deliverables are Drawings, Specifications, Data sheets, Calculations, Reports and Bill of Quantities.

3. PIPING DESIGN

3.1 Design procedure

The problem of design procedure is to find a pipeline configuration and size within the constraints, which is both safe and economical.

The steps in pipeline design are as follows, (Geothermal Institute University of Auckland):

I. Determining the problem, which includes:
   a. The characteristics of the fluid to be carried, including the flow rate and the allowable headloss;
   b. The location of the pipelines: its source and destination, and the terrain over which it will pass, the location of separator station and the power plant;
   c. The design code to be followed; and
   d. The material to be used.

II. The determination of a preliminary pipe route, the line length and static head difference.

III. Pipe diameter based on allowable headloss.

IV. Structural analysis.
   a. Pipe wall thickness; and
   b. Stress analysis.

V. The stress analysis is performed in pipe configuration until compliance with the code is achieved.

VI. Support and anchor design based on reaction found in the structural analysis.

VII. Preparation of drawings, specifications and the design report.

3.2 Fluid characteristics

Important factors to be considered are the mass flow rate, pressure, temperature, saturation index and the allowable headloss over the pipeline length.

Two phase piping
The steam and water flow patterns in the pipe vary from annular, slug to open channel flow; depending on the velocity and wetness of the steam. Slug flow generates high dynamic load and vibration that can damage the piping system. The preferred flow regime in the pipes is usually the annular flow.

Pipes need to be sized correctly and run flat or on a downhill slope to achieve annular flow. The Baker or Mandhane maps combined with a simple understanding of the value of superficial velocity can be used in predicting the flow pattern inside a pipe. Uphill sloping pipes are not desirable as this encourages slugging in the pipe.

The pressure loss in a two-phase line is usually high and not easy to predict. Correlations for two-phase flow regimes and pressure drops in pipes and fittings are derived from Harrison, Mukherjee and Brill, Freeston, ESDU data Item 89012.

The piping for two-phase fluids has to be designed for high pressure, dynamic load, possible slug flows, erosion, corrosion, minimum pressure loss (by running the pipe as short as possible), the desired flow regime (by selecting the correct fluid velocity and slope for the pipes), and vibration prevention.

Brine piping
The brine leaving the separator is at saturated conditions. If the pressure at any point in the line is less than the saturation pressure, brine will flash into steam. This will cause slug flow which can result to dynamic forces that can damage the pipes. Brine lines are designed to gain static head pressure. Reinjection wells should be located lower than the separator.

Brine pipes have the highest hydrostatic head pressure at the lowest elevation due to the water column. Some brines pipes that have been designed have an elevation shift of 400 to 500 meters.

The pressure at the lowest point is usually high, where in this case, the pipe has to be divided into several pressure class ratings.

Brine flow is a combination of open channel and full flows, depending on the geometry of the line. On a sloping line, the flow commonly starts as an open channel flow and develops to a full flow.

The minimum slope of the line required for an open channel flow is predicted by Chezy's or Manning's equations. Full flow velocity is in the order of 2 to 3 m/s and the pressure drop can be predicted by the Darcy Weisbach equation with the friction factor calculated from Colebrooke's equation.

Rock fragments carried by the fluid from the production well are removed from the steam by the separator. They eventually travel down the brine pipe to the reinjection well. Like in the two-phase flow, this will cause erosion of the pipes and can clog the wells.

When designing brine pipes, the following factors need to be considered: erosion, corrosion, scaling due to silica saturation, residence time of the brine, pressure to be maintained above saturation pressure (to prevent flashing and slugging), high hydrostatic pressure, dynamic load from potential slug flow and water hammer, open channel flow, pressure, temperature and provisions for drainage.

Steam piping
For a given mass flow rate, the high specific volume of steam makes the pipe diameter bigger. Steam from the separators contains non-condensable gases, chlorides and other chemical species that can cause corrosion along the pipes, turbines, and related equipment of the power plant. These chemical species can be dissolved in the condensate, which then are collected in drain pots and discharged by means of steam traps.

The steam velocity is typically 40 m/s. The pressure drop can be predicted using Darcy-Weisbach's equation and Colebrooke's friction factor.

Steam pipe sizing is based on velocity, pressure drop and capital cost. Low fluid velocity is usually correlated to a low pressure drop, however, this results in large diameter pipes which are generally expensive. High fluid velocity usually translates to small diameter pipes, which reduces capital cost but results in unacceptable high pressure losses. Within the limit of the acceptable velocity range for a given service, a compromise needs to be made between pressure drop and capital cost. This is often termed as "sizing the pipe by economic pressure drop".

Factors needed to be considered for a steam pipe design are scrubbing the steam, steam velocity, corrosion allowances, pressure drop, pressure and temperature.

3.3 Separator location

The separator location is controlled by site topography, process and control system requirements and the pipes.

One option is to locate the separator close to the production well, which can reduce the overall line pressure drop from the well to the turbine. The separator pressure will be similar to the wellhead pressure, which means a lower flash ratio, therefore we will obtain less steam and more brine to dispose.

The other option is to locate the separator close to the turbine. The advantage is a lower separator pressure, which produces a higher flash ratio, to obtain more steam and less brine to dispose. A long two-phase line usually has a high pressure drop from the well to the turbine.

When the resource pressure is relatively low (where every Kpa represents additional flow and generation), two-phase pipelines produce 3 to 5 times higher pressure loss than a single-phase steam line, and may not be the best method.

For a high pressure and high flow rate well resource, the reservoir engineers must provide estimates on the well deliverability and the projected decline rate. Initially, two-phase flow pipelines can be a viable option, however, in the future, conversion to a steam and birne pipeline may be required.

It is preferred to have the separator located as close as possible to the production well pads to minimize process risk due to unpredictable two-phase flow. Figures 1 and 2 show the separation station location in the Berlín geothermal field.

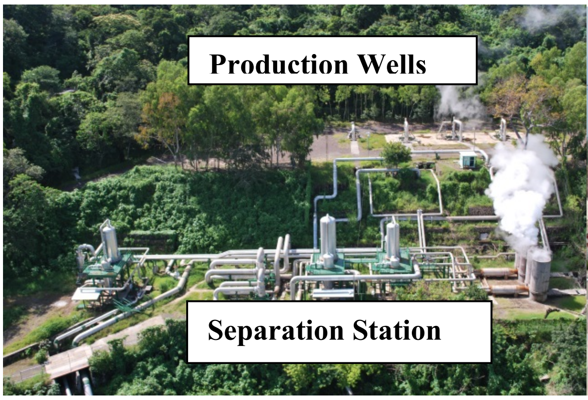

FIGURE 1: TR-5 Well Pad

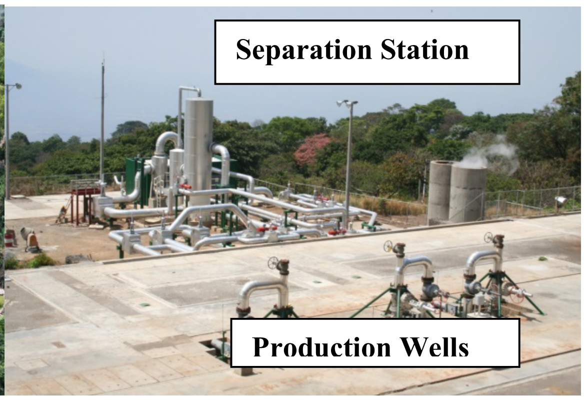

FIGURE 2: TR-17 Well Pad

3.4 Pipe types and application

Seamless Pipe (SMLS)
These pipes are extruded and have no longitudinal seam. There is no weld and they are the strongest of the three types of pipes mentioned.

Submerged Arc Welded Pipe (SAW)
These pipes are manufactured from plates, normally rolled and seam welded together. The welding has a joint efficiency of 0.95.

Electric Resistance Welded Pipe (ERW)
These pipes are manufactured from plates, where the seam weld is done by electric resistance welding. The welding efficiency is 0.8.

3.5 Design codes

The principal design codes used for piping design are the ANSI/ASME B31.1 (Code for Power Piping) and ANSI/ASME B31.3 (Code for Process Piping).

Complementing these codes are the ASME VIII (Code for Pressure Vessel) and British Standard BS5500 for an unfired fusion welded pressure vessel.

The basic consideration of the B31.1 Code is safety. It includes (ASME, 2007):

a. Material and component standards;
b. Designation of dimensional standards for elements of the piping system;
c. Requirements for design of components – including supports;
d. Requirements for evaluation and limitation of stresses, reactions and movements associated with pressure, temperatures and external forces;

e. Requirements for fabrication, assembly and erection; and
f. Requirements for testing and inspection before and after assembly.

Pipes
For pipes, the materials used in geothermal application are normally A53-B, A106-B and API 5L-B pipes, with mill tolerance. Commercial available pipes normally have a mill tolerance of 12.5% and pipe schedule numbers based on B36.10.

Fittings
For elbows, tees, and reducers, the material used in geothermal application is normally A234 WPB. All dimensions are in accordance with B16.9.

Flanges and valves rating
Flanges are rated to the ANSI B16.5 standard. For those up to 24" diameter, they are rated to ANSI 150, ANSI 300, ANSI 600 and ANSI 900.

For flanges 26" and bigger, ANSI B16.47 applies. The flanges are usually classified series A and series B. The material used for these flanges are A181 grade I and A105 grade I.

Valve rating is similar to the flange rating selected for the pipe.

3.6 Pipe routes

Aerial photographs and a contour plan of the area are sufficient information to identify a preliminary route for the pipes and suitable locations for the plant components. The preliminary route is then inspected on site to check land ownership, houses, swamps, soil condition for foundations, anchors and expansion loops, hot spots, slip risk, road crossings, watercourses, change in elevation, and access.

Using the preliminary pipe route, an estimate of equivalent line length can be made. The design flow and enthalpy are determined from the well data, and with this information, the optimum diameter for the pipes can be known. Figure 3 shows a contour plan of the Berlín geothermal field.

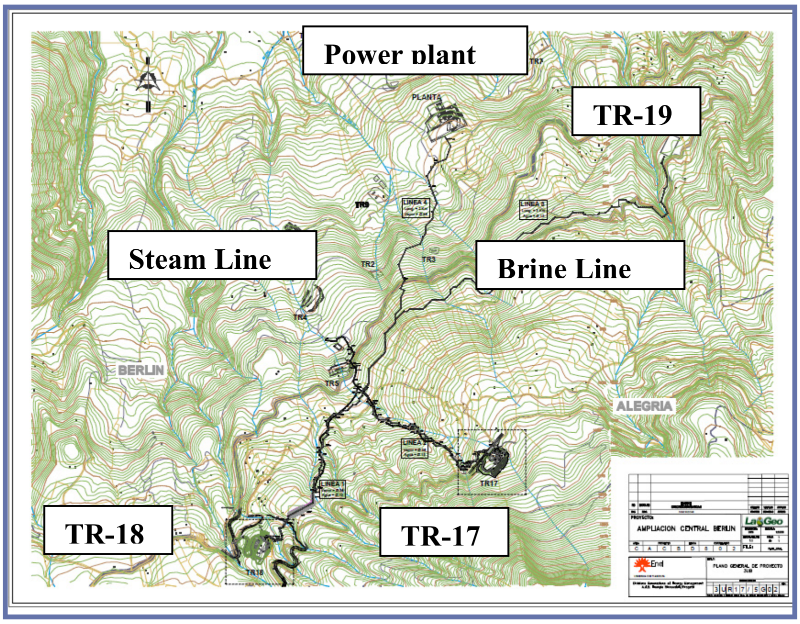

FIGURE 3: Contour plan of the Berlín geothermal field

3.7 Structural analysis

Circumferential stress or Hoop stress due to pressure and vacuum is considered for sizing and selecting the pipe with a suitable wall thickness.

Equations for pipe stress analysis are given in the design code. The first step is the determination of wall thickness required by B31.1.

$$Tm = \frac{PD_o}{2(SE + Py)} + A \tag{8}$$

where Tm = Wall thickness in millimeters;
P = Design pressure in kilopascals;
D_o = Pipe outside diameter in millimeters;
SE = Allowable stress in kilopascals;
Y = 0.4, for most geothermal application is a factor based on temperature range and steel type; and
A = 3 mm corrosion and erosion allowance.

Stress analysis should be carried out for the following load cases for compliance with the code requirement and support load calculation. B31.1 requires that a pipeline shall be analyzed between anchors for the effects of:

1. Sustained loads, Gravity + Pressure;
2. Operation loads, thermal expansion stress alone or thermal expansion stress + sustained loads;
3. Occasional loads, sustained loads + seismic load or wind load perpendicular to the general alignment of the pipe;
4. Occasional loads, sustained loads + seismic loads along the general direction of the pipe;
5. Reverse the direction of seismic or wind loads; and
6. Modes of thermal operation need to be considered in the analysis.

In addition to this, an analysis should be carried out for zero friction to determine the maximum load on the anchors in the event of an earthquake. Other dynamic loads that can be considered are fluid hammer effects, thrusts from safety valves, and slugging flow. Figure 4 shows the well pad piping analysis using the PipePlus software.

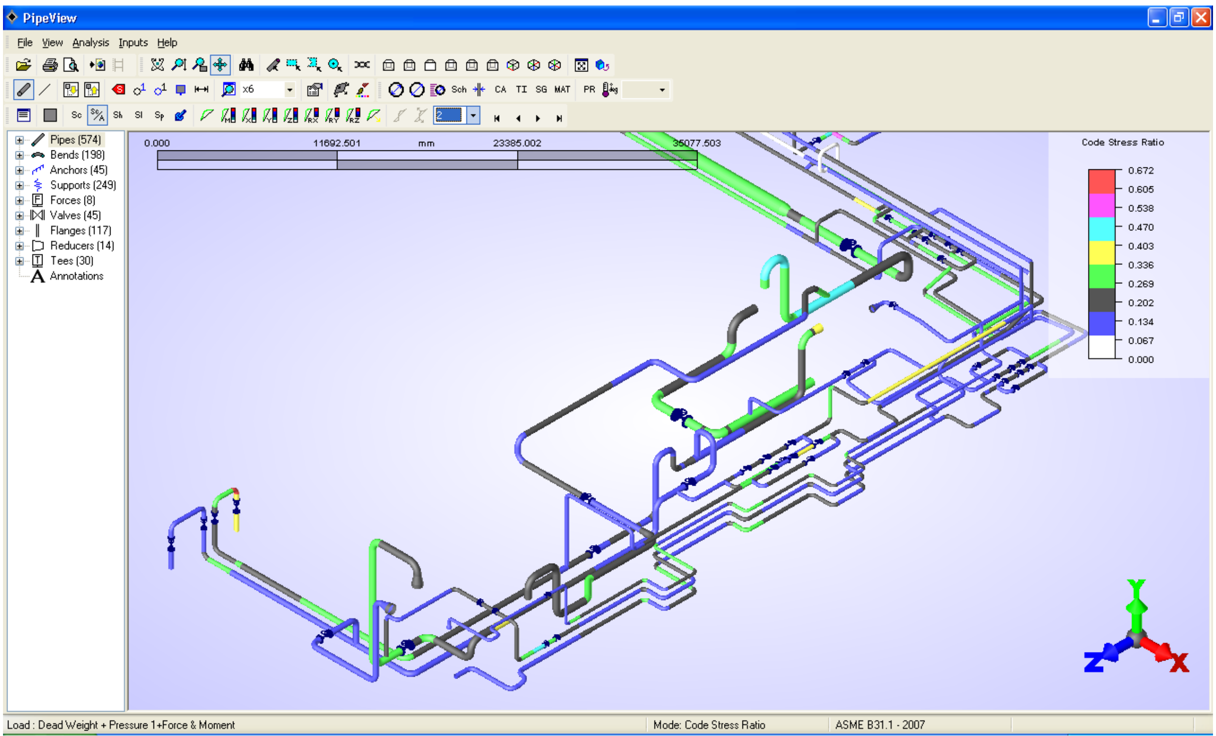

FIGURE 4: Pipe view in the Pipe plus software. Well pad design.

3.8 Expansion loops, pipe supports and anchors locations

Expansion loops are the most commonly used in cross-country pipelines to handle thermal expansion. On standard runs, L bends, Z bends, conventional 90 degree elbows and V bends are the most used pipe configurations for the design. Z bends can be very stable on downhill runs. Horizontal loops are very effective in congested areas. Custom designs based on following the natural configuration of the terrain can be very effective in cross-country designs.

Anchors shall be strategically located to reduce the magnitude of the resultant load. This reduces the size of the foundation. Typically, a cross-country pipe run without compensators will require an anchor every 150 to 200 meters.

The types of supports used are the Y stop, Guide, Line Stop, Constant Weight Support, and Shock absorbers. Reducing the number of pipe supports by spacing them as far apart as the maximum pipe span is allowed. There should be a pipe support located near every bend, as it reduces eccentric loading on the pipe and minimizes vertical vibration at bends, especially in two-phase lines.

Pipes are run close to the ground to reduce the overturning moment effect on the pipe support and anchors, which then reduce the foundation size and hence the cost. Figures 5 to 7 show expansion loops commonly used in Berlín and Figure 8 the types of support for the pipe lines.

FIGURE 5: V bend expansion loop

FIGURE 6: Omega bend expansion loop

FIGURE 7: Z bend connecting to the vessel

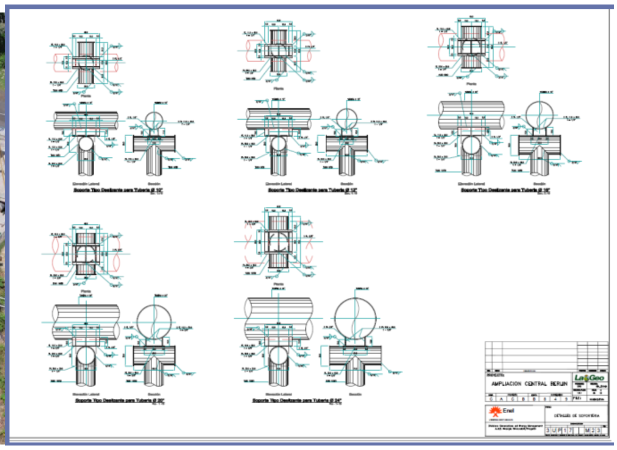

FIGURE 8: Support types

4. OTHER ASPECTS OF THE PIPING DESIGN

Software

In order to simplify the process for calculations and stress analysis, computer programs are available. Some are listed here: AutoCAD, PlantFow, EES, Autopipe, Caesar II, PipePlus, Finite Element Analysis-FEA.

Nozzles connection–Pressure vessel, Pumps, Turbines, etc.

Nozzle connection is beyond the scope of this paper. Generally, the piping designer works with the load limitation given by the manufacturer or a finite element specialist. As a general rule of thumb, loading on the nozzle should be less than 40 Mega Pascals. All care must be employed to protect the nozzle connect on vessel, equipment, well-heads and attachments.

Pipe buckling

Large diameter thin wall steam pipes supported by an anchor in a long steep slope is subjected to a high gravity load near the anchor. This could cause the pipe to fail by local buckling. The load required to cause this can be calculated using Euler's equation or by FEA.

Cost of the pipe system

The piping installation cost is made up of materials 30%, fittings 10%, installation labour 25%, installation equipment 10%, support 15% and P&G 10%. The total cost can vary from US$600 to US$1200 per meter, depending on pipe diameter, slope of the terrain, cross-country or well pad piping.

REFERENCES

ASME, 2007: *ASME B31.1- 2007. Power piping.* The American Society of Mechanical Engineers, New York.

DiPippo, R., 2008: *Geothermal power plants. Principles, applications, case studies and environmental impact.* Elsevier, Oxford, 520 pp.

Fisher, 2010: *Valves handbook, fourth edition.* Emerson process management. Web site: http://www2.emersonprocess.com/en-us/brands/fisher/Pages/FisherValvesInstruments.aspx

Geothermal Institute University Auckland*: Pipe Design for geothermal steam system*. Lecture

Jung, D.B., 1997: Making geothermal cost competitive: Production equipment and facilities cost reduction. *GRC Transaction, 21,* 547 -553.

APPENDIX 1: Control system for steam separation station

1. PRODUCTION WELLPAD PROCESS DESCRIPTION

A geothermal production wellpad consists of the following main equipments: Steam separator, water tank, ball valve, instrumentation system, control system and electrical system.

The steam separator receives the two-phase fluids from the geothermal wells and separates the steam and the water. The steam is sent directly to the power plant for the generation process. The separated water is sent to the water tank and then to the reinjection wells.

The ball valve is located in the steam line after the steam separator and protects the steam line against the presence of humidity. In case of the operation of the ball valve, there is a motorized valve that isolates the steam line and permits the draining of the ball valve to normalize the operation of the steam line. Figure 1 shows the P&ID for a typical geothermal production pad in El Salvador.

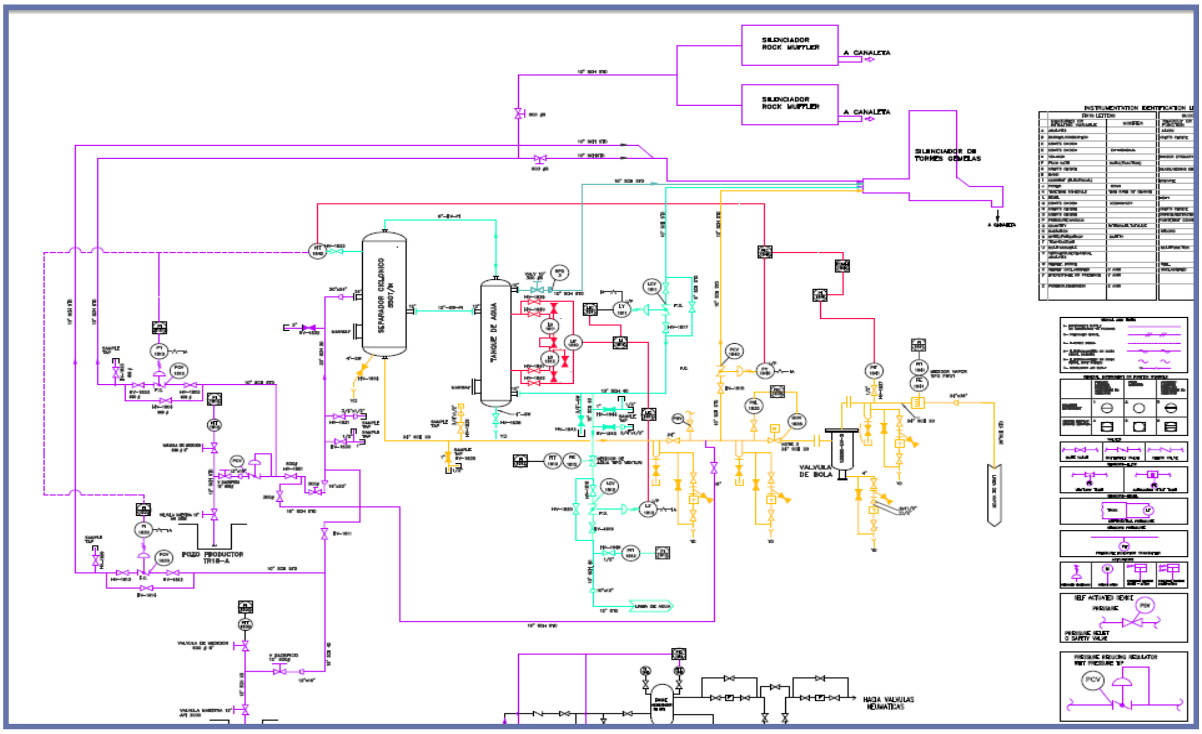

FIGURE 1: P&ID for a production pad

The instrumentation system is in charge of the measurement and control of the most important mechanical variables of the process. The measurement equipment includes different kinds of transmitters like pressure transmitter, level transmitter and flow transmitter that send their measurement to the control system as an electrical variable.

The control system processes the electrical signal and sends commands to the final control element that modifies the process conditions. The final control elements include control valves that are operated by electrical and pneumatic actuators.

The electrical system feeds all the electrical equipment required in the production wellpad like control system, instrumentation system, electrical actuators, compressors, lighting systems and auxiliary outlets for maintenance works, which is normally provided from the power plant. Because of the long distance between the power plant and the production wellpads, a medium voltage line (13.2 kV) is installed from the power plant to the production wellpad to minimize the electrical losses in the cable because of the distance. A substation is located in the wellpad that converts the voltage from 13.2 kV to 0.48 kV.

The control system is a Programmable Logic Controller, PLC, with different kinds of input and output cards like analog input (AI), analog output (AO), digital input (DI) or digital output (DO) that receive the electrical signals from the instrumentation system. The PLC has power source, CPU communication cards and communication network redundancy to ensure the safety and availability of the process. The wellpad control system is in communication with the main control system in the power plant and allows a remote monitoring of the process. For this separation station remote control is not allowed to ensure that the control system will not fail in case of communication lost. Figure 2 shows a control system architecture used for production pad.

The most important control loops in a geothermal production wellpad are the ones for the pressure in the steam separator and the level in the water tank. The pressure loop avoids pressure increases that can create disturbances in the steam supply and affect the power generation process. The level loop avoids the water to go into the steam line and trips the ball valve, or the steam to go into the water line and reduce the electrical generation.

The pressure loop is described as follows: if the pressure in the steam separator increases, the control system operates a pneumatic valve that sends the steam to the silencers and relieve the pressure on it. The type of valve used for this application is a butterfly valve with a spring opposed single acting cylinder actuator, because a high speed operation is required.

The level control is described as follows: there are two pneumatic valves in the water line, the main one is connected to the reinjection line and the other one to the silencer line.

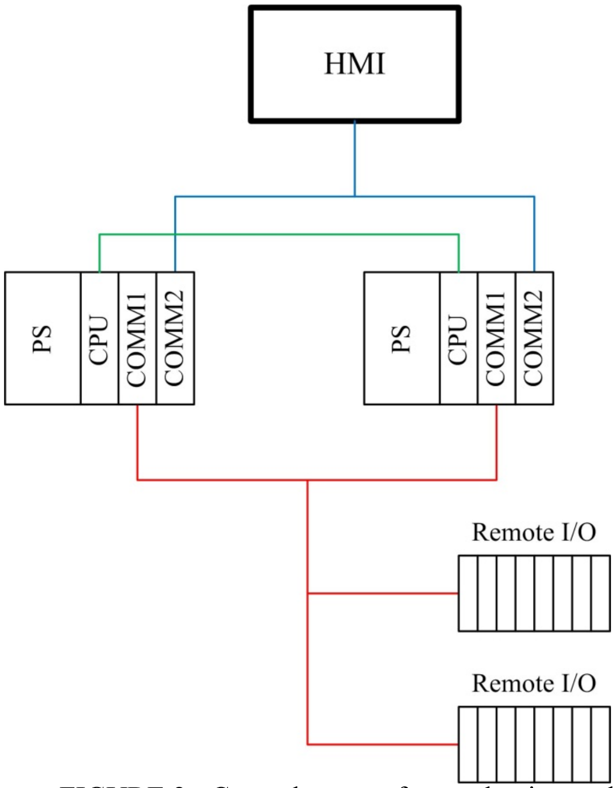

FIGURE 2: Control system for production pad

The reinjection valve is operated to control the level in the water tank under normal operation conditions. The silencer valve starts to work in case of an abnormal condition in the system where the high level in the water tank can't be controlled by the reinjection valve. Each control valve has a different level set point where the reinjection valve set point is lower than the silencer valve set point. If there is a level increase in the water tank, both valves open, according to their own set point, reducing the water level and if the level decreases, both valves start to close.

2. INSTRUMENTATION AND CONTROL SYSTEM SELECTION

2.1 Transmitter's main characteristic

For the pressure transmitter selection, the most important characteristics to be considered are the temperature rating, precision, NEMA classification, hart protocol available, electrical transient protection and LCD display.

The temperature rating for the transmitters is based on the geothermal fluid temperature, (190 °C in Berlin). In case the transmitter rating is not available for this temperature, an alternative installation method permits the transmitter to be used under this temperature condition.

The precision of the transmitter will depend on the application of any particular case. High precision is required for critical application like flow or pressure measurement at the turbine input or level in the condensers. A typical precision for geothermal application is 0.1% of the calibrated span.

NEMA classification refers to the grade of protection for outdoor use. Adequate protection for dust and water is necessary. Typical protection for geothermal application is NEMA 4X or IP66. Because of the presence of H_2S in the atmosphere, all the equipment should be corrosion resistant. All the instrument parts that are in contact with geothermal fluid should be made of stainless steel.

Hart protocol permits the easy configuration of the transmitter. There are special tools to access to the transmitter and configure them, like portable hart communication tools or software. Hart protocol is used too to create special network that permits the communication of more than one transmitter to a Scada system for multiple transmitter configuration or monitoring.

Electrical transient protection protects the transmitter against electrical variation in the system, produced by external faults or atmospheric discharges. This protection can be integrated in the transmitter or be installed externally. LCD display permits the local monitoring of the different variables. Typical instrumentation brands used in geothermal power plants are listed in Table 1.

TABLE 1: Instrumentation and control valves common brands

Description	Brand
Transmitters	Rosemount, Honeywell, Foxboro, Yokogawa
Control valves	Fisher, Vanessa, Masoneilan, Limitorque

2.2 Pressure transmitter description

The pressure transmitter has two main elements: sensor and transmitter. The most common sensor used is a piezoelectric sensor that changes its vibration frequency with pressure changes. The transmitter takes the sensor signal and converts it into an industrial standard, typically a 4-20 mA that is proportional to the measurement range in the equipment.

2.3 Level transmitter description

The most common method used in the application in Berlin for level measurement is the differential pressure between the high and low sections of the containers. Differential pressure is proportional to the water level. The differential transmitter used for level measurement has the same principle as that of the pressure transmitter described below, but has two sensors where the transmitter receives both signals and gives the difference between them.

2.4 Flow transmitter description

The flow transmitter has three main elements: flow element, sensor and transmitter. The most common method used for flow measurement is the pressure drop caused by a flow element that is proportional to the flow in the pipe using the averaging Pitot tube for steam flow measurement and the Venturi tube for water measurement. The transmitter used for flow measurement is a differential pressure transmitter that has the same principle that the pressure transmitter described below.

2.5 Control valves main characteristic

For geothermal production wells, there are two types of control valves: pneumatic valves and electric valves. Pneumatic valves are used for steam pressure control and water reinjection control. Electrical valves are used in steam and two phase line to isolate the process in case of emergency or maintenance activities.

Pneumatic valves normally work as regulation valves operated by compressed air and have three main components(Fisher, 2010):

a) Mechanical valve - the part that is in contact with the fluid process, usually of three kinds: the Butterfly valve, ball valve and gate valve.

b) Actuator - a powered device that supplies force and motion to open or close a valve, usually of two types: cylinder spring-opposed single acting and diaphragm spring opposed.
c) Positioner - a controller that is mechanically connected to its actuator and automatically adjusts its output to the actuator to maintain a desired position in proportion to the input signal. It is electro-pneumatic type and receives an electrical signal (4-20 mA), which then converts it to a pneumatic signal (3-15 psi)

Electrical valves are normally gate valves type with an electrical actuator that supplies motion to the valve by an electrical motor and a gear box. The electrical actuator has an integral electronic control and protection functions. This valve are normally used as on/off valves.

Steam pressure control valve controls the separation pressure and in case of an overpressure, it opens to relieve the pressure through the silencer in the wellpad. This valve is normally butterfly type valve with eccentric disk to avoid shaft stuck because of silica deposition. The actuator used in these valves is a spring-opposed single acting as piston that provides high torque, characteristic for valve operation.

Water reinjection valves control the level in the water tank to avoid water to go into the steam line, or the steam going into the water line. These valves are normally segmented ball valves with a V-shape, which permit good seal characteristics and help against silica deposition in the valve body and entrained solids in the water.

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

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NEW DEVELOPEMENT IN THE ORC TECHNOLOGY

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ABSTRACT

This paper treats a few aspects of the Organic Rankine Cycle technology. The benefits of variable geometry inlet guide vanes (IGV's) in radial turbines for the ORC cycle are presented and discussed. One of the areas where variable IGV's are beneficial is cogeneration of power and district heat. Cogeneration and how the district heating should be connected to the power plant is presented, as well as the benefits from the variable IGV's. The third theme treated is the so-called transcritical ORC cycle, which is already established in waste heat recovery, but is now making its entry into geothermal power production. Finally a hybrid power plant is discussed, in this case a back pressure steam turbine is used together with an ORC plant, making release of non-condensable gases easier, as well as enabling the use of wells with lower wellhead pressure than what a flash plant could use.

1. THE ORC TECHNOLOGY FOR GEOTHERMAL POWER PRODUCTION

The most common technology for geothermal power production is a flash cycle, where the geothermal fluid is allowed to boil and the generated steam is expanded through a steam turbine in one or two pressure stages (single/double flash), usually in a condensing plant. Back pressure turbines have low efficiency and are seldom used. Some geothermal fields have very high enthalpy, so that the fluid from the wells is only steam, and no separation of brine and steam is needed. Then all the well fluid can be directly expanded trough a turbine (dry steam cycle).

If the enthalpy of the geothermal fluid is low, then the steam generated in a flash cycle will not have sufficient quality for power production. The ORC technology is used to produce power from such sources.

Power generated from geothermal heat is divided on the various power plant types as shown in Figure 1.

The ORC plants are usually smaller that the flash plants. The average size of a geothermal ORC plant is around 5 MW. The number of geothermal power plants of each type is shown on Figure 2.

The ORC technology traces its origins back to early last century. The first application of ORC in a geothermal application was a research plant in Paratunka, Kamchatka in 1967. The first geothermal ORC turbine built by Atlas Copco started operations in 1982 in East Mesa, California. A photo of this turbine is shown on Figure 3.

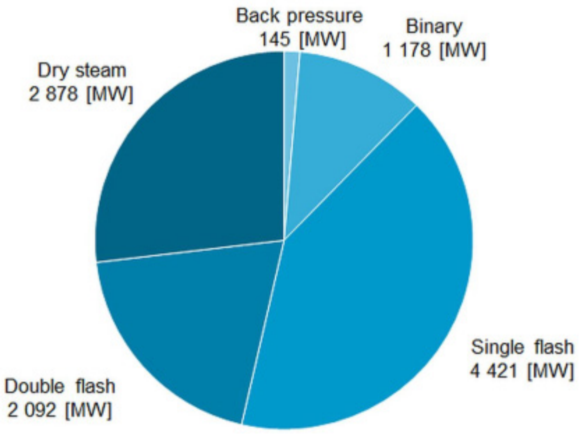

FIGURE 1: Installed power in geothermal power plants 2010 (Bertani, 2010)

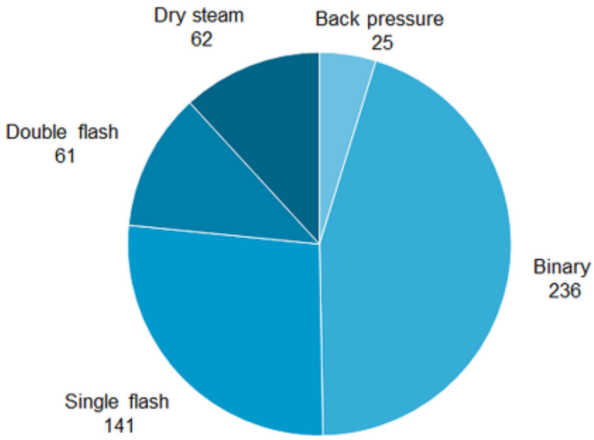

FIGURE 2: Number of geothermal power plants by type 2010

FIGURE 3: The Atlas Copco geothermal ORC turbine in East Mesa 1982

The basic ORC cycle does not offer much innovation. The boundary conditions for a geothermal power plant are far from being similar from field to field, from location to location.

The geothermal resources are vastly different from field to field. Some fields have non-condensable gas mixed with the fluid, some have mineralized brine requiring special design to avoid scaling, some have high enthalpy and consequently some have low enthalpy.

The cold end conditions for the power plant are also different from location to location. In some cases cooling and condensation can be done by natural cooling water from the ocean or a river. Sometimes no water at all is available, leaving an air cooled plant at the mercy of sun and high air temperatures. The third dimension is the question if there is a market for the residual heat from the plant in the form of district heating of buildings, industrial drying or aqua/agriculture.

Therefore this paper will focus on the adaption of the ORC cycle to different boundary conditions – an area where most improvements are likely to happen in the future.

2. RADIAL TURBINES WITH VARIABLE GEOMETRY INLET GUIDE VANES

The inlet guide vanes to a turbine stage accelerate the fluid by converting enthalpy into kinetic energy. The velocity of the fluid exiting the guide vanes is thus dependent on the pressure difference over the vanes as well as the inlet pressure, enthalpy and mass flow.

The turbine has to run at a fixed rotational speed in order to keep the frequency of the electricity generated constant.

This means that if the guide vane exit velocity vector is not exactly at the design value (both size and direction), the angle of attack as the flow meets the leading edge of the rotor blade will not be correct. Variations in this angle of attack lead to losses, and thus a drop in the isentropic efficiency of the turbine.

Variations in the flow of the working fluid through the turbine in an ORC power plant are most frequently caused by variations in the amount of geothermal fluid available to the power plant, this can be caused by variations in the flow produced by the wells or because of demand for the geothermal fluid by other processes, such as district heating on a cold day.

Variations of the pressure difference over the guide vane stage are most frequently caused by variations of the temperature of the cooling air or water, which in turn will influence the condenser pressure.

A radial inflow turbine can be built with inlet guide vanes which can be moved. Such turbine is capable of handling large pressure ratios, so they have only one stage – or only one set of inlet guide vanes. The construction of the Atlas Copco radial inflow turbine is shown on Figure 4.

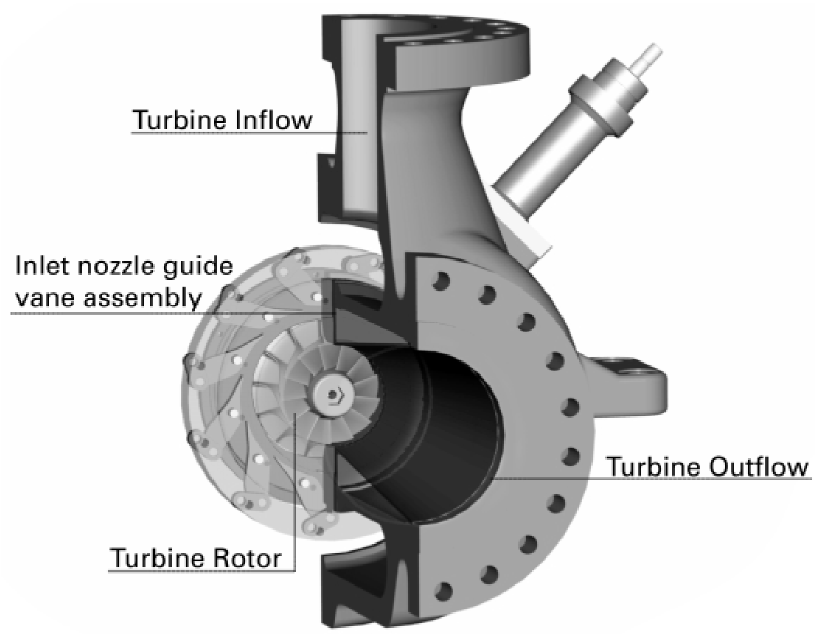

FIGURE 4: Schematic of the Atlas Copco radial ORC turbine

The guide vanes are moved in such a way that the flow area between the vanes changes, and work thus similarly to a turbine control valve in an axial turbine. But the difference is that the flow change in the radial turbine is not made by throttling the flow, but by changing the flow area for acceleration of the fluid. The direction of the flow vector is changed at the same time by ingenious design of the guide vane form.

A simplified picture of the inlet guide vane system in the Atlas Copco turbine is shown on Figure 5.

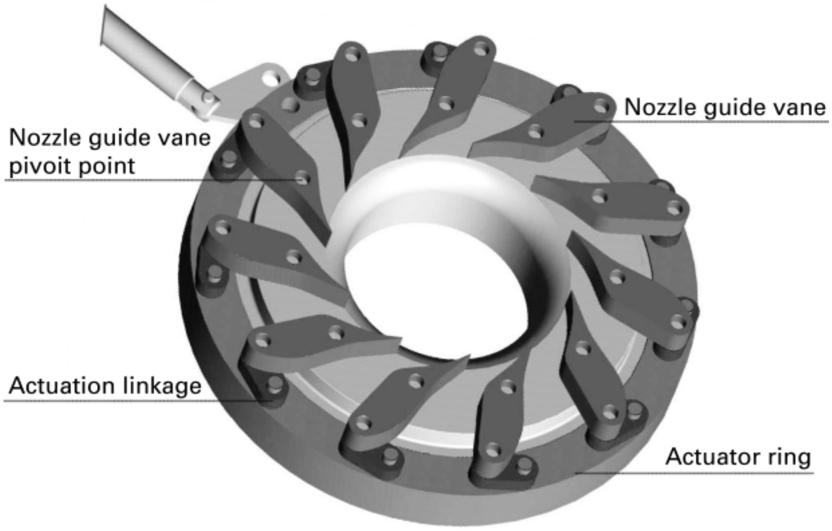

FIGURE 5: Schematic of the Atlas Copco variable IGV system

The result of this is that the turbine is able to maintain high isentropic efficiency over a wide range of operating conditions. This is especially important for power plants with air cooled condensers, where the pressure ratio changes due to air temperature variations. The same applies for cogeneration power plants where the district heating has to get preference during cold days.

3. COGENERATION OF POWER AND DISTRICT HEAT IN AN ORC POWER PLANT

An ORC power plant may have residual heat which can be used as a heat source for district heating. Heating of buildings is in fact just to keep the indoor temperature at 20°C, so theoretically it should be sufficient to supply heat at 21°C to the building heated. In reality there are many geothermal district heating systems having supply temperature as low as 50-70°C all year. Most of the buildings in Iceland have district heating supply temperature at or below 80°C all year (Samorka, 2014). The geothermal district heating in China may have supply temperature as low as 50°C.

An ORC power plant which has no limitation on the temperature of the geothermal fluid due to scaling or secondary process requirements has frequently highest power production at a return temperature around 70°C. This is of course dependent on the cycle design, but can be taken as a "not unusual" value. It is obvious that if the geothermal fluid can be cooled more, that heat will be free of charge for a district heating network.

Therefore the main issue in operating an ORC power plant in cogeneration with a district heating system is how the coupling between the systems can be arranged so that as much as possible of the heat supply to the district heating system is free of charge.

It is obvious that the lower the district heating return temperature from the district heating system to the power plant is, the more of the heat needed for reheat will be free of charge. The only way to lower the district heating return temperature is to stimulate the consumers to install large surface radiators, allowing a minimal temperature difference between the indoor air and the return temperature. Usually this has to be done through the tariff system.

The connection which is recommended by Atlas Copco is shown on Figure 6.

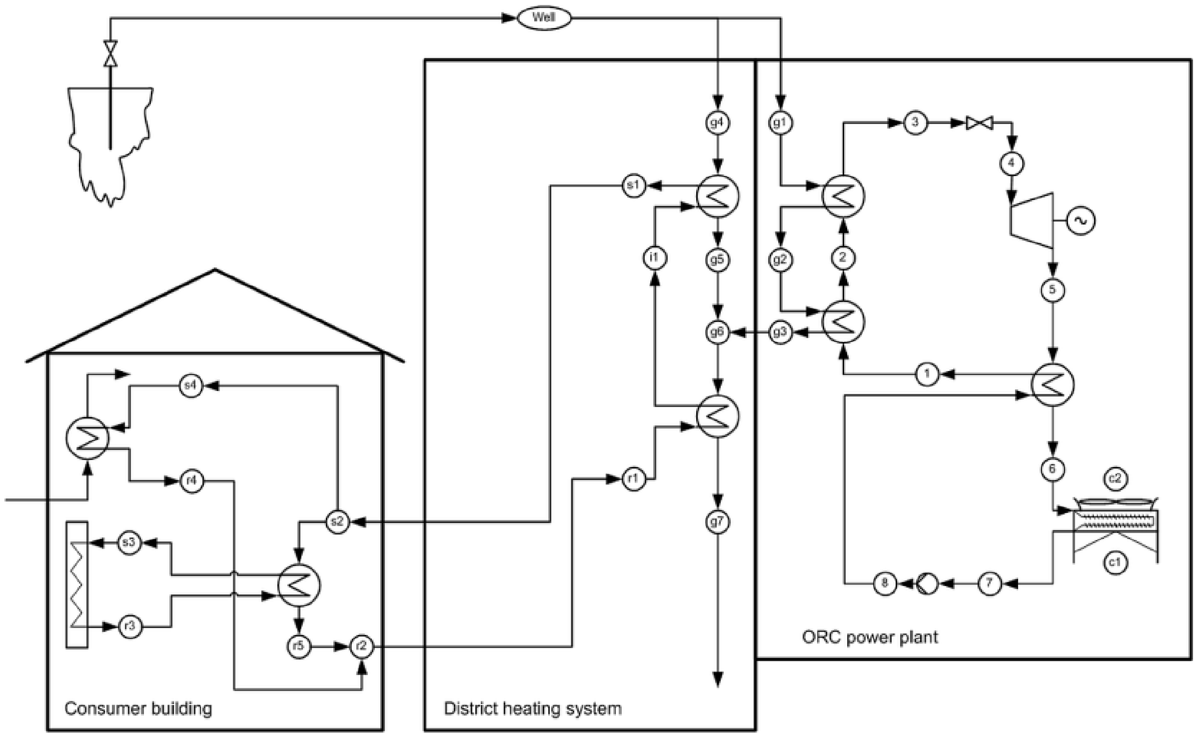

FIGURE 6: Schematic of the Atlas Copco district heating cogeneration connection

The geothermal fluid which is used at point g4 is taken away from the power plant and will reduce what is available for the plant in point g1. This flow is therefore very costly, and the cost is represented by lost revenue because of reduction in electrical power output. But the fluid in point g3 has given all the useable heat to the power plant. All heat from this source can be seen as free of charge.

The lost revenue is shown on Figure 7 as an area in a duration diagram for a design made by Atlas Copco.

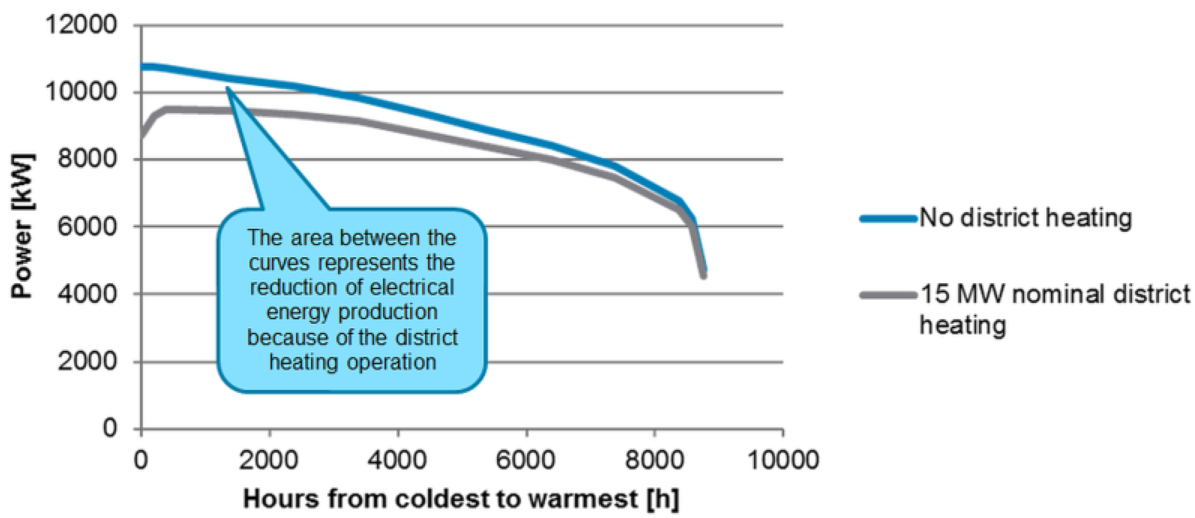

FIGURE 7: Power duration curves for a sample case of cogeneration

The quality of the cogeneration connection is best seen by looking at the reduction of flow available to the power plant because of the district heating. Figure 8 is a similar diagram as in Figure 7, but now with the flows of geothermal fluid to the plant and to the district heating system:

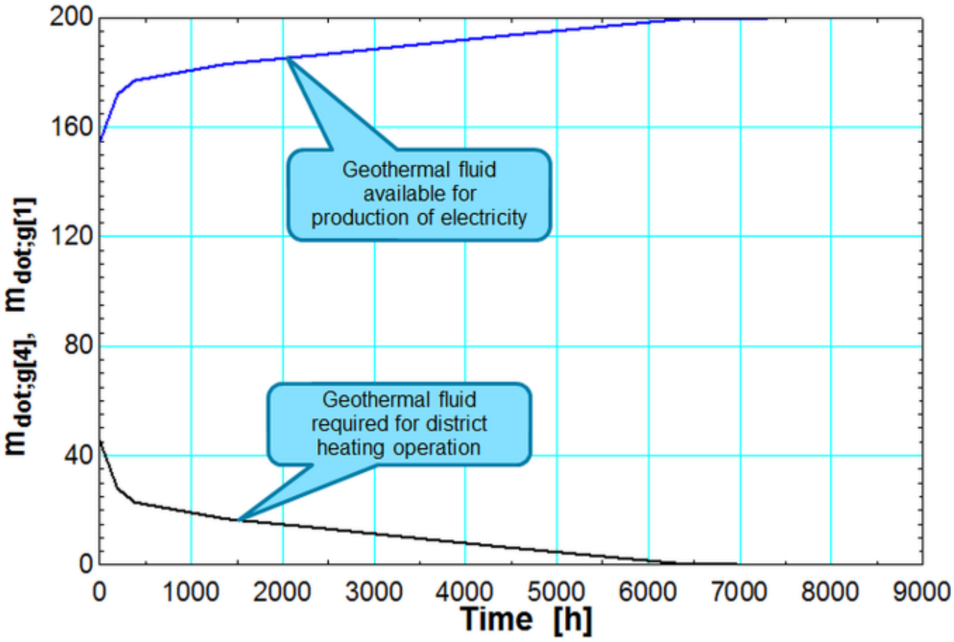

FIGURE 8: Flow duration curves for a sample case of cogeneration

These flow changes will lead to change in working fluid mass flow through the turbine. As these flow changes are related to the outside air temperature (building heating load changes) the condenser pressure will change at the same time. Thus the velocity vector from the turbine inlet guide vanes will change, unless the change is compensated for by movement of the vanes. The duration curve of the Atlas Copco variable inlet guide vane radial turbine is shown on Figure 9.

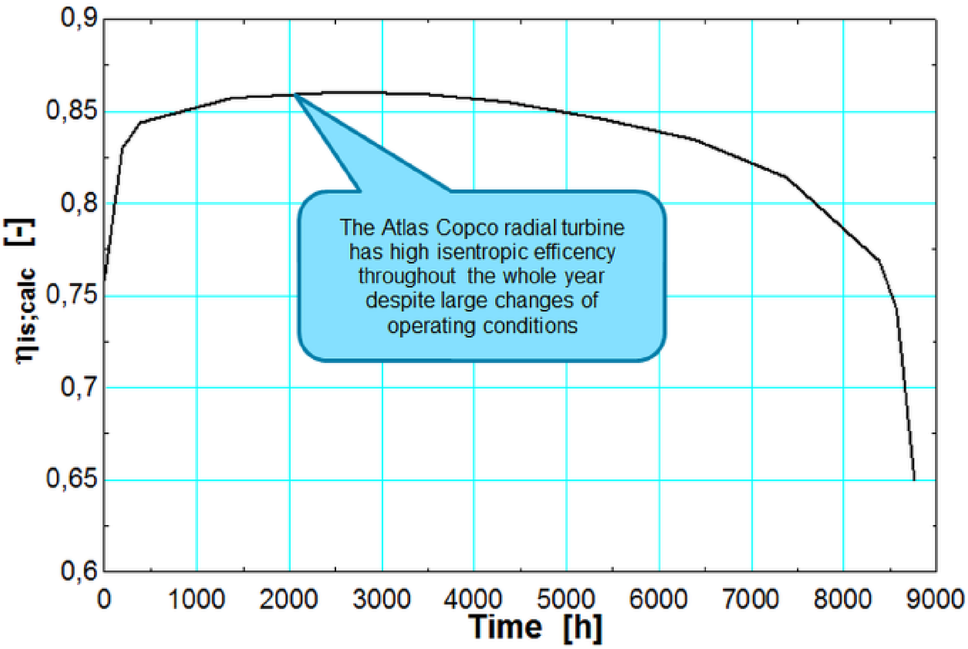

FIGURE 9: Turbine isentropic efficiency duration curves for cogeneration

4. TRANCRITICAL ORC POWER PLANTS

A transcritical ORC power plant has pressure higher than the working fluid critical pressure on the high pressure side of the plant. The condenser is operating in the same way as in a conventional ORC plant, having pressure well below the working fluid critical pressure. The working fluid is thus supercritical on the high pressure side and subcritical on the low pressure side, leading to the logical designation "transcritical" for the cycle.

The working fluid enters the high pressure side as compressed liquid. Heat is added to the fluid, but as the pressure is higher than the critical pressure, the fluid cannot boil. There are no bubbles created, there is no interface anywhere between a vapour phase and a liquid phase. The fluid just gets less dense and more vapour-like as the temperature increases. When the fluid has been heated to sufficiently high temperature, it can be expanded through a turbine.

The benefit of the transcritical cycle is that the temperature difference over which the heat is transferred in the "vaporizer" can be made less than what it is in a conventional ORC cycle, provided that the source fluid has only sensible heat. If heat is transferred over a finite temperature difference, entropy will be generated and exergy will be lost. This is minimised in the transcritical ORC cycle. Therefore the transcritcal cycle is at its best when the source fluid is liquid water or gas, and no condensation (latent heat) is in the source fluid.

A temperature-heat duty diagram of a transcritical cycle is shown on Figure 10.

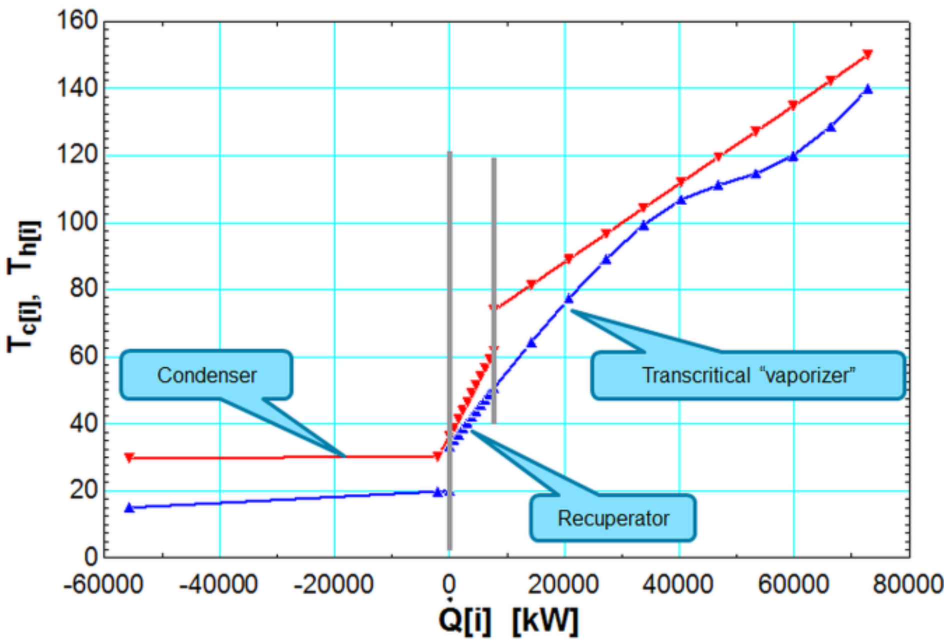

FIGURE 10: A temperature-heat duty diagram for a transcritical ORC cycle

Atlas Copco has already built and commissioned a transcritical 2 MW ORC plant for waste heat recovery in Judy Creek, Canada in December 2012. The design and construction of this plant has given valuable insight into the transcritcal ORC cycle, and is now as well offered for geothermal applications. Figures 11 and 12 show the main plant components.

5. NON-CONDENSABLE GAS (NCG) AND HYBRID ORC POWER PLANTS

High enthalpy geothermal wells usually deliver a mixture of brine, steam and non-condensable gas. The mixture is separated in a flash cycle, and the steam-gas mixture is then expanded through a turbine. The brine is disposed of at a temperature corresponding to the separator pressure, which is in turn a result of an optimisation, taking well productivity and cycle performance into consideration. In many cases the brine can be cooled to a still lower temperature before scaling occurs.

The selected separator pressure sets a limit to which wells can be used. If a well has not sufficient wellhead pressure to bring a decent amount of fluid to the separator, then the well is unusable and the investment in the well has to be written off.

The gas which went through the turbine will not condense, and has to be removed from the condenser. This may require considerable effort, as the condenser pressure in a flash plant is 90% or so of absolute vacuum. Figure 13 shows a simple schematic of such a flash plant.

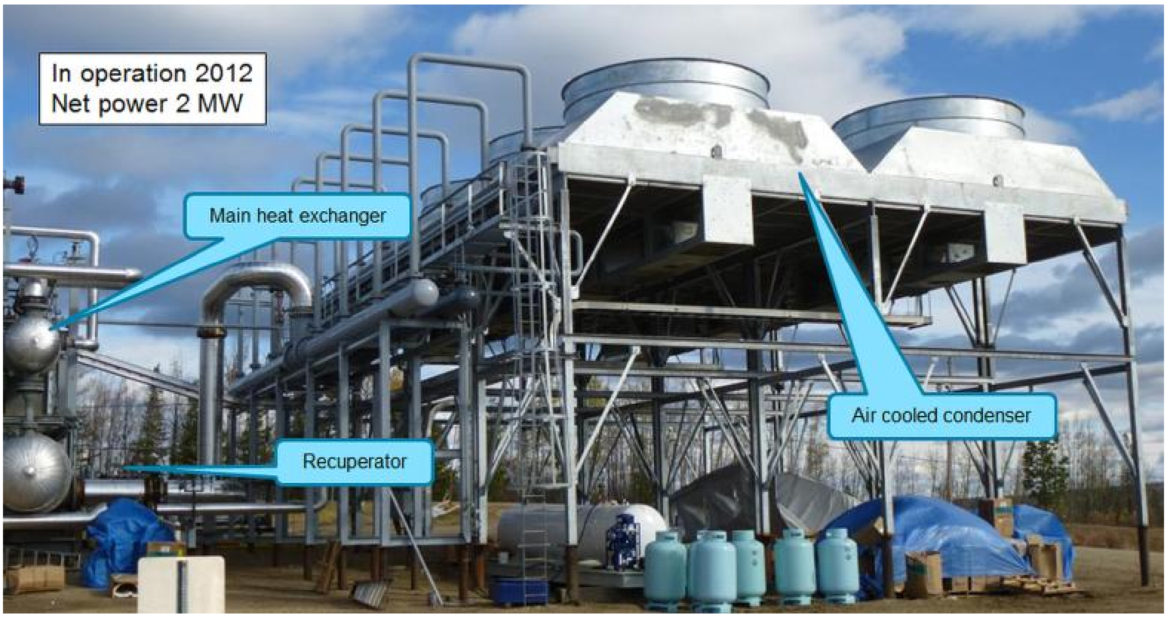

FIGURE 11: The cold end of the transcritical ORC plant in Judy Creek, Canada

FIGURE 12: The hot end of the transcritical ORC plant in Judy Creek, Canada

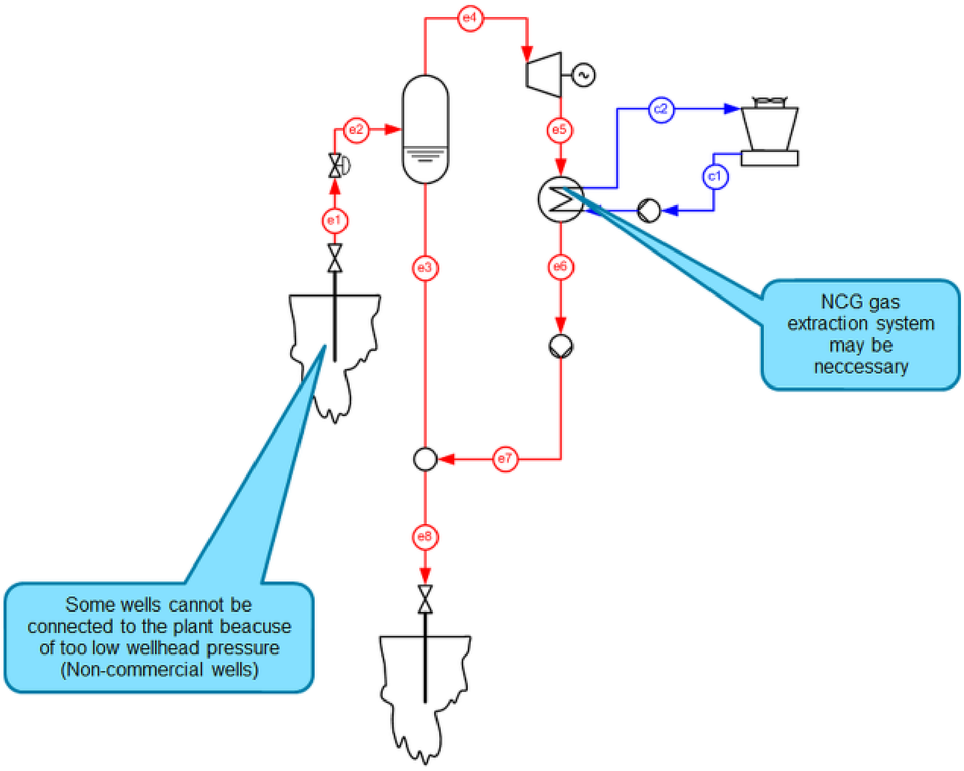

FIGURE 13: Simple flash plant schematic

A hybrid plant has both a steam turbine and an ORC cycle attached. The steam turbine is then a back pressure turbine, and serves the purpose of lowering the pressure against which the wells will have to produce. The back pressure of the steam turbine has to be higher than atmospheric pressure to facilitate easy disposal of the non-condensable gas, but still low enough to allow wells with lower wellhead pressure to be connected. Figure 14 is a simple schematic of a hybrid geothermal power plant.

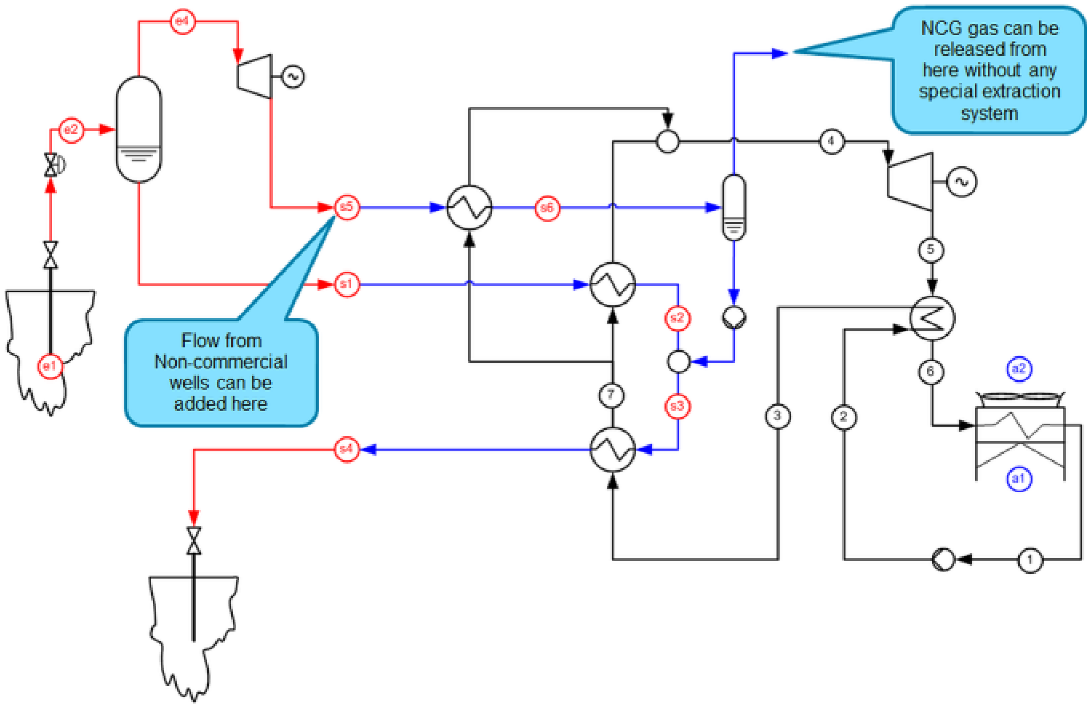

FIGURE 14: A simple schematic of a hybrid geothermal plant

An added benefit of the hybrid plant is that the steam condensate can be mixed with the brine before it gets really cold. Having diluted the brine will result in that the brine scaling limit is lowered and more heat can be extracted from the geothermal source fluid.

REFERENCES

Bertani, R., 2010: Geothermal power generation in the world 2005–2010 update report. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 41 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0008.pdf

Samorka, 2014: *Upplýsingar um hitaveitur á Íslandi (Information on district heating systems in Iceland)*. Icelandic Energy and Utilities. Website: http://samorka.is/Apps/WebObjects/SW.woa/wa/dp?id=2162

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PROBLEMS IN GEOTHERMAL OPERATION – SCALING AND CORROSION

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ABSTRACT

Geothermal systems are found around the world in various geological settings. The high temperature fields are found in the volcanic regions, but medium and low temperature fields are found in most parts of the world. The largest of those are found in sedimentary basins where water heats up to useful temperatures (50-150°C) due to the continuous heat flux through the crust to the surface and in fracture systems in seismically active areas where surface water penetrates into the crust through active fractures and mines the heat out of the formations at few kilometre depth forming a water convection system within the crust.

Geothermal energy resources have been utilized by mankind through the centuries for bathing and domestic uses i.e. for washing, cooking and baking. The utilization spectrum changed drastically at the beginning of last century when technology to produce electricity from geothermal steam became available and various direct uses of geothermal were developed i.e. for space heating and greenhouse heating, in aquaculture and industry and in snow and ice melting in addition to the balneology uses. The utilization of geothermal increased steadily during the last century and the most rapid development during the last decades has been the dramatic increase in use of geothermal heat pumps for space heating and cooling.

The utilization of geothermal has not been without technical, environmental and political/cultural problems. On the technical side, the most common problems have been related to the chemistry of the geothermal fluids which sometimes contain quite considerable concentrations of minerals and gases, which can cause scaling and corrosion in wells and surface installations which the geothermal fluids flow through. Many of these technical problems have been solved, or minimized at least, by improved well design and well operation, proper material selection and chemical treatment of the geothermal fluids, including use of chemical inhibitors.

This paper gives a short overview of the chemistry of geothermal fluids, their corrosive nature and the most common scales and depositions formed in geothermal wells and installations with case histories from Iceland.

1. INTRODUCTION

Geothermal resources are found throughout the world but exploited geothermal systems are mainly found in regions of high geothermal gradients. Even though the greatest concentration of geothermal energy is associated with the Earth´s plate boundaries, geothermal energy resources are found in most countries and the exploitation of geothermal systems in normal and low geothermal gradient areas has been gaining momentum during the last decades.

Geothermal systems and reservoirs are classified on the basis of different aspects, such as reservoir temperature, enthalpy, physical state or their nature and geological settings. Table 1 summarizes classifications based on the first three aspects.

TABLE 1: Classifications of geothermal systems on the basis of temperature, enthalpy and physical state (Bodvarsson, 1964; Axelsson and Gunnlaugsson, 2000).

<table>
<tr><td>***Low-temperature*** (LT) systems with reservoir temperature at 1 km depth below 150°C. Often characterized by hot or boiling springs.</td><td rowspan="2">***Low-enthalpy*** geothermal systems with reservoir fluid enthalpies less than 800 kJ/kg, corresponding to temperatures less than about 190ºC.</td><td rowspan="2">***Liquid-dominated*** geothermal reservoirs with the water temperature much below, the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir.</td></tr>
<tr><td>***Medium-temperature*** (MT) systems with reservoir temperature at 1 km depth between 150-200°C.</td></tr>
<tr><td rowspan="2">***High-temperature*** (HT) systems with reservoir temperature at 1 km depth above 200°C. Characterized by fumaroles, steam vents, mud pools and highly altered ground.</td><td rowspan="2">***High-enthalpy*** geothermal systems with reservoir fluid enthalpies greater than 800 kJ/kg.</td><td>***Liquid-dominated*** geothermal high temperature reservoir with the water temperature at, or below, the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir. Steam may be present, especially in the hotter systems where the temperature and pressure follow the boiling point curve through the reservoir</td></tr>
<tr><td>***Vapour-dominated*** *reservoirs* where temperature is at, or above, boiling at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some liquid water may be present.</td></tr>
</table>

Geothermal hot springs have been used by mankind through the centuries for bathing and for washing, cooking and baking. The hot springs for these uses were mostly outflows from underlying low temperature (LT) reservoir. At the beginning of last century the technology developed to utilize geothermal steam from geothermal high temperature (HT) wells to generate electricity and to use geothermal waters from hot springs and wells for space heating on a large scale. The steam for power generation was obtained from high temperature (HT) reservoirs, first from vapour dominated fields but later from two-phase liquid dominated systems. For conventional geothermal turbines using the steam directly the inlet pressure is in the range of 2-20 bar (Eliasson et al., 2014) On a much smaller scale electricity is also generated from medium temperature resource and low temperature resource for reservoir temperature, or as a "bottoming cycle" using waste water from conventional generation, at temperatures as low as 120°C with the use of binary turbines. The geothermal direct uses also developed during the last century and soon included greenhouse heating, industrial drying and agricultural drying, fish farming and cooling and snow melting and more. Country reviews presented at the World Geothermal Congress in 2010 confirmed that geothermal energy resources have been identified in over 90 countries and 78 of them utilize geothermal resources. Installed geothermal electric power was 10.7 GW in 2009, producing 67 TWh/y of electricity (Bertani, 2010) and direct uses were estimated to be 122 TWh/y (Lund et al., 2010).

Large scale geothermal utilization has been ongoing for more than a century. The development has not been without problems, of course. The operational problems are of different type and include political, cultural and environmental issues on top of technical problems in harnessing the geothermal resources. The most common technical problems in geothermal utilization have been related to the chemistry of the geothermal fluids which sometimes contain considerable concentrations of minerals and gases which can cause scaling and corrosion in wells and surface installations which the geothermal fluids flow through.

This paper gives a short overview on the chemistry of geothermal fluids with respect to the corrosive nature of these fluids and the most common scales found in geothermal installations. Examples of corrosion and geothermal scales experienced in geothermal exploitation in Iceland are discussed and how they have been handled. Iceland is at a plate margin characterized by high heat flow. Due to the high heat flow hot springs are abundant in the country. About 1000 geothermal localities have been recognized in Iceland. Geothermal water is generally of meteoric origin, i.e. it is rainwater which has fallen to earth and sinks deep beneath the earth's surface where it is heated up by hot substrata and magma intrusions.

The high-temperature geothermal fields are all located within the volcanic zone (Figure 1) and there the temperature is higher than 200°C at 1000 m depth. The thermal manifestations are boiling water, mud pools, fumaroles and steam vents. The low-temperature fields are located at the flank of the volcanic zone, and there the temperature is lower than 150°C at 1000 m depth. The thermal manifestations are warm water to boiling hot springs.

The most significant use of geothermal energy in Iceland is for space heating and the low-temperature geothermal fields are the main source for this utilization.

The chemistry of the geothermal fields differs in composition mainly according to temperature. In the low-temperature fields the water is usually dilute. In the district heating utilities the water is usually used directly in flow through system. Most of the high-temperature geothermal fields are also of the dilute type except the fields on the Reykjanes peninsula. The water flows through basaltic lavas resulting in high pH of the low-temperature waters, usually pH between 9 and 10.

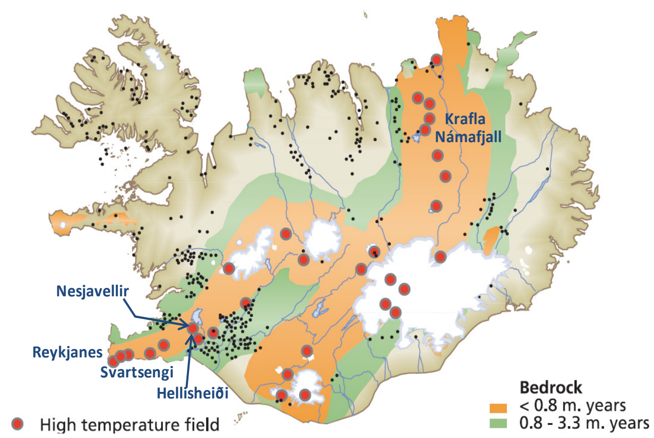

FIGURE 1: Location of geothermal fields in Iceland. The developed high temperature geothermal fields are shown with blue text.

2. GEOTHEMAL RESERVOIR FLUIDS AND THEIR CLASSIFICATION

Geothermal fluids refer to the fluids (steam, water, gas) in geothermal reservoir. These are liquid waters with dissolved solids and gas for the low- to medium temperature reservoirs but in boiling high temperature system geothermal liquid, steam and gas are found separately or together. Whatever state the fluid is in, depends on the reservoir temperature and pressure. When the fluid travels as a mixture of liquid and vapour (water and steam), it is referred to as two-phase. The dissolved minerals, silica and salts, are practically only found in the liquid phase. Another component of the geothermal fluids is the gas, mainly carbon dioxide, which is dissolved in the liquid phase inside the reservoir but is transferred to the steam phase upon boiling of the water. Other common geothermal gases are hydrogen sulphide, hydrogen, methane, nitrogen and argon. Oxygen, however, is usually of very low concentration in geothermal fluids for three reasons (1) the solubility of oxygen in water decreases rapidly with temperature from atmospheric and is practically zero at temperatures above 100°C and (2) geothermal fluids usually contain hydrogen sulphide which reacts with the oxygen and eliminates it from the fluid solution and (3) down to a temperature of about 80°C oxygen is taken up by rock in water-rock reactions. Oxygen is therefore only found in low temperature (<80°C) non-sulphide fluids in geothermal systems at relatively shallow depths in the crust.

Geothermal waters in-land areas are mainly of meteoric origin but oceanic waters are found in geothermal systems in coastal areas and in systems under the oceanic floor. Magmatic waters have been detected in geothermal waters in volcanic systems. Ellis and Mahon (1978) classified geothermal water into four categories based on major ions:

- Alkali-chloride water: pH 4-11, least common in young rocks, e.g. Iceland. These are mostly sodium and potassium chloride waters although in brines Ca concentration is often significant. Alkali-chloride water is however found in some mature geothermal waters in Iceland, e.g in the Theistareykir system.
- Acid sulphate water: These waters arise from the oxidation $H_2S \rightarrow SO_4$ near the surface and most of its constituents are dissolved from surface rock. Thus such water is generally not useful for prediction of subsurface properties.
- Acid sulphate-chloride water: such water may be a mixture of alkali chloride water and acid sulphate water, or it can arise from the oxidation $H_2S \rightarrow SO_4$ in alkali-chloride water or dissolution of S from rock followed by oxidation. Sulphate-chloride waters need not be very acid and may then reflect subsurface equilibria and be used for prediction of subsurface properties.
- Bicarbonate water: Bicarbonate water may derive from CO_2 rich steam condensing or mixing with water, it is quite common in old geothermal waters or on the peripheries of geothermal areas in outflows. They are commonly at equilibrium and may be used to predict subsurface properties. This is probably the most common group in equilibrated waters in Iceland.

A good way of distinguishing between the different types of geothermal water is the use of the chloride-sulphate-bicarbonate ternary diagram described by Giggenbach (1991). An example from Uganda is shown in Figure 2, where the geothermal water from one area, Kibiro, is a typical alkali-chloride water, the water from another, Buranga is a relatively alkaline chloride-sulphate-bicarbonate water, but the geothermal water from the third one, Katwe, is a sulphate water. The cold groundwater in the areas is scattered.

The dissolved constituents of geothermal water may originate in the original meteoric or oceanic water, but more likely they are the result of water-rock interaction and possibly modification by magmatic gas. They are divided into rock forming constituents, e.g. Si, Al, Na, K, Ca, Mg, Fe, Mn and incompatible constituents, e.g. Cl, B, Br.

Products of geothermal alteration are of rocks is controlled by temperature, pressure, chemical composition of water (e.g. CO_2, H_2S), original composition of rock, reaction time, rate of water and steam flow, permeability and type of permeability and these products in turn control the chemical composition of the fluid. Some of the effects are that the silica concentration of the reservoir water depends on the solubility of quartz/chalcedony which is temperature dependent Al-silicate ion-exchange equilibria control Na/K, Na/Rb ratios, pH is controlled by salinity and Al-silicate equilibria involving hydrogen and alkali ions, Ca^{+2} and HCO_3^- concentrations depend on pH and CO_2 concentration because of equilibrium between the fluid and calcite, F^- and SO_4^{-2} concentrations are related to that of Ca^{+2}, limited by solubility of fluorite and anhydrite and temperature and salinity dependent silicate equilibria control a very low Mg^{+2} concentration. The results of alteration studies show that the chemical composition of geothermal fluids originates in controlled reactions dependent on temperature, pressure and rock composition. Therefore it is possible to deduce the properties of subsurface water, e.g. the reservoir temperature, from the chemical composition of water which has been collected at the earth's surface.

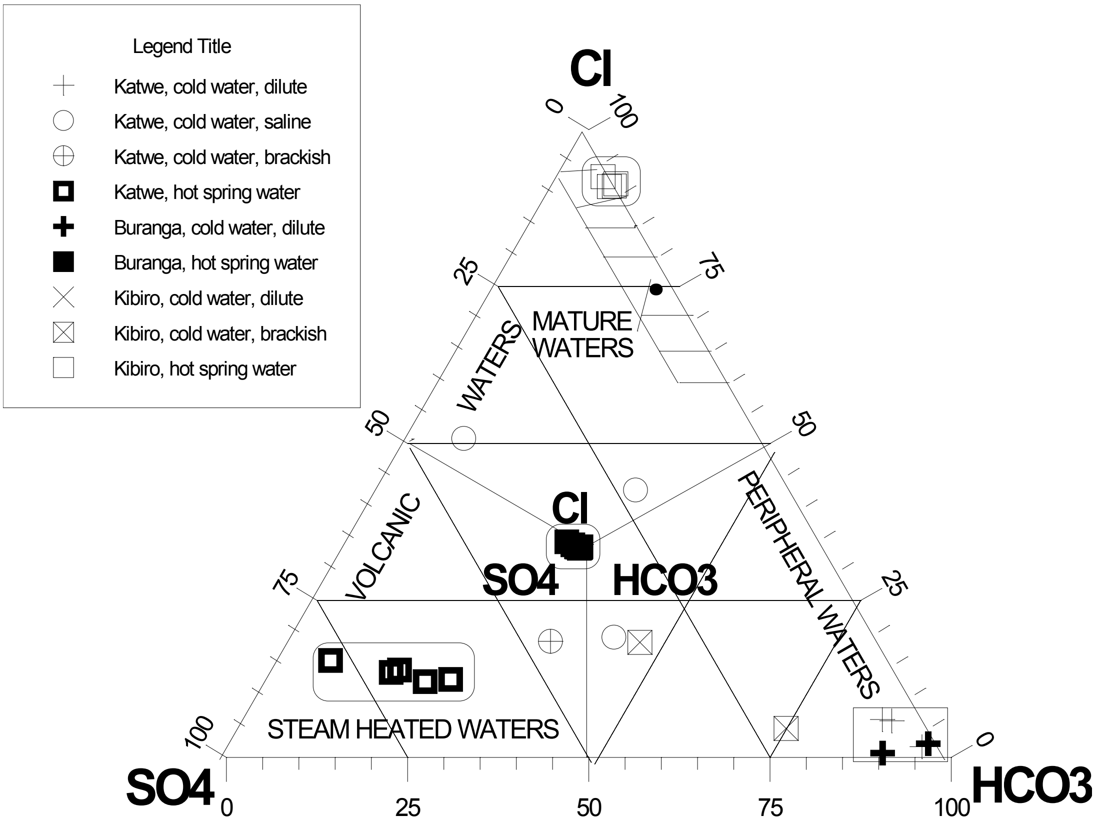

FIGURE 2: A ternary Cl-SO_4-HCO_3 diagram showing the characteristics of waters from different Ugandan geothermal systems

3 CORROSION FROM GEOTHERMAL FLUIDS

The corrosive potential of geothermal fluids is very variable. Miller (1980) identifies the main species in geothermal that are of interest regarding corrosion. These are:

- Hydrogen Ion: The corrosions rates of most materials increases as the pH of the fluid decrease. Geothermal low temperature waters are usually of high pH (pH 8-10) and high temperature fluids near neutral (pH 6-8) but extreme waters exist with pH as low as 2 and as high as 12. Low pH waters corrode carbon steel and cause corrosion cracking in in stainless steels. Thus the most common material selected for casings, pipes and vessels in contact with geothermal fluids is simply mild steel.

- Chloride: The chloride ion accelerates corrosion of metallic surfaces. The corrosion often happens in localized areas so-called “pitting” as well as uniform corrosion. Many grades of stainless steel are susceptible to stress corrosion cracking when exposed to waters high in chloride mild temperatures and oxygen.
- Hydrogen Sulphide. Copper and its alloys are attacked by hydrogen sulphide. Sulphide stress cracking in high strength steels is a potential problem in geothermal and use of these steels should be minimized and mild steels used instead. Hydrogen Sulphide reacts with mild steel and forms a productive coating and perhaps a thin crust of scaling and are thus protective on the inside of pipes and vessels.
- Carbon Dioxide: Carbon dioxide is a mild oxidizing agent that causes increased corrosion of plain carbon steels.
- Ammonia: Ammonia causes increased corrosion of copper-based alloys, and is especially important in relation to plain stress corrosion cracking. Mild steels are adversely affected by ammonia.
- Sulphate: Sulphate is the primary aggressive ion in some geothermal fluids.
- Oxygen is usually not present in geothermal fluids except in fluids at low temperature. Oxygen corrosion is therefore uncommon in geothermal wells but intrusion or diffusion of traces of oxygen into the geothermal fluid as it flows through the geothermal installations can make the water highly corrosive. Hydrogen sulphide in the geothermal water will on the other hand react with the oxygen and prevent corrosion as long as it is found in the solution.

The selection of materials for the construction of geothermal wells and fluids (liquid, steam or both) installation is one of the factors of importance in the original design of geothermal utilization schemes which are expected for long service life. Most geothermal fluids are, however, not corrosive and the main casing and pipe material selection is simply to use mild steel. There are localized problems of corrosions found in most geothermal installations, but most of them are manageable with proper material selection, operation and maintenance. The condensate is, however, corrosive and then stainless steel pipes or fibreglass are required. Copper cannot be used in presence of H_2S in the fluid and H_2S found in the ambient air around geothermal power plants, requires the air in control rooms and electrical switchgear to be filtered to remove any H_2S from the atmosphere to protect the copper wiring.

Acid fluids from geothermal wells. Truesdell et al., (1989) and D‘Amore et al., (1990) came to the conclusion after the study of several areas (e.g. Tatun, Taiwan, Larderello, Italy, The Geysers, USA and Krafla, Iceland) that the origin of acid fluids in geothermal systems was magmatic.

Acid fluids in the Krafla geothermal system, North-Iceland. Since the beginning of the development of the Krafla field in 1974, the output and the chemical properties of steam and water from wells has been closely monitored.

Initially the wells were drilled in fields north of the power plant (Leirbotnar and Vítismór). It turned out that in these areas the reservoir is of dual character. The shallow part down to 1000 to 1400 m depth contains hot water (210 to 220 °C). The water in this upper zone contains little gas and has alkaline character. Silica and other dissolved ions are in close equilibrium with the rock minerals at measured temperature.

In these shallow wells the CO_2 gas concentration increases towards the fissure Hveragil (Figure 3) that is considered the main upflow path for steam from the deep reservoir to the surface. In the shallow wells close to the Hveragil fissure, calcite precipitation causes well blocking while in wells, just few hundred meters to the west, this problem is absent (Ármannsson et al., 1982).

Initially deep wells were cased down to 600 m depth and the inflow was both from the shallow hot water aquifer and also from aquifers at around 1800 to 2200 m depth. The temperature of the deep aquifers was 300 to 340 °C and the inflow water and steam and in some cases superheated dry steam. Few months after the construction of the plant started there was an eruption in the Leirhnjúkur volcano to the northwest of the power plant. At that time only three wells had been flow tested. Well KG-3 was a good producer with a low steam gas concentration. Shortly after the eruption there was a sudden increase of steam gas concentration in this well. The output of the well decreased rapidly and the well was unusable after few months (Gíslason and Arnórsson 1976).

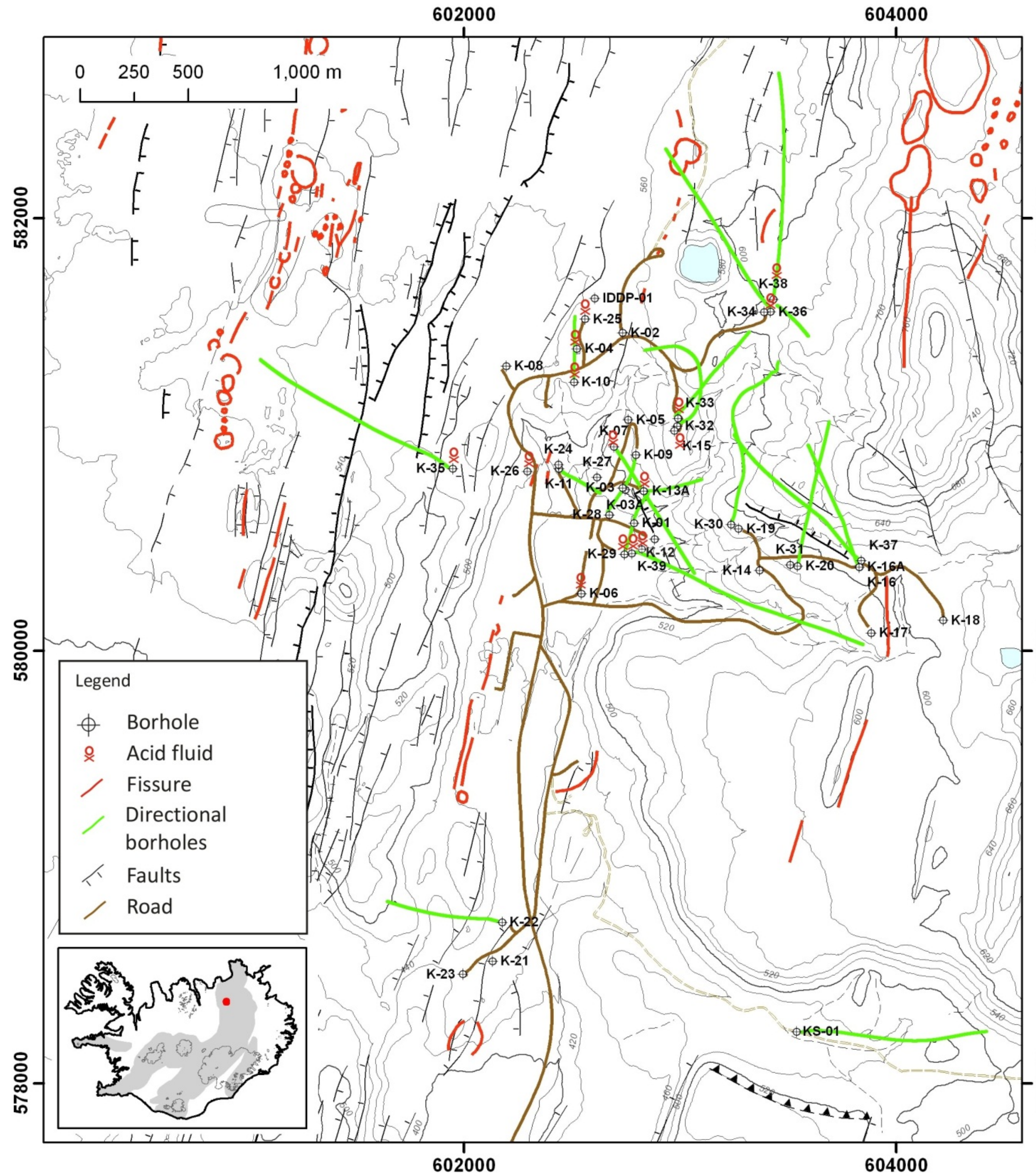

FIGURE 3: Krafla - wellfields and wells

Well KG-4 was being drilled when the eruption started. Before well completion, high-pressure steam, from deep aquifers, flowed up the well and into the shallower aquifers of the upper zone. The well was completed in a hurry but the wellhead was not designed for the high pressure and started to leak. The steam contained acid and the wellhead corroded rapidly and in the end the situation was uncontrollable and the well went out of control and formed a crater. The water, which flowed from the crater, had a pH of 1.86 (Gíslason and Arnórsson 1976).

Further drilling was postponed and the well design revised. The casing depth was increased to 800 m and the wellhead pressure-class increased.

Some of the wells drilled subsequently in Leirbotnar and Vítismór (KJ-6, KJ-7 and KG-10) turned out to be high in enthalpy and high in gas concentration. The effluent water had a black colour caused by precipitation of iron sulfides and silicates that formed in the well when acid fluids, containing iron from the corroding liner, mixed with alkaline water from the upper aquifers. The output of these wells decreased rapidly, produced mostly from the upper zone and were unusable. They were reamed and found to be clogged with iron sulfide and silicate scales (Swanteson and Kristmannsdóttir 1978). When flow tested, after reaming they were rapidly clogged again.

The well design was again revised and the casing depth increased to block the inflow from the upper zone and avoid precipitation of iron compounds in the wells. Well KG-12 was drilled to 2222 m depth and cased to 985 m. Its flow was superheated dry steam containing hydrogen chloride (HCl) which was converted to hydrochloric acid upon condensation. Examination of the wellhead showed great damage by acid corrosion and the turbine blades suffered erosion by iron chloride dust formed during the corrosion. The corrosion was most rapid at sites with conductive cooling (vents and flanges) and where the flow speed was high (orifices and bends). To make the steam usable for the plant the wellhead was insulated to prevent condensation and the steam mixed with alkaline water from the nearby well KJ-9 (Hauksson 1979).

Well KG-12 produced for a few years but the enthalpy dropped gradually and water started to flow from the well. The steam flow decreased rapidly for the first two months but was after that relatively stable until 2004 when the wellhead pressure was too low for the well to be usable (Hauksson and Benjamínsson 2005).

The CO_2 gas concentration in steam from the wells in Leirbotnar field decreased steadily after reaching a maximum soon after the eruptions started. A few wells have been drilled over the years to check whether the acid character of the deep zone was also decreasing (KG-25, KG-26 and KJ-29). The flow from the deep aquifers turned out to be acid as before, despite the decrease in CO_2 gas concentration of the steam.

It became evident that the drilling field would have to be relocated in order to supply the plant with sufficient good quality steam. Wells were drilled in the south slopes of the Krafla mountain (Suðurhlídar) and in an area south of the power plant (Hvíthólaklif) where chemical analysis of steam from fumaroles had indicated less magmatic influence than in the Leirbotnar and Vítismór (Ármannsson et al., 1982).

The steam quality was better but the productivity of the wells was insufficient. The plant was thus operated at half power for several years. The gas changes due to the magmatic activity were described in detail by Ármannsson et al., (1982, 1989).

Later (1997 to 2000) a new drill field in the west slopes of the Krafla mountain was explored (Vesturhlíðar). This field was productive and since 1999 the power plant has been operated at full power (Guðmundsson 2001). The concentration of CO_2 and H_2S gas in well steam is relatively high, but acid steam was not observed.

Recently seven new wells have been drilled to obtain steam for further expansion of the Krafla power plant.

Well KJ-35 was located northwest of the plant and directionally drilled towards the Leirhnúkur volcano. It was a good producer but the output declined steadily during flow test. The chemical analysis of the fluid collected at wellhead did not show clear evidence of acid or iron precipitation in the well (Giroud et al., 2008). Logging of the well showed blocking at 1960 m depth and a plug consisting of iron sulfide and silicate similar to the scale that had blocked other acid wells in Krafla.

Well KJ-36 was located southeast of the Víti crater and directionally drilled to northwest under the crater. When flow tested the well was very powerful. The steam collected at the wellhead was acid and corrosive. The flow test was stopped after 6 days when a hole had formed in the wellhead pipe. The well was tested again for 32 days after fortification of the wellhead. The steam was still acid but turned from dry steam into saturated steam after a while. The corrosion rate was very rapid so the well was shut in and the acid aquifer blocked off by cementing (Hauksson and Gudmundsson 2008). Now the well produces from aquifers at 1600 to 1700 depth and the steam is used for the plant.

Well KJ-38 is located on the same platform as well KJ-36 and drilled to the north. It has also hit acid aquifers.

The location of the wells in Krafla is shown in Figure 3 and those wells, that have hit acid aquifers, are shown with a red symbol. Generally wells, which are deeper than 2000 m and west of the Hveragil fissure, have hit acid aquifers. Wells east of this fissure have not been contaminated.

Collection of representative samples from the deep acid aquifers has been difficult. The first wells were of dual character and alkaline water from the upper zone obscured the character of the deep zone steam. By mass balance calculations it was possible though to show that the inflow was of acid character (Hauksson 1980).

Well KG-12 was drilled with a 985 m deep casing and a sample of the deep steam could be obtained (Hauksson 1979). The casing in well KG-25 was drilled was 1145 m deep but the upper alkaline zone reached deeper there and alkaline water flowed into the well at a depth of 1455 m (Ármannsson and Gíslason 1992).

In well KJ-36 the deep acid aquifer was very powerful and initially the flow from shallower aquifers did not obscure the character significantly (Hauksson and Gudmundsson 2008).

The first Iceland Deep Drilling project well was drilled in Krafla in the first half of 2009 (IDDP-01, Figure 3). The drill rig hit magma at about 2100 m depth and drilling was stopped. The well was designed to be drilled into a high temperature hydrothermal system with the goal of finding a 400 – 600 °C hot superheated or supercritical fluid. The composition of the superheated steam shows acidity similar to that of wells K-12 and K-36 but appears relatively benign. The chloride concentration was considerably higher in both wells KG-12 (112 mg/kg) and KJ-36 (400 mg/kg) fluid. The pH is certainly not lower and there seems no chance of condensation during the steam‘s passage to the surface so no acid fluid should be formed until the steam has reached the surface and condensed and can be dealt with adequately. The acid gas could effectively be scrubbed from the steam with water. The steam contained a gaseous sulphur compound (80–100 mg/kg S), which could only be scrubbed from the steam with alkaline water. The steam contained both silica dust and dissolved silica which was effectively washed from the steam with wet scrubbing. Experiments on corrosion and erosion resistance of metals and alloys were problematic to run because of equipment clogging by silica dust.

4. GEOTHERMAL SCALES

Several types of scales are observed in geothermal wells and installations. These include carbonate minerals (calcite and aragonite), amorphous silicates, and metal oxides and sulphides. The most common geothermal scales are silica (SiO_2) and calcite ($CaCO_3$). Both these scales are white coloured and visually not easy to tell apart. The silica scales often appear grey or black due to small amounts of iron sulphide, a corrosion product found inside all geothermal pipelines. A quick method to distinguish these two is to put a drop of hydrochloric acid on a scale sample and if bubbles are formed it is calcite.

Scale analysis is otherwise a tedious process where X-ray diffraction (XRD) for identification of crystalline substances and electron microscopy (SEM) for distributive and qualitative analysis, are used together with wet chemistry analytical methods (Figure 4).

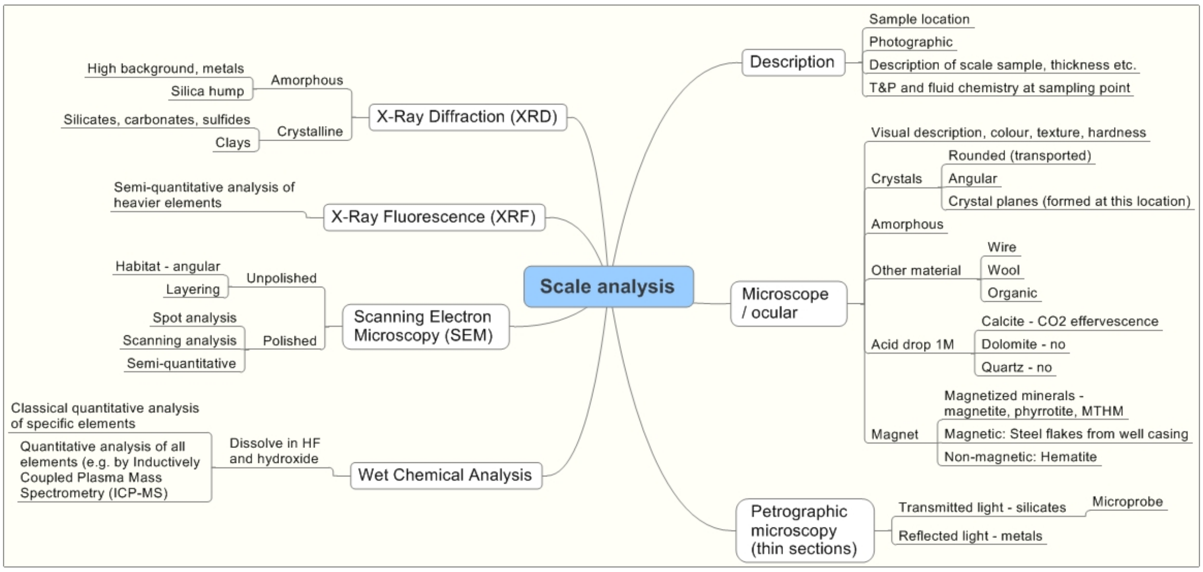

FIGURE 4: Methods used for geothermal scale analysis in Iceland (Thórhallson, 2012)

Silica scales. Silica scales are found to some extent in all high temperature geothermal installations but by maintaining the temperature above the solubility level for amorphous silica (the non-crystalline form of silica), the scaling should not occur and thus this is one of the design criteria for most geothermal plants. In this way the high-pressure separator will not scale, nor the reinjection pipeline, assuming that the so called "hot-injection" method is used. In the high temperature reservoir before the fluid is extracted, the silica concentration is usually in equilibrium with quartz, the crystalline form of silica. Once the water starts to boil and cool down, the silica concentration in the water increases due to the steam loss. The water immediately becomes quartz supersaturated but quartz precipitates are not formed because of the slow growth of quartz crystals. Silica scales are first formed when the amorphous silica solubility curve is passed (Figure 5). Looking at these two curves it is clear that the "window of opportunity" for operating the geothermal plants free of silica scaling lies between the quartz and amorphous curves. This means in practice that only some 25% of the water can be converted by "flashing" into steam from liquid dominated reservoirs without the danger of silica scales, almost independently of the temperature of the resource (flashing= rapid conversion of water into steam). A silica "rule of thumb" may say that it is only possible to cool the water by some 100°C without the risk of scaling. Reservoir water of 240°C has thus to be

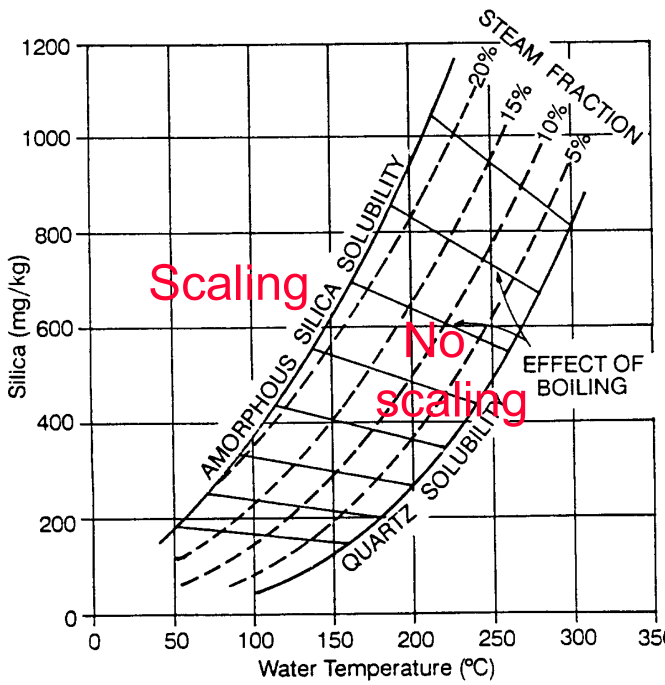

FIGURE 5: Solubility of silica in water. Scaling occurs above the amorphous silica solubility curve.

separated above 140°C to avoid scaling. For this reason it is not of as great importance as one might think that the reservoir temperature be as high as possible, because the higher the reservoir temperature, the higher the temperature of re-injected water needs to be that puts a lid on the thermal efficiency.

In the combined heat and power geothermal plants the precipitation of amorphous silica can occur when the separated water flows through heat exchangers. In the heat exchangers the separated water is cooled down and becomes supersaturated with respect to amorphous silica. This commonly causes scaling in the tubes of the heat exchangers which have to be removed regularly. In the dilute high temperature fields where the chloride concentration is low the precipitation of amorphous silica can be postpone by slow flow rate through heat exchangers allowing the aqueous silica to form polymers in the solution. This has been applied at the Nesjavellir power plant reducing silica scaling in the heat exchangers. After heat exchangers the separated water flows through a large retention tank for further polymerisation of the silica before condensate is mixed with the separated water and re-injected into subsurface.

In low temperature geothermal systems the silica content is governed by the solubility of the silica mineral chalcedony at low temperature and quartz at higher temperature. In water from the low-temperature areas, although it is cooled in the district heating systems down to about 20°C, silica saturation does not occur.

Iron silicate scales. If there is a significant concentration of iron in the fluid, deposition of iron silicates will set in at a higher temperature than the silica deposition but at lower temperatures iron tends to be deposited in the form of oxides. They often form with sulphide scales in saline geothermal fluids or in fluids disturbed by the effects of volcanic gas. These scales normally do not form at higher pressures than 16-18 bar and are contained by keeping the wellhead pressure above that.

Sulphide scales. In saline geothermal fluids or in fluids disturbed by the effects of volcanic gas sulphide deposits are prone to form by reaction of metal(s) with H_2S. In saline solutions these tend to comprise PbS (galena), ZnS (wurtzite, sphalerite), CuS (covellite), Cu_2S (chalcocite), $CuFeS_2$ (chalcopyrite) and bornite (Cu_5FeS_4). In Mt Amiata, Italy SbS_2 (stibnite,) is a major deposit. Where volcanic gas affects the system FeS_2 (pyrite) and FeS (pyrrhotite) are the most common sulphides. As recounted above such scales along with iron silicates were observed in several wells in Krafla, North Iceland during the Krafla fires 1975-1984 (Figure 6). In Reykjanes, Iceland wurtzite deposits are observed at high pressures but sphalerite becomes the dominant sulphide scale with pressure lowering. Galena, chalcopyrite, pyrrhotite and traces of bornite have also been observed (Ármannsson and Hardardóttir 2010). No specific measures have been taken there to deal with such deposits but one well was reamed due to loss of power and sulphide deposits removed but this did not help restore the power of the well.

FIGURE 6: Iron sulphide and silicate deposits in flow from a Krafla well

Calcium carbonate scales (in the crystalline forms calcite or aragonite) are common in wells with reservoir temperatures of 140-240°C, and are primarily found at the depth where the water starts to boil in the well. Flashing causes CO_2 stripping and a pH increase, which may lead to calcite deposition according to

$$Ca^{+2} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$$

Calcite solubility is retrograde, i.e. it decreases with increasing temperature and as the water and steam travel up the well, the calcite deposition stops rather suddenly. Calcite scales are thus primarily found over a 100-300 m long section in the well. The extent of supersaturation can be calculated and the reaction is very fast so rate experiments need not be carried out. A certain degree of supersaturation needs to be reached for calcite scaling to set off, so there is a small "window of opportunity" in this case. Geothermal water is saturated with respect to calcite at <240°C in the reservoir but at >260°C calcite deposition is usually not a problem.

Prediction of calcite scaling in Krafla wells. During the early stages of production from the Krafla field calcite scaling was observed in some of the shallower wells and reaming with a drill rig was the chosen method for controlling the scaling. It was important to know the extent of formation, its rate and the depth at which it was formed. The first step is to predict whether or not a deposit will form which is carried out by a thermodynamical calculation in which the supersaturation of calcite is found by comparing analysed values with theoretical values. In Figure 7 there is an example of a diagram showing supersaturation for well KJ-9 in Krafla. The diagram shows that at the reservoir temperature at the bottom of the well the sample is saturated but as the sample boils and cools it becomes significantly supersaturated but less so with further cooling. Deposition is expected to start soon after the initial boiling, rise to a maximum and then diminish.

A method of finding the extent of deposition is to collect a downhole fluid sample below the boiling level and compare the calcium concentration with that of a wellhead sample collected at a similar time and assume that the difference in concentration is due to calcite deposition. Information on flow from the well and the time of production can then be used to calculate the total mass of deposit formed in the well. This was done for well KJ-9 and a check could be carried out on this method because it was decided to deepen the well and the liners were removed from it. Thus it was possible to measure the length and thickness of the scale inside the liner and combine with caliper logs from the casing to determine the volume of scale formed. Analysis of the scale was 98.6% calcite and its density 2500 kg/m^3 and thus it was possible to calculate the mass of the deposit. The two results were compared as presented in Table 2.

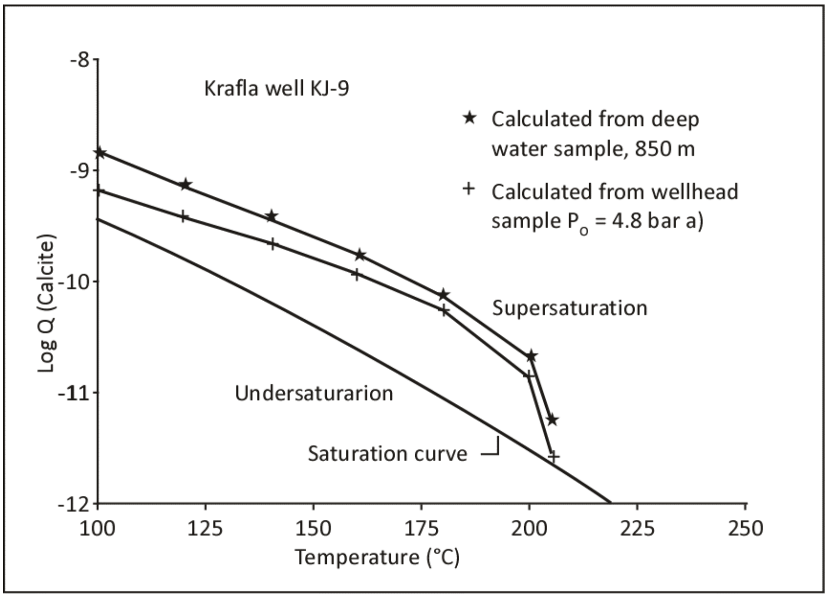

FIGURE 7: Calcite supersaturation in samples from well KJ-9, Krafla, North Iceland

TABLE 2: Quantity of calcite formed in well KJ-9, Krafla in 1977 according to determinations of volume of deposit and by calculation based on differences in calcium concentrations at wellhead and close to the bottom of the well.

Method	Volume determined (m^3)	Mass determined (kg)
Caliper log and thickness measurements	1.1	2700
Chemical analysis		2400

Thus it was confirmed that the method of determination of calcium in downhole and wellhead samples and assuming the difference to be due to calcite deposition was justified. It was also important to know how fast the deposition was taking place and this was observed by monitoring the flow of the wells and determining when a decrease in flow started. Generally when a decrease started it was very fast and the well soon became a very poor producer. The monitoring results for well KJ-9 (KJ-9, before deepening, KJ-9b after deepening showed that the period of relatively undisturbed flow was similar between reamings and this helped very much in planning the use of the well, the time at which the drill rig should be brought in for reaming. As is to be expected the wellhead pressure affects the scale formation because it will affect the depth at which the scale is formed. The higher the wellhead pressure the shallower is the depth at which deposits form. The clogging of the well occurs when the opening through which the fluid flows has become extremely narrow and therefore it is possible to prolong the period of relatively undisturbed flow by varying the wellhead pressure although this means that a greater quantity of deposit forms. Wangyal (1992) used the program Hola (Björnsson and Bödvarsson 1987) to calculate the flashing depth at different wellhead pressures for several wells in Iceland with the results shown in Figure 8. It is clear that by controlling the wellhead pressure the depth of deposit formation can be varied and if the producer can tolerate the reduced flow due to high pressure a smaller and cheaper drill rig may be deployed for reaming wells with deposits at a shallow depth.

Calcite inhibition. Several inhibitors have been used to prevent calcite deposition in geothermal wells. Examples of much used inhibitors are Dequest 2006 (Aminotri (methylene phosphonic acid) 38-42%), Nalco 95D0666 (Polymaleic acid 30-60% ,maleic acid 1-5%), Nalco 1340 HP (Polyacrylate) and Drewsperse 747A (Polycarboxylic acid 40-55% (Acrylic copolymer)). Tests in Krafla proved Nalco 1340HP most effective Hauksson et al., 1999), but a 5% concentration was too low because of precipitation due to bacterial growth and polymerization of the inhibitor. Increasing the concentration to 10% and using deionized, instead of geothermal water was successful.

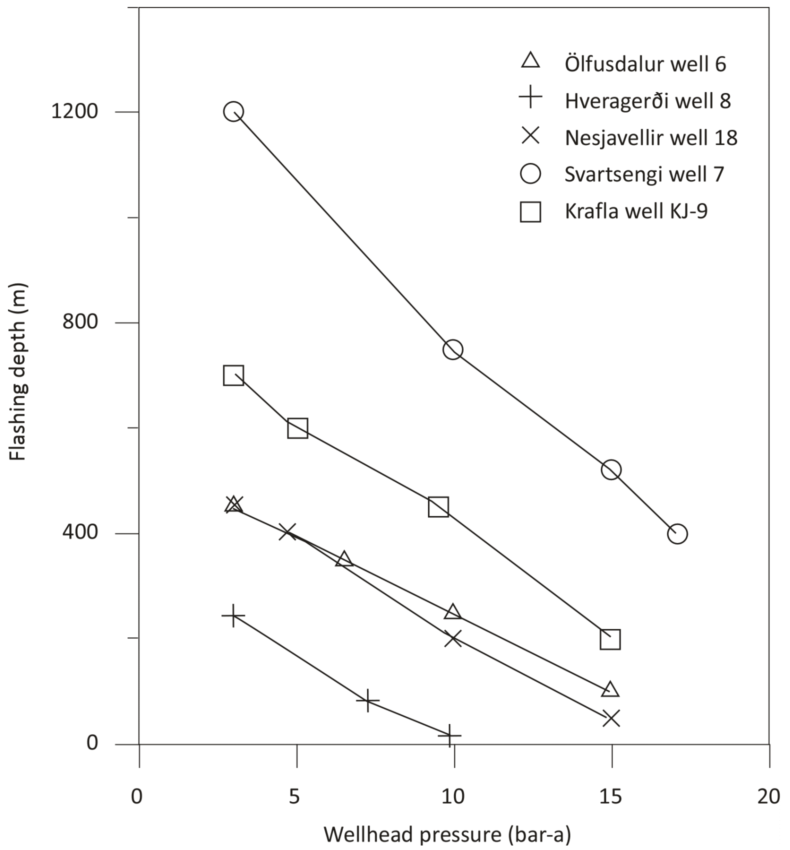

FIGURE 8: Flashing depth versus wellhead pressure in some geothermal wells in Iceland

Calcite scaling in low temperature geothermal fields in Iceland. The most significant use of geothermal energy in Iceland is for space heating and the low-temperature geothermal fields are the main source for this utilization. The geothermal reservoir water is in equilibrium with calcium carbonate and the silica content is governed by the solubility of the silica mineral chalcedony at low temperature and quartz at higher temperature. Saturation with respect to amorphous silica is not reached in water from the low-temperature areas although it is cooled in the district heating systems down to about 20°C. Here two examples will be given of calcite scaling in low-temperature fields in Iceland.

Sudureyri district heating. Sudureyri geothermal field is located in Northwest Iceland. This district heating started operation in 1978 serving the village of Sudureyri with about 350 inhabitants. Two drillholes are productive and both with calcite scales (Ólafsson, 1999). During exploitation chloride concentration increased up to 300 mg/l during 1975-1987 but reduced when a new well was drilled to 70 mg/l leading to supersaturation of calcite as higher calcium concentrations are in the chloride rich water of seawater origin (Figure 9). The scaling has been overcome by injection of a poly-phosphate inhibitor through a capillary tube to a position below the pump.

Laugarnes geothermal field Reykjavík. Exploitation from the Laugarnes geothermal field in Reykjavík was initiated in 1930. In the beginning only artesian flow was used from relatively shallow drillholes. Deep drilling began in 1958 and the first downhole pump was installed a year later. Artesian flow ceased in 1965 due to draw-down and since then downhole pumps have been operated in the wells (Gunnlaugsson and Ívarsson, 2010). The maximum production rate during the coldest part of the year is about 330 l/s. The fluid from the field was low in total dissolved solids, about 350 mg/kg, of which about 35 mg/kg was chloride.

Production from the field has caused pressure drawdown within the production well field. The exploitation of the field has not had any effect on the production temperature, but some gradual changes have been measured in the fluid chemistry after 1980 when production was increased in the western part of the field. The concentration of chloride has doubled in some of the wells while other remains as initially. Two wells produced water in excess of 100 ppm chloride concentration. The changes in chemistry are most likely caused by infiltration of highly saline water into the uppermost part of the reservoir.

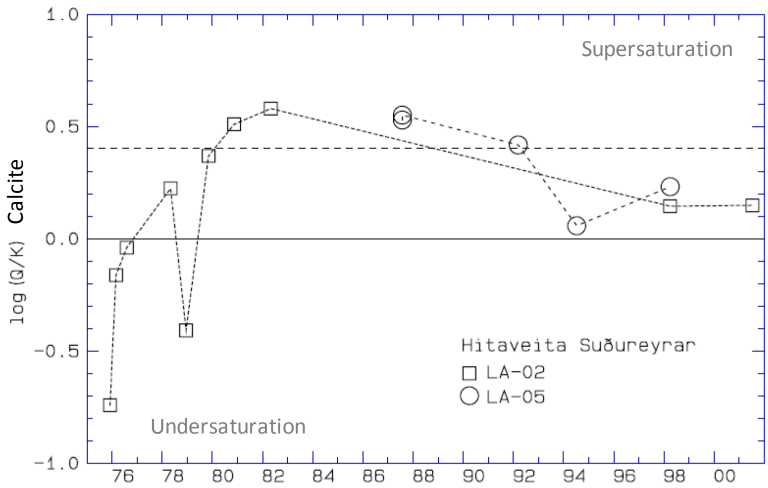

FIGURE 9: Calcite saturation for water from Sudureyri district heating (from Hardardóttir, 2002)

The mixing of the reservoir fluid with more saline water has caused calcite deposition in downhole pumps where the chloride concentration is higher than 100 ppm. Figure 10 shows the equilibrium curve for calcite as a function of temperature and comparison of calculated activity product for calcite for water samples from all wells in the Laugarnes field (Gunnlaugsson, 2004). Most samples are close to equilibrium at given temperature but water samples with higher chloride concentration (some of the red dots) show deviation from equilibrium. Figure 11 shows a graph where the solubility product of calcite for samples from one well with increasing chloride concentration is plotted against chloride concentration. The calculations are performed at 120°C and the equilibrium constant for calcite at that temperature is shown on the graph as horizontal line.

Some of the saline water enters the reservoir through wells due to shallow casings. To avoid leakage of saline water into the reservoir, the contamination has been stopped by plugging by cement some of the older drillholes in the field which showed inflow of saline water.

Magnesium silicate scaling. Magnesium silicates are formed upon heating of silica containing ground water or mixing of cold ground water and geothermal water. They have been shown to consist mainly of poorly developed antigorite (Gunnarsson et al., 2005) Their solubility decreases (deposition increases) with increased temperature and pH. The rate of deposition has been found to increase linearly with supersaturation but exponentially with temperature.

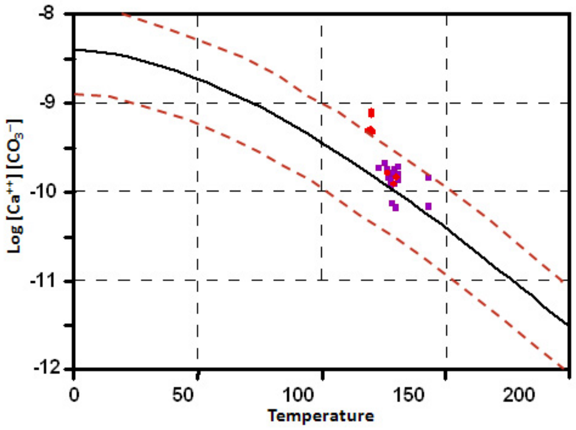

FIGURE 10: Solubility of calcite and degree of saturation of water from the Laugarnes field

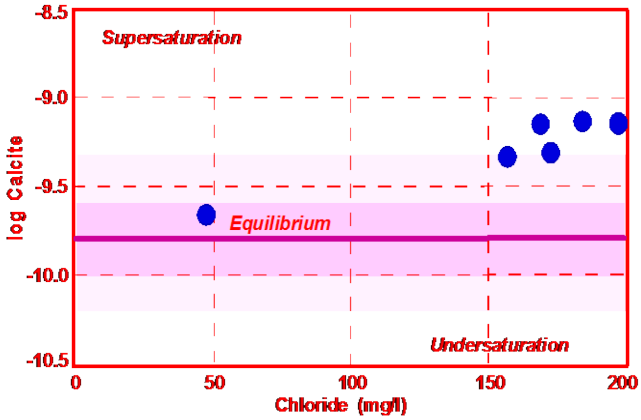

FIGURE 11: Changes of the solubility product of calcite with increasing chloride concentration

Magnesium silicate scaling has been encountered in several geothermal district heating systems in Iceland. The scaling occurs in power plants where heated freshwater after thermal deaeration reaches a high pH and also when geothermal and fresh waters are mixed.

Magnesium-silicate scaling in Icelandic district heating systems was first encountered in Hveragerdi where high temperature geothermal water and fresh water were mixed. In other district heating systems where magnesium rich fresh water is heated, precipitation of magnesium silicate may occur.

In 1990 the Reykjavík District Heating began utilizing heated freshwater from the Nesjavellir power plant. Previously, the company had only used low temperature waters from the geothermal fields in Reykjavik and the surroundings. Pilot plant experiments had indicated that some mixing of the deaerated freshwater and geothermal water could be tolerated if the mixing ratio was carefully controlled (Gunnlaugsson and Einarsson, 1989). After introducing the water from Nesjavellir, the deaerated water and heated freshwater was allowed to mix with the geothermal water, but control of the mixing ratio was insufficient and heavy scaling occurred in the pipeline system. It soon became evident that scaling was more severe than expected and an elaborated study of the problem was initiated. The results of experiments lead to the abandonment of any mixing and the distribution system was modified to keep the waters in two separate distribution networks, each serving different regions of the city (Hauksson et al., 1995).

The presence of magnesium silicate can be explained by studying the chemical composition of the water and compare it to the solubility of magnesium silicate precipitate.

The solubility of magnesium-silicate can be described by:

$$MgSiO_3 \cdot H_2O + H_2O = Mg^{++} + H_3SiO_4^- + OH^-$$

The solubility constant for the reaction depends on what precipitate is formed. The material has showed to be near amorphous magnesium silicate. In experiments in connection with magnesium scaling in Reykjavík the solubility of the precipitate was determined at few temperature values from 60 to 120°C, as shown in Figure 12 (Hauksson et al., 1995). The equilibrium constant can be described by the equitation:

$$\log(K_{sp}) = -12.90 + 0.00262T - 0.00006212 * T^2 \quad (1)$$

where T is in °C.

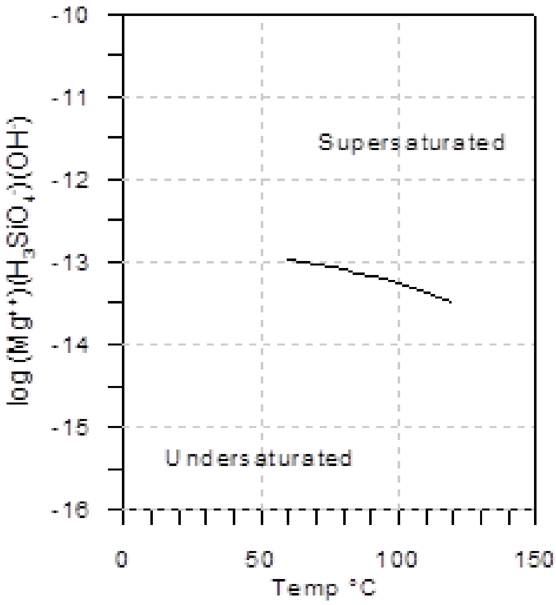

FIGURE 12: Solubility of magnesium silicate in the temperature range 60 to 120°C

REFERENCES

Axelsson, G., and Gunnlaugsson, E. (convenors), 2000: Long-term monitoring of high- and low-enthalpy fields under exploitation. *World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu District, Japan*. International Geothermal Association, 226 p.

Ármannsson, H., and Gíslason, G., 1992: The occurrence of acidic fluids in the Leirbotnar field, Krafla, Iceland. In: Kharaka, Y.K, and Maest, A.S. (editors), *Water-rock interaction.* Balkema, Rotterdam, Holland, 1257-1260.
.
Ármannsson, H., and Hardardóttir, V., 2010: Geochemicqal patterns in saline high temperature geothermal systems. In: Birkle, P., and Torres-Alvarando, I.S. (editors), *Water-rock interaction.* CRC Press, Taylor and Francis Group, London, 133-136.

Ármannsson H., Benjamínsson J., and Jeffrey A., 1989: Gas changes in the Krafla geothermal system, Iceland. *Chem. Geol., 76*, 175-196.

Ármannsson, H., Gíslason, G., and Hauksson, T., 1982: Magmatic gases aid the mapping of the flow pattern in a geothermal system. *Geochim. Cosmochim. Acta*, *46*, 167-177.

Bertani, R., 2010: World geothermal power generation 2005–2010. Update report. *Proceedings World Geothermal Congress 2010, Bali, Indonesia,* 41 pp.

Björnsson, G., and Bödvarsson, G.S., 1987: A multi-feedzone wellbore simulator. *Geothermal Research Council Transactions, 11*, 503-507.

Bödvarsson, G., 1964: Physical characteristics of natural heat sources in Iceland. *Proceedings UN Conference on New Sources of Energy, Volume 2: Geothermal Energy, Rome, Italy*. United Nations, New York, 82-89.

D'Amore, F., Truesdell, A.H., and Haizlip, J.R., 1990: Production of HCl by mineral reaction in high temperature geothermal systems. *Proceedings 15th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States*, 23-25.

Eliasson, E.T., Thorhallsson, S., and Steingrimsson, B., 2014: Geothermal power plants. *Presented at "Short Course on Utilization of Low- and Medium Enthalpy Geothermal Resources and Financial Aspects of Utilization, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador*, 16 pp.

Ellis, A.J., and Mahon, W.A.J., 1977: *Chemistry and geothermal systems.* Academic Press, New York, NY, United States, 392 pp.

Fournier, R.O., and Rowe, J.J., 1966: Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells. *Am. J. Sci*., *264*, 685-697.

Giggenbach, W.F., 1991: Chemical techniques in geothermal exploration. In: D'Amore, F. (coordinator), *Applications of geochemistry in geothermal reservoir development.* UNITAR/UNDP publication, Rome, 119-142.

Giroud, N., Ármannsson, H., and Ólafsson, M. 2008: *Well KJ-35, Krafla. Chemical composition of liquid and steam during a flow test in autumn 2007.* Iceland GeoSurvey, report ÍSOR-08056 (in Icelandic), 8 pp.

Gíslason, G., and Arnórsson, S., 1976: *Framvinduskýrsla um breytingar á rennsli og efnainnihaldi í borholum 3 og 4 í Kröflu (A progress report on flow and chemical compostion of fluids from boreholes 3 and 4 in Krafla)*. Orkustofnun, report OS-JHD-7640 (in Icelandic), 14 pp.

Gudmundsson, Á., 2001: An expansion of the Krafla Power Plant from 30 to 60 MW_e. Geothermal considerations. *Geothermal Research Council Transactions, 25*, 741-746.

Gunnarsson, I., Arnórsson, S., and Jakobsson, S. 2005: Precipitation of poorly crystalline antigorite under hydrothermal conditions. *Geochim. Cosmochim. Acta, 69*, 2813-2828.

Gunnarsson, I., Arnórsson, S., and Jakobsson, S., 2005: Precipitation of poorly crystalline antigorite under hydrothermal conditions. *Geochim. Cosmochim. Acta*, *69*, 2813-2828.

Gunnlaugsson, E., 2004: Examples of chemical monitoring of geothermal water used for district heating in Reykjavík. *International Geothermal Days, Poland 2004*.

Gunnlaugsson, E., and Einarsson, Á., 1989: Magnesium silicate scaling in mixture of geothermal water and deaerated fresh water in district heating system. *Geothermics*, *18-1/2*, 113-120.

Gunnlaugsson, E., and Ívarsson, G., 2010: Direct use of geothermal water for district heating in Reykjavík and other towns and communities in SW-Iceland. *Proceedings World Geothermal Congress 2010, Bali, Indonesia,* 6 pp.

Hardardóttir, V., 2002: *Sudureyri district heating system. Borehole water chemistry 2000-2001*. Orkustofnun, report OS-2002/028 (in Icelandic), 10 pp.

Hauksson, T., 1979: *Well KG-12*. Orkustofnun, Well Letter No. 11 (in Icelandic), 5pp.

Hauksson, T., 1980: *Krafla. Calculated chemical composition of liquid and steam in boreholes*. Orkustofnun, report OS-80018/JHD10 (in Icelandic), 30 pp.

Hauksson, T, and Benjamínsson, J., 2005: *Krafla and Bjarnarflag. Borehole production and the chemical composition of water and steam in boreholes and production equipment in 2004*. Landsvirkjun, report (in Icelandic), 78 pp.

Hauksson, T., and Gudmundsson, 2008: *Krafla. Acid wells*. Landsvirkjun, report, 17 pp.

Hauksson, T., Thórhallsson, S., and Guðmundsson, Á., 1999: *Calcium carbonate deposits in Krafla boreholes. Chemical inhibition of deposition.* Orkustofnun, report OS-99033, 48 pp.

Hauksson, T., Thórhallson, S., Gunnlaugsson, E., and Albertsson, A., 1995: Control of magnesium silicate scaling in district heating systems. *Proceedings World Geothermal Congress 1995, Firenze, Italy*, 2487-2490.

Lund, J.W, Freeston, D.H., and Boyd, T.L., 2010: Direct uses of geothermal energy 2010 worldwide review. *Proceedings World Geothermal Congress, Bali Indonesia,* 23 pp.

Mahon, W.A.J., 1966: Silica in hot water discharged from drillholes at Wairakei, New Zealand. *New Zealand Jour. Sci., 9*, 135-144.

Miller, R.L., 1980: Chemistry and materials in geothermal systems. In: Casper, L.A., and Pinchback, T.R. (editors), *Geothermal Scaling and Corrosion. ASTM STP 717*. American Society for Testing and Materials, 3-9.

Ólafsson, M., 1999: *Sudureyri district heating system. Borehole water chemistry 1998.* Orkustofnun, report OS-99011 (in Icelandic), 13 pp.

Swanteson, J., and Kristmannsdóttir, H., 1978: *The chemical composition of altered rock in Krafla*. Orkustofnun, report OSJHD-7822 (in Icelandic),

Thórhallsson, S., 2012: *Common problems faced in geothermal generation and how to deal with them.* Presented at “Short Course on Geothermal Development and Geothermal Wells, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, 14 pp.

Truesdell, A.H., Haizlip, J.R., Ármannsson, H., and D‘Amore, F., 1989: Origin and transport of chloride in superheated geothermal steam. *Geothermics*, *18*, 295-304.

Wangyal, P., 1992: *Calcite deposition related to temperature and boiling in some Icelandic geothermal wells.* United Nations University Geothermal Training Programme, report 11, 33 pp.

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

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DIRECT USE OF GEOTHERMAL RESOURCES

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ABSTRACT

This paper presents an overview of direct use of geothermal resources and key considerations for their development.

1. INTRODUCTION

Although electricity production is nowadays under the lights because of the highly praised value of electricity, direct use of geothermal resources should not be neglected. Direct heat use is actually one of the oldest and most common form of geothermal utilization.

In 2010, direct use applications installed capacity was about 50 GW_{th} with a total annual use of about 438 PJ/year (according to the International Geothermal Association database; without GSHP).

The most spread forms of direct use are space heating, balneology, horticulture, aquaculture and some industrial uses. Geothermal heat pumps are furthermore currently the most widespread type of direct utilization of low temperature energy.

2. DIRECT USE

1.1 Definition

The direct use of geothermal resources is the use of the heat energy or the fluid from geothermal resources without intervening medium as opposed to its conversion to other forms of energy such as electrical energy.

Most direct use applications can be applied for geothermal fluids in the low to moderate temperature range 20 - 120°C. Low to medium temperature geothermal resources have been used for ages especially in a first time for bathing and later on for space heating and farming applications.

Low and medium temperature geothermal fields can be found in many places around the world. Such fields can hardly be utilized for power generation in steam turbines nor binary plants, mainly due to economic reasons. These fields might however fit perfectly for direct use applications.

In addition to being more common than high temperature fields, low and medium temperature fields are often more accessible and/or closer to potential end-users, which makes direct use of geothermal resources an interesting option.

3. MARKET PROSPECTS

3.1 Direct use of geothermal resources worldwide

It is rather difficult to obtain an accurate picture of the actual amount of heat used for direct use overall and per application. It is partly due to the broad range of applications concerned and to the fact that such use is somehow more difficult to monitor at local or national level as it may be used for individual decentralized units or applications. The International Geothermal Association holds an inventory every 5 years. Figure 1 shows an overview of the countries with the highest direct use yearly energy consumption as of 2011.

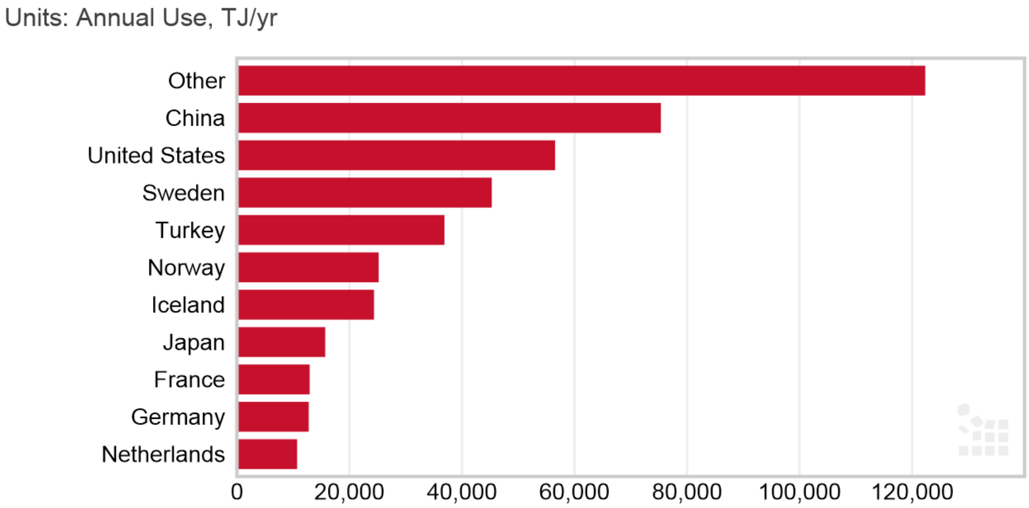

FIGURE 1: Direct use – Top 10 countries in 2011 (Íslandsbanki, 2011)

The total heat used for direct use of geothermal, excluding the ground source heat pumps amounted to nearly 26,000 GWh per annum in 2010 in the member countries of the International Energy Agency Geothermal Implementing Agreement (IEA-GIA). According to the same source, the heat used for ground source heat pumps in these countries amounted to approximately 30,000 GWh/a in 2010. On a world scale, the heat used in such applications was estimated to be about 60,000 GWh/a.

Figure 2 shows the heat used for direct use among the IEA-GIA countries in 2010 combining the ground source heat pumps with other applications. Disregarding ground source heat pumps that may be applied for various uses (space heating, swimming pools etc.), district heating and space heating accounted for the most current direct uses of geothermal resources in the IEA-GIA countries in 2010.

3.2 Potential market

About 25% of US energy use occurs at temperatures < 120°C and most of it comes from burning natural gas and oil.

Figure 3 shows the spectrum of U.S. thermal energy use and may be extrapolated to some extent to other parts of the world. In any case, the potential for utilizing low and medium temperature geothermal resources is huge. Direct use of geothermal resources should always be in the picture when considering potential applications for a given field.

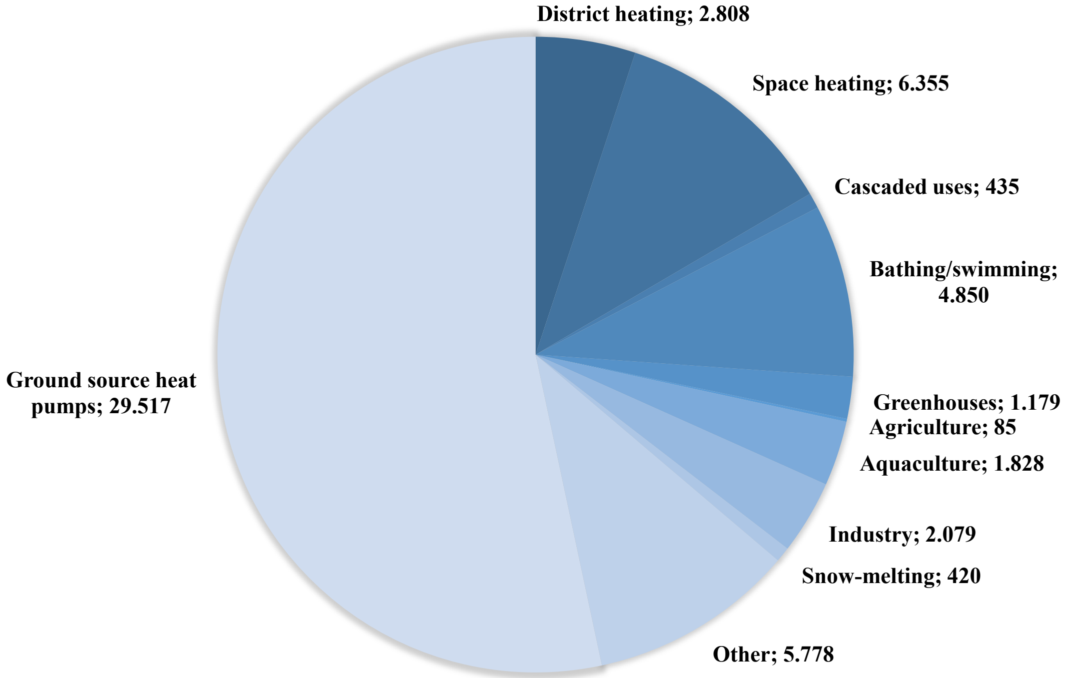

FIGURE 2: Direct use of geothermal heat in 2010 among the IEA-GIA countries (GWh/a) (Ganz, 2012)

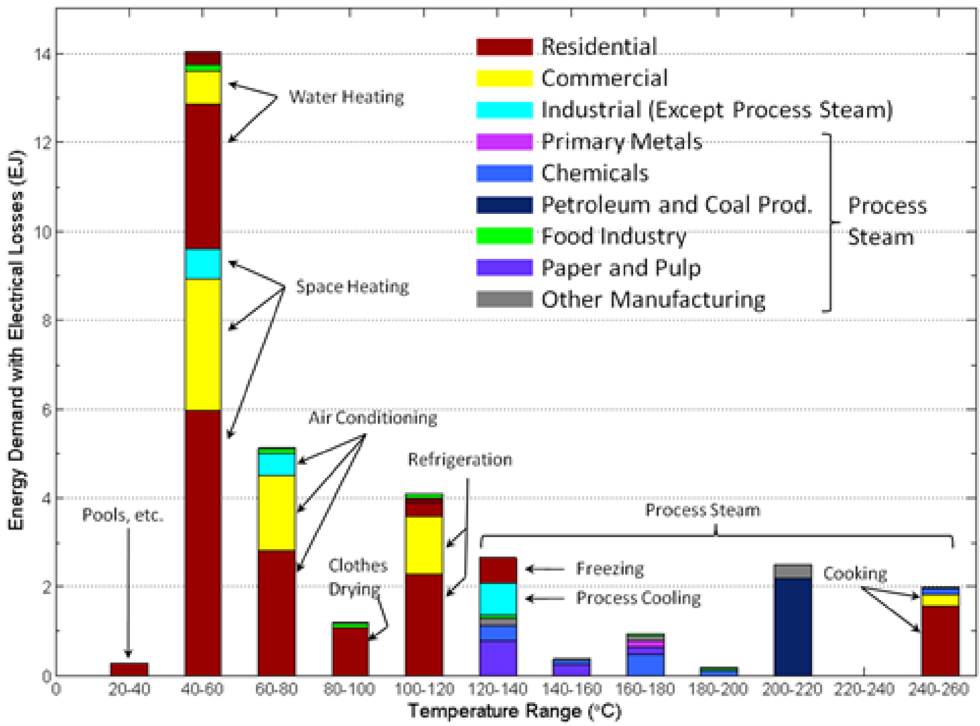

FIGURE 3: The thermal spectrum of U.S. energy use. Energy consumed as a function of utilization temperature (Tester, 2013)

4. POTENTIAL USE OF LOW TO MEDIUM TEMPERATURE GEOTHERMAL RESOURCES

Finding an adequate application for geothermal resources is not always a straight forward task as the way a geothermal resource may be utilized will be highly dependent on various factors such as:

- The characteristics of the resource: temperature, flow, chemistry and other parameters related to its sustainable utilization.
- Economic considerations related not only to the potential market for the product resulting from the resource exploitation or how easily available the resource is but also to the capability of the entity entitled to exploit the resource in terms of experience in exploiting geothermal resources and experience in the field of the application selected.

The utilization of geothermal energy depends on the resource temperature as is shown in Figure 4.

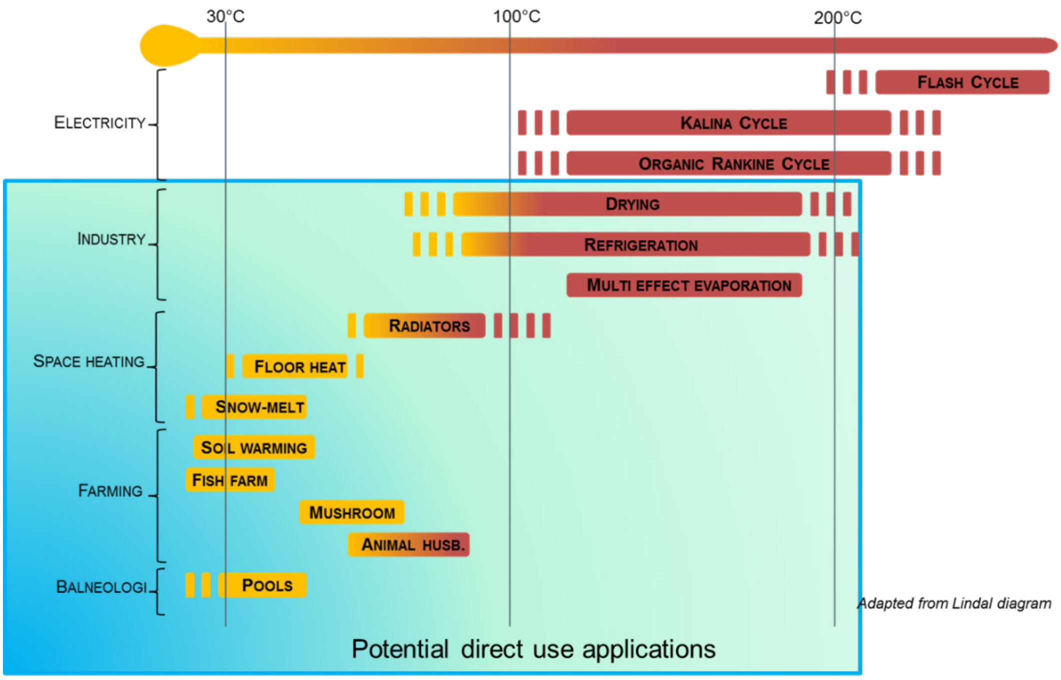

FIGURE 4: Geothermal utilization (adapted from the Líndal diagram)

The figure is mainly indicative and may contribute to narrowing down the potential uses for a given geothermal resource. The most common geothermal direct use applications are briefly presented below.

4.1 Swimming, bathing and balneology

Thermal waters have been used for centuries all around the world. Hot spring resorts are very popular places. In some cases the thermal waters are well known for their therapeutic properties and health centres have been in place for decades or centuries. Geothermal heat can also be used in swimming pools and spas. The temperature of the resource and its mineral content are important parameters

4.2 Space heating and cooling

Geothermal district heating is defined as the utilization of the earth's thermal energy for space and water heating. It can also be applied to space cooling. Space heating and cooling can either be developed for individual users or as district systems.

District systems usually combine wells, gathering and distribution systems, heat central and peak load equipment to supply heating or cooling to a group of buildings. It can also be used in co-generation cases. Iceland has been a pioneer in this field with a total installed heating power amounting to 1.4 GWth in 2011 and around 90% of homes use geothermal energy for space heating. The first house being heated with geothermal water in Iceland was as early as 1909 and the first commercial geothermal district heating system was fully developed in 1930.

Geothermal heat pumps also play an important part for individual space heating or cooling with the use of either ground or water source heat pumps. Such applications are fairly common now in Europe. Space cooling from geothermal can be successfully achieved with heat pumps.

4.3 Horticulture

Geothermal resources are ideal for horticultural applications especially when a large amount of low temperature geothermal fluid is available for heating greenhouse, soil warming and irrigation.

Geothermal horticulture was first experimented with in Iceland in naturally warm soil to grow potatoes in 1850 (Hansson, 1982). All kind of crops – tomatoes, mushrooms, cucumbers, paprika but also potted plants or flowers - can be grown thanks to the use of geothermal heat (Figure 5). Such use might contribute to significantly reduced operation cost and is seen as an interesting option for commercial operation in cold climates, with high heating requirements. In hot regions, the geothermal energy might be used for humidity control or to counteract the night cold in desert areas. It might also be a source of CO_2 for enrichment inside greenhouses.

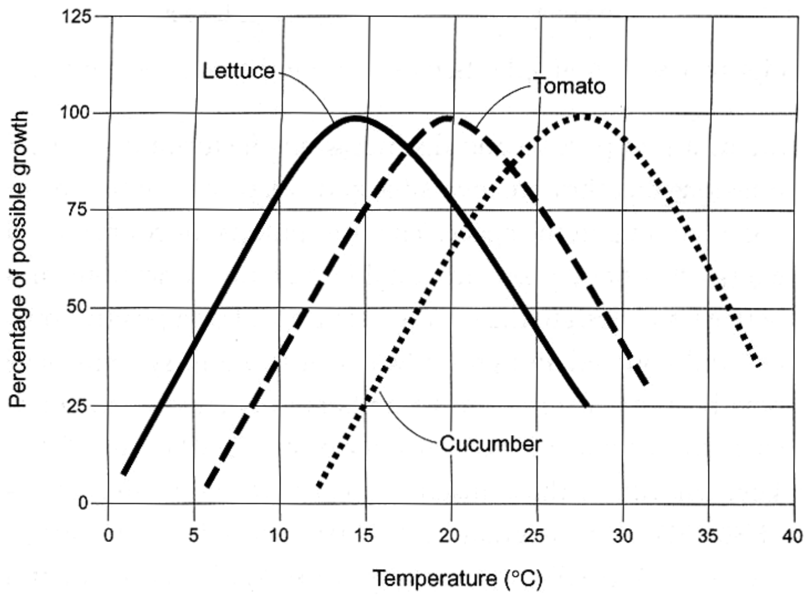

FIGURE 5: Optimum growing temperature for various species (Beall and Samuels, 1971)

4.4 Aquaculture and livestock farming

Aquaculture or aqua farming is the raising of aquatic animals such as fish, crustaceans, molluscs and aquatic plants. The farming activities are practiced under controlled conditions. The most common species raised are catfish, bass, tilapia, sturgeon, shrimp, and tropical fish. One of the purposes is to enhance the growth rate. Livestock farming is also a rather common application.

The use of geothermal resources in aquaculture depends on the type of aquatic animals raised, the quality of water and its composition. The geothermal fluid is in general used directly in the pond or pool to provide the heat required. Heat exchanger might be required if the geothermal fluid is unfit for the aquatic animals raised. Typical water temperature range is 13-30°C (Figure 6).

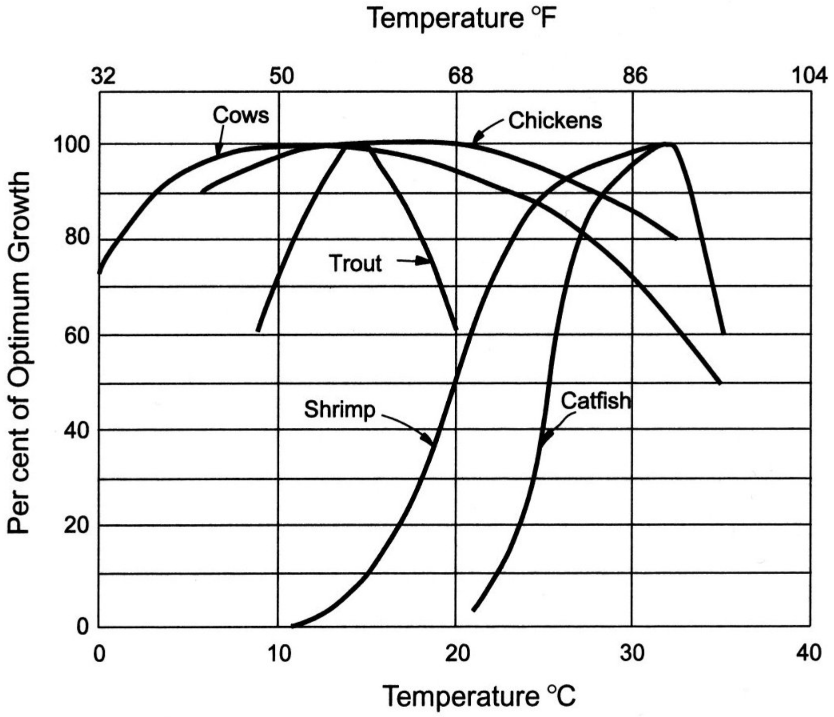

FIGURE 6: Optimum growing temperature for various species (Beall and Samuels, 1971)

4.5 Industrial applications

Industrial applications encompass a rather wide range of industrial activities requiring fluid at low to medium temperature for instance to preheat, wash, evaporate, distillate or dry. They may also be used to produce salt and other chemicals. Geothermal resources might also be used for refrigeration via heat pumps. Higher temperatures than those required for the applications described above might be required. For instance, drying and refrigeration usually require temperature above 90°C. Typical applications are presented in Figure 7.

There is a broad range of industrial applications that may use geothermal resources. Conventional industrial processes that utilize heat can in many cases be used with minor adaptation in a technically efficient and economically feasible way.

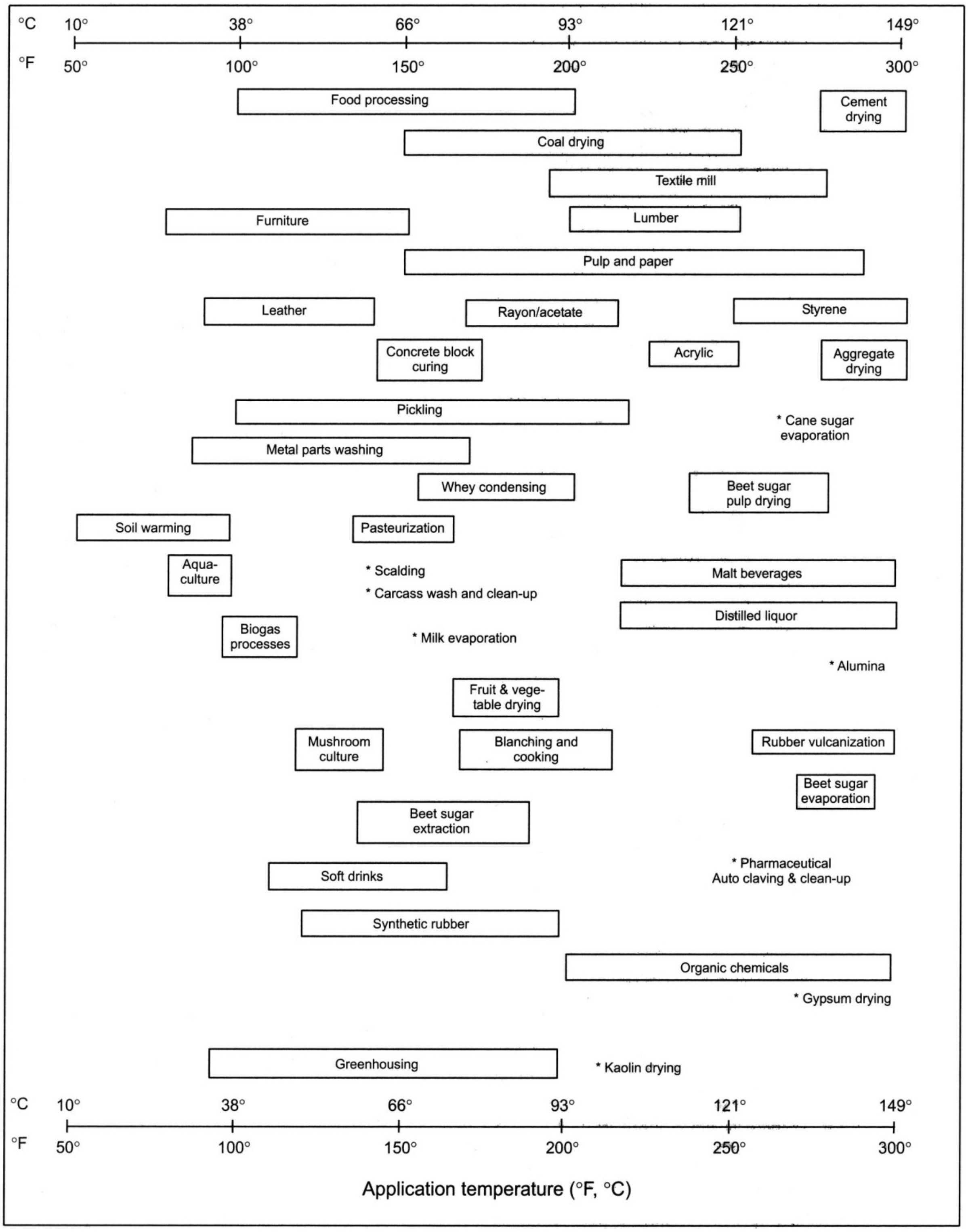

FIGURE 7: Temperature range for some industrial processes and agricultural applications

5. RESOURCE CONSIDERATIONS AND TECHNICAL ASPECTS – BRIEF OVERVIEW

The development of a geothermal project is in most cases a rather lengthy process. A greenfield geothermal resource takes 5-10 years to come to a full development, from early exploration to the time the resource is ready to be exploited. Various factors will impact the project duration. For instance, a green-field project with little information at hand regarding the resource might take longer time in its identification and exploration phases than a field which has previously been identified.

Geothermal projects are usually developed in successive phases at the end of which the project developer decides to carry on with the project or not. The development stages can be divided into 4 major phases: 1) Identification, 2) Exploration, 3) Design and construction, 4) Operation and maintenance. Geothermal projects imply high upfront costs with assessment of the geothermal resource and above all drilling of the first successful well(s). Significant investment, and therefore financial risk, is required prior to establishing whether the resource is viable or not. A common approach to manage risks associated with geothermal projects is to have milestones and decision points included in the successive phases.

Basic factors influencing the development of a geothermal applications are the temperature and available flow rates. They determine the resource energy potential for the application under consideration. The thermal energy extraction is directly proportional to the water temperature drop that can be achieved by the application. Table 1 below gives an idea of how much energy can be extracted from geothermal fluid.

TABLE 1: Hot water required to give an equivalent of 1 MWth for various temperature drops

ΔT	**(l/s)**
40	6
30	8
20	12

Exploitation of a geothermal resource has to carefully take into consideration long term extraction to avoid unsustainable extraction rates causing serious water level drawdown in the reservoir. In any case, re-injection should always be considered as a high priority reservoir management practice to replenish the geothermal reservoir and contribute to its sustainable use.

Chemistry of fluid is also an important factor for the direct use of geothermal resources as geothermal fluids are commonly richer in mineral than cold groundwater. The chemistry of the fluid might impact the feasibility of a geothermal application as expensive material may be required for the application. The equipment selection is generally affected by components such as: silica, oxygen, chlorides, calcium, magnesium, hydrogen sulphide and the pH of the fluid. The materials selected for the equipment could be mild steel, stainless steel, fiberglass or even titanium depending on the fluid and the application under consideration. Furthermore, the water chemistry may change over time due to inflow of cold of groundwater or seawater into the geothermal system. Deposition is not expected to be a major problem in low-temperature utilization compared to high-temperature utilization (calcite, sulphides, silica). Mixing of geothermal water with cold groundwater is not desirable due to the potential magnesium silicate scaling that might result from such mix.

Finally, although low and medium temperature geothermal fields can be found in many places around the world and are often more accessible and/or closer to potential end-users, the distance from potential market might be an obstacle to the development of given applications. This is probably of most relevance for district heating system where it might be uneconomical to transport hot water over long distances. The economic radius will be dependent on the parameters affecting the investment costs, i.e. pipelines and equipment, and the operation costs, related to heat losses, pumping costs or others.

The design of direct use of geothermal resources is highly dependent on the local climate, the characteristics of the geothermal resource and on the local market. However, the efficiency of geothermal direct use applications can be quite high, especially when different forms of utilization are combined in either an integrated or cascaded arrangement.

6. CONCLUSION

There is a broad range of geothermal direct use applications, the most common being bathing and space heating either in a centralized system – district heating – or with decentralized units such as ground source heat pumps. Although most of the applications mentioned in this paper can be rather easily implemented using conventional equipment or systems with minor adaptation, their conceptual design will have to take into account a few peculiar parameters, specific to geothermal resources such as the chemistry, temperature and mass flow of the geothermal fluid or other local conditions, e.g. the weather or the market targeted for the application, impacting the feasibility of the application.

REFERENCS

Beall, S.E., and Samuels, G., 1971: The use of warm water for heating and cooling plant and animal enclosures. Oak Ridge National Laboratory, report ORNL-TM-3381, 56 pp.

Ganz, B. (editor), 2012: *Trends in geothermal applications – Survey report on geothermal utilization and development in IEA-GIA member countries in 2010*. International Energy Agency Geothermal Implementing Agreement, 42 pp. Web: http://iea-gia.org/wp-content/uploads/2012/08/GIA_Trends GeothermalApplications-2010_Vs2_1-Ganz-29Aug121.pdf

Hansson, Ó.V., 1982: Útiræktun við jarðvegsupphitun (Soil heating in vegetable production). In: Gudmundsson, J.S. (editor), *Nýting jarðhita við garðyrkju (Geothermal utilization in horticulture)*, Orkustofnun, report OS-82027/JHD-03 (in Icelandic), Reykjavík, Iceland, 8-14. Web: http://www.os.is/gogn/Skyrslur/OS-1982/OS-82027.pdf

Íslandsbanki, 2011: *Products and services – Energy dashboard*. Website: http://www.islandsbanki.is/english/products-and-services/energy/energy-dashboard/

Tester, J., 2013: *The potential role of geothermal energy as a major supplier of primary energy in the U.S.* Iceland Geothermal Conference, lecture notes, 61 pp.

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

UTILIZATION OF GEOTHERMAL RESOURCES FOR SPACE HEATING

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ABSTRACT

Space heating is among the most successful geothermal direct applications in countries with cold climate and is often achieved via a district heating system. Geothermal district heating systems are not conventional district heating systems, although they share certain features with them. If geothermal heat is used in an unsuitable system, the utilization of the energy source will be poor and the resource will not be used responsively. Among other things, the overall design of such systems should be set up to optimize energy extraction for the geothermal fluid and encourage energy saving behaviors. In addition to presenting the main components of a geothermal space heating system, the paper focuses on critical issues for the design of space heating systems from geothermal with focus on the space heating system at the end users and metering and tariff design.

1. INTRODUCTION

Geothermal district heating systems are not conventional district heating systems, although they share certain features with them. The nature of the source of energy has to be taken into account when planning such system. The geothermal fluid is extracted and re-injected at given capital cost – drilling and geothermal fluid gathering and pumping equipment - and operational cost – mostly pumping whenever required. Geothermal resource management furthermore implies controlling the energy extraction from a geothermal resource so as to maximize the resulting benefits, without over-exploiting the resource. It is therefore important for the economy of geothermal heating systems and for the reservoir management sustainability to optimize the energy extraction for the geothermal fluid and encourage energy saving behaviors. Another aspect to be taken into account is the fact that geothermal systems often come in replacement of existing systems. To be able to use low temperature geothermal fluid, i.e. 70-80°C the overall size of a radiator must be larger than in conventional systems.

This paper is an introduction to the main features of a geothermal district heating system. It also draws light on the design of house heating devices and of the metering and tariff system with the overall purpose to obtain a sustainable district heating system.

2. GEOTHERMAL DISTRICT HEATING SYSTEMS – OVERVIEW

2.1 Geothermal district heating system components

In general, geothermal district heating systems receive geothermal energy coming either from a low-temperature geothermal resource, with temperatures expected to range from 30°C to 125°C, or from co-generation from high temperature geothermal resource.

A geothermal district heating system aims at providing the end users with energy for space heating and, depending on the context, for domestic hot water. The energy is usually delivered to the end users in the form of hot water via a distribution system.

As of the energy production itself, it is usually produced on one hand by the geothermal energy production, relying on the geothermal resources located under the production site, and by the additional energy production system on the other hand. Depending on the local conditions, it is often advisable to make use of this last production system in order to provide the peak energy. The heat central(s) constitute(s) the connection point between the energy production systems and the end users.

The distribution system carries the energy in the form of hot water to the end users, connecting them to the heat central(s). Each of the elements above mentioned has to be assessed thoroughly in order to evaluate the suitability of the area for geothermal district heating and the feasibility of the projects (Figure 1).

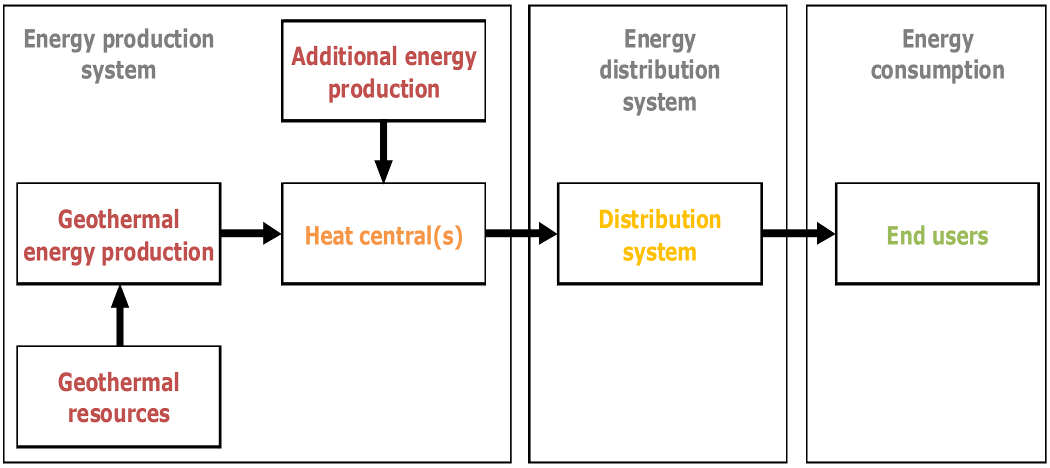

FIGURE 1: Main elements of a geothermal district heating system

2.2 General considerations and planning

The preferred water temperature for space heating from geothermal is in the range 60-90°C. Geothermal heat pump can be used if the temperature of the resource is too low for direct application. Common return water temperature is 25-40°C.

When considering a geothermal resource for space heating purposes, the chemical composition of the geothermal brine plays an important part and might impact the feasibility of the project depending on whether the brine can be used directly in the system or not. Radiators or floor heating systems are commonly used for geothermal space heating although air heating systems are also possible.

Another criteria for planning of geothermal district heating systems is the population density of the area being considered as it is important for the economy of the system. Large distance from the market increases the capital cost and the running cost (heat loss, pumping). The market should furthermore be checked for compatibility with a geothermal space heating system as discussed further in this paper.

In addition to this and apart from the geological aspects presented in other papers during the short course, the main steps for sketching the major elements of geothermal district heating at a preliminary stage include:

- Assessment of the main local factors: climate, population, market…
- Assessment of power and energy requirements of the community.
- Preliminary sizing of the energy production systems.
- Preliminary assessment of the distribution system.

Prior to presenting the main design steps of a geothermal district heating, the authors of this paper would like to draw the reader's attention to an issue which is often overlooked when planning geothermal space heating systems: the space heating system itself and its design.

2.3 System concept

Various concepts may be applied to use geothermal resources for space heating depending on the characteristics of the geothermal fluid, the elements of the system already in place or other technical or economical aspects. Figures 2 and 3 present the most common concepts: the single pipe systems and the double pipe systems.

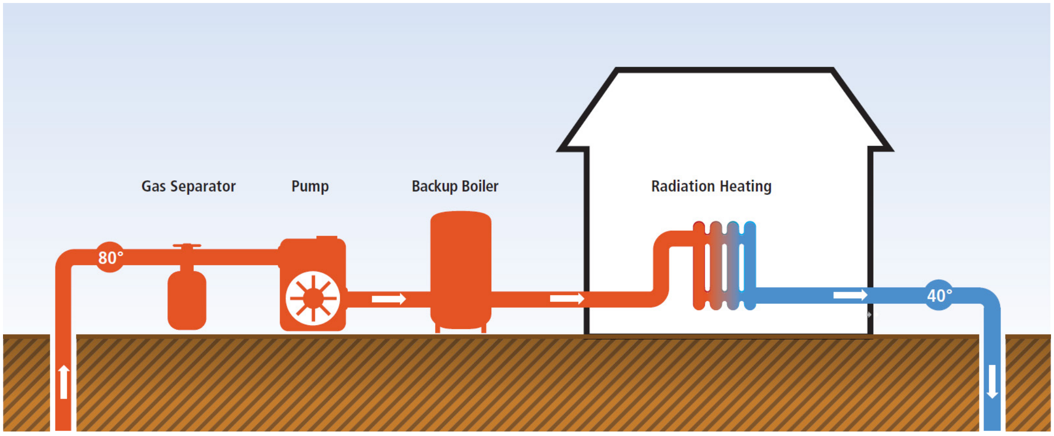

FIGURE 2: Single pipe system (Goldstein et al., 2011)

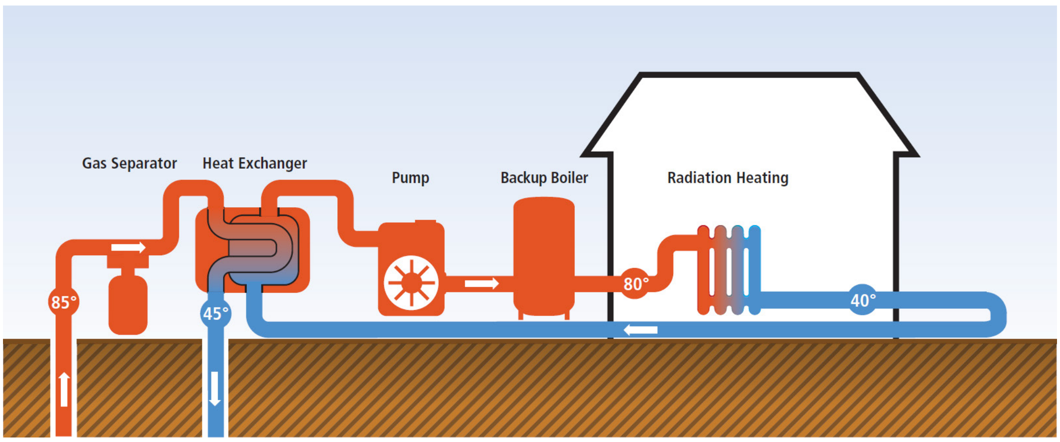

FIGURE 3: Double pipe system (Goldstein et al., 2011)

A single pipe system is an open system using the geothermal fluid directly in the space heating elements. A double pipe system is a closed system using the geothermal fluid via heat exchanger. Peak load boiler may be installed in both configurations, depending on the capacity of the geothermal resource and on the peak space heating demand.

2.4 Cost estimate for geothermal district heating system

Cost estimates for geothermal district heating systems and possible energy price will be highly dependent on the local conditions. Table 1 indicates possible cost and price ranges.

TABLE 1: Investment cost and energy price for geothermal heat applications, including energy production system and distribution system

Heat application	**Investment cost, USD/kW**	**Energy price, USD /kWh**
Geothermal district heating system	800-2000	0.036 – 0.090[1)]
Individual ground source heat pumps	1000-4000	-
Reykjavík Energy	1000	0.022[2)]

[1)] Number of utilization at max power pr. year = 2200

[2)] Number of utilization at max power pr. year = 4500

3. GEOTHEMAL SPACE HEATING DESIGN

This section introduces the space heating design theory.

House heating systems in geothermal district heating systems are among the most critical components for using a geothermal heat source. If geothermal heat is used in an unsuitable house heating systems, the utilization of the energy source will be poor and the resource will not be used responsively.

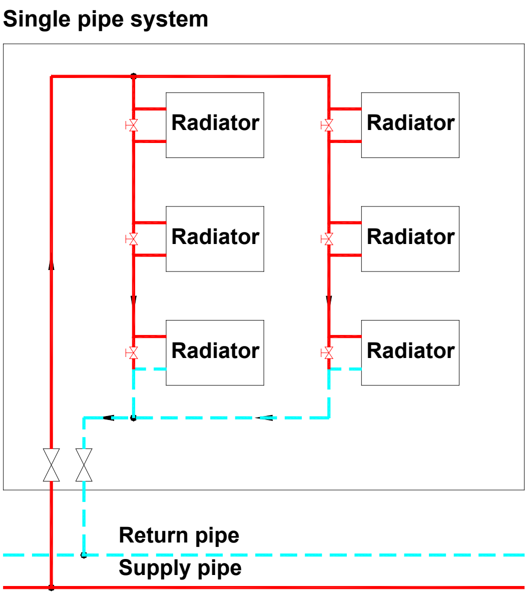

FIGURE 4: Typical space heating system with heating elements connected in series

Many places in the world have a single piping system to connect district heating system to in-house radiator systems. The main principle is that water is led up to the highest floor and the radiators are connected in series so that the return water from a high level radiator is led to the next floor supply below (Figure 4). A throttle valve is sometimes installed parallel to the radiator to ensure that the water runs through the radiators on each floor. As a result, the supply water to radiators situated on lower levels will be colder than the supply water to radiators higher up in the building. This means that radiators on the lower levels must be installed larger than the radiators higher up. The overall temperature drop can be measured from top to bottom of each building. A common temperature drop is from 90°C to 70°C during periods of maximum heat load for an average apartment building.

To be able to use low temperature fluid, i.e. 70-80°C the overall size of a radiator must be large. A preferred and more efficient way of connecting heating elements is the connection in parallel as shown in Figure 5. All heating elements can be sized based on the same design parameters and the system is more balanced.

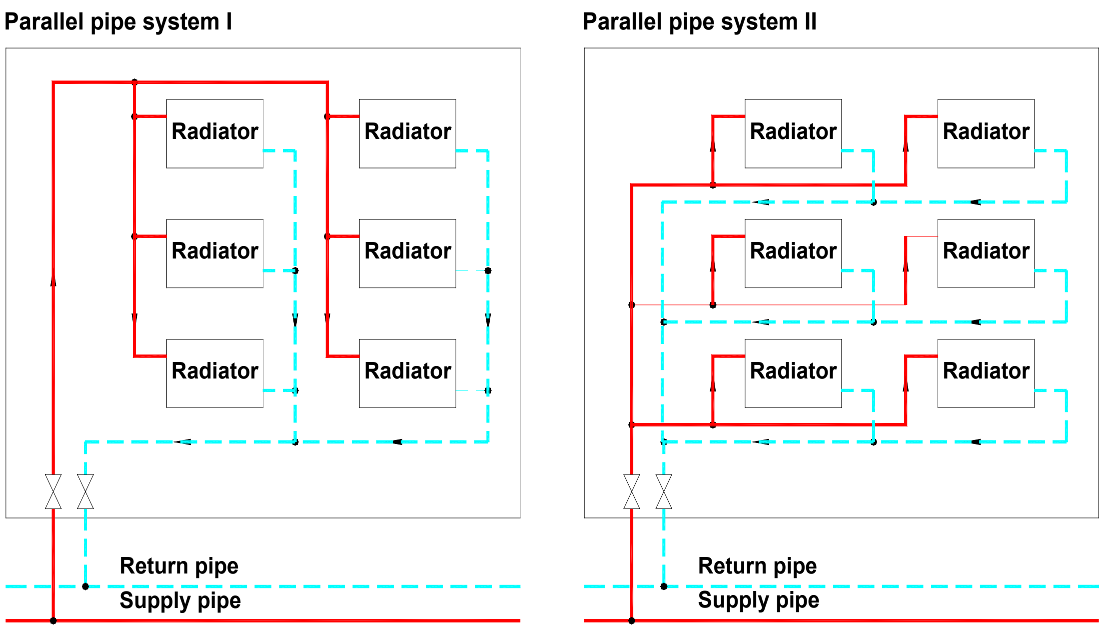

FIGURE 5: Typical space heating system with heating elements connected in parallel

Furthermore, the type of heating system used in houses should be carefully chosen, in adequacy with the enthalpy level of the fluid provided by the district heating system. Possibly cascaded system using radiators with supply/return temperatures 80/40 combined to floor heating system could be installed.

3.1 General guidelines for geothermal space heating system design

House heating with water, without any phase change, is not very complicated. The most basic heat transfer is from the water to the space being heated via house heating equipment at the consumer. The formula describing the matter is as follows:

$$Q = c_p \cdot dm/dt \cdot (T_{in} - T_{out}) \tag{1}$$

where Q = Heat released (kW);
c_p = Specific heat of fluid (kJ/(kg·°C));
dm/dt = Mass flow (kg/s);
T_{in} = Temperature of fluid into the heating system, supply temperature (°C); and
T_{out} = Temperature of fluid out of the heating system, return temperature (°C).

It is specially noted, that the following notation for mass flow might be suitable in further context:

$\dot{m}$ = Mass flow (kg/s) (another notation).

The maximum temperature utilization is when the return temperature approaches the temperature inside the heated space, or $T_{out} \rightarrow T_{inside\ space}$. That is:

$$Q_{\max temp,utlization} = c_p \cdot \dot{m} \cdot (T_{in} - T_{inside\ space}) \tag{2}$$

This is never reached in practice, though, as it would result in an infinitely slow flow through any heating device.

When the upcoming temperature is limited, as is the case in geothermal heating, T_{in} is rather low, especially when compared to coal heating. To utilize the temperature further down, T_{out} has to be lowered closer to $T_{inside\ space}$ than before.

As the sought outcome when utilizing geothermal energy is an optimized energy extraction, design of space heating systems should always follow the principles introduced below:

- Utilize the temperature as much as possible, or economically feasible in one step;
- Keep the systems simple; and
- Get as high DT as possible in the first step.

The water coming back from the space heating system should in most cases be pumped back to the heat central as 100% re-injection is always the future goal, especially when renewal of water occurs slowly in the reservoir. As discussed further in section 6, metering and tariff systems might also be designed to contribute to serving these purposes.

3.2 Power and energy demand for space heating

Energy consumption of space heating depends mainly on:

- Climate (indoor / outdoor); and
- Insulation of the building

Table 2 presents typical power and energy demand for space heating depending on the type of building.

TABLE 2: Space heating power and energy demand for various type of buildings

Building type	**Power demand (W/m^2)**	**Energy demand (kWh/m^2 p. annum)**	**Energy demand kWh per annum pr. dwelling unit (80 m^2)**
Old	100	210	16,800
Modern	50	105	8,400
Energy efficient	20	42	3,360

These figures actually vary greatly depending on the country, its customs, climate and history:

- Old European/China – 210 kWh/m^2 per annum;
- Norway – 140 kWh/m^2 per annum;
- Sweden – 120 kWh/m^2 per annum;
- Germany – 125 kWh/m^2 per annum;
- UK – 100 kWh/m^2 per annum;
- Denmark – 80 kWh/m^2 per annum;
- Reykjavík 2010 – 200 kWh/m^2 per annum; and
- Europe low energy target: 40-60 kWh/m^2 per annum.

3.3 Radiator systems

Heat loss from buildings can be expressed by the equation:

$$Q_{loss} = k_l(T_i - T_o) \tag{3}$$

where Q_{loss} = Heat lost from building (W);
k_l = Overall building heat transfer coefficient (W/°C);
T_i = Indoor temperature (°C); and
T_o = Outdoor temperature (°C).

This equation can be expressed in terms of the reference/design conditions of the radiator. The relative heat loss form the building is

$$\frac{Q_{loss}}{Q_{loss,0}} = \frac{(T_i - T_o)}{(T_{i,0} - T_{o,0})} \tag{4}$$

where $T_{i,0}$ = Reference indoor temperature (°C); and
$T_{o,0}$ = Reference outdoor temperature (°C).

The heat emission by hot water radiators can be expressed as

$$Q_{rad} = \dot{m}c_p(T_s - T_r) \tag{5}$$

where Q_{rad} = Heat emitted from radiator (W);
$\dot{m}$ = Mass flow through radiator (kg/s);
T_s = Water supply temperature to the radiator (°C); and
T_r = Water return temperature from the radiator (°C).

Relative heat duty of the radiator, in terms of reference/design conditions, can therefore be written as

$$\frac{Q_{rad}}{Q_{rad,0}} = \frac{\dot{m}(T_s - T_r)}{\dot{m}_0(T_{s,0} - T_{r,0})} \tag{6}$$

Where $\dot{m}_0$ = Reference mass flow through radiator (kg/s);
$T_{s,0}$ = Reference water supply temperature to the radiator (°C); and
$T_{r,0}$ = Reference water return temperature from the radiator (°C).

There is a relationship between the load on a water radiator system and the mean temperature difference. This relationship can be specified as

$$\frac{Q_{rad}}{Q_{rad,0}} = \frac{UA\Delta T_m}{U_0A_0\Delta T_{m,0}} = \frac{A}{A_0}\left(\frac{\Delta T_m}{\Delta T_{m,0}}\right)^{4/3} \tag{7}$$

Where U_0 = Overall heat transfer coefficient of radiator at reference/design conditions (W/(m^2·°C));
U = Overall heat transfer coefficient of radiator (W/(m^2·°C));
A_0 = Surface area of radiator at reference /design conditions (m^2);
A = Surface area of radiator (m^2);
$\Delta T_{m,0}$ = Mean temperature difference at reference/design conditions (°C); and
ΔT_m = Mean temperature difference at other conditions (°C).

If the radiator surface area remains unchanged and this equation can be simplified to

$$\frac{Q_{rad}}{Q_{rad,0}} = \left(\frac{\Delta T_m}{\Delta T_{m,0}}\right)^{4/3} \tag{8}$$

The radiators may be regarded as counter-flow heat exchangers for which the mean temperature difference is determined by the equation

$$\Delta T_m = \frac{(T_s - T_r)}{ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \tag{9}$$

Assuming steady state, the heat emission by the radiators is in equilibrium with the heat loss from the building. Furthermore it is assumed that the walls have no heat capacity; that is no heat is stored in the walls.

$$\frac{Q_{rad}}{Q_{rad,0}} = \frac{Q_{loss}}{Q_{loss,0}} \tag{10}$$

Combining equations (4), (8) and (9), a relationship can be found for the return temperature of the radiator. Here the return temperature, T_r, can be obtained with iteration.

$$\left[\frac{T_s - T_r}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \frac{ln\left(\frac{T_{s,0} - T_{i,0}}{T_{r,0} - T_{i,0}}\right)}{T_{s,0} - T_{r,0}}\right]^{4/3} = \left[\frac{T_i - T_o}{T_{i,0} - T_{o,0}}\right] \tag{11}$$

The building heat loss coefficient can be calculated directly from reference conditions

$$k_l = \frac{\dot{m}_0 c_p (T_{s,0} - T_{r,0})}{(T_{i,0} - T_{o,0})} \tag{12}$$

In Iceland, the most common geothermal radiator design is 80°C/40°C/-15°C/20°C (supply temp./return temp./outdoor temp./indoor temp.). Figure 6 illustrates how such radiator system functions with varied supply temperature. Given 80°C supply water the radiators would return 40°C water at -15°C outdoor temperature, as the reference/design condition indicates. If water is supplied to the radiator at lower temperature the radiator would return water at higher return temperature than at reference/design conditions. This yields lower ΔT through the radiator, resulting in poorer efficiency of the radiator and utilization of the geothermal water.

Figure 7 shows the mass flow ratio of the water through the radiator as a function of the outdoor temperature. The mass flow ratio expresses how much more water a radiator would need if run at other conditions than reference/design conditions. As an example, 80/40/-15/20 radiator with 65°C supply temperature would need 2.5 times more mass flow at -15°C outdoor temperature than if the radiator would be run at 80°C supply temperature. If the supply temperature would be much lower than 60°C, the radiator would most likely not be able to deliver the desirable heat to the building at -15°C, since at 60°C supply temperature the radiator would need almost 6 times more mass flow than at reference/design conditions.

It is interesting to see how the return temperature changes as the radiator size increases. Figure 8 illustrates this phenomena for various supply temperatures. If the raditator size increases by 40%, the radiator would return water at 34°C, if supplied with water at 70°C, and 39°C, if supplied with water at 60°C. This is is a clear gain as the utilization of the geothermal reservoir would be much better. Instead of cooling the geothermal water down to 53°C (if supply temperature is 60°C) it could be cooled down to 39°C, given that the radiator is sized properly.

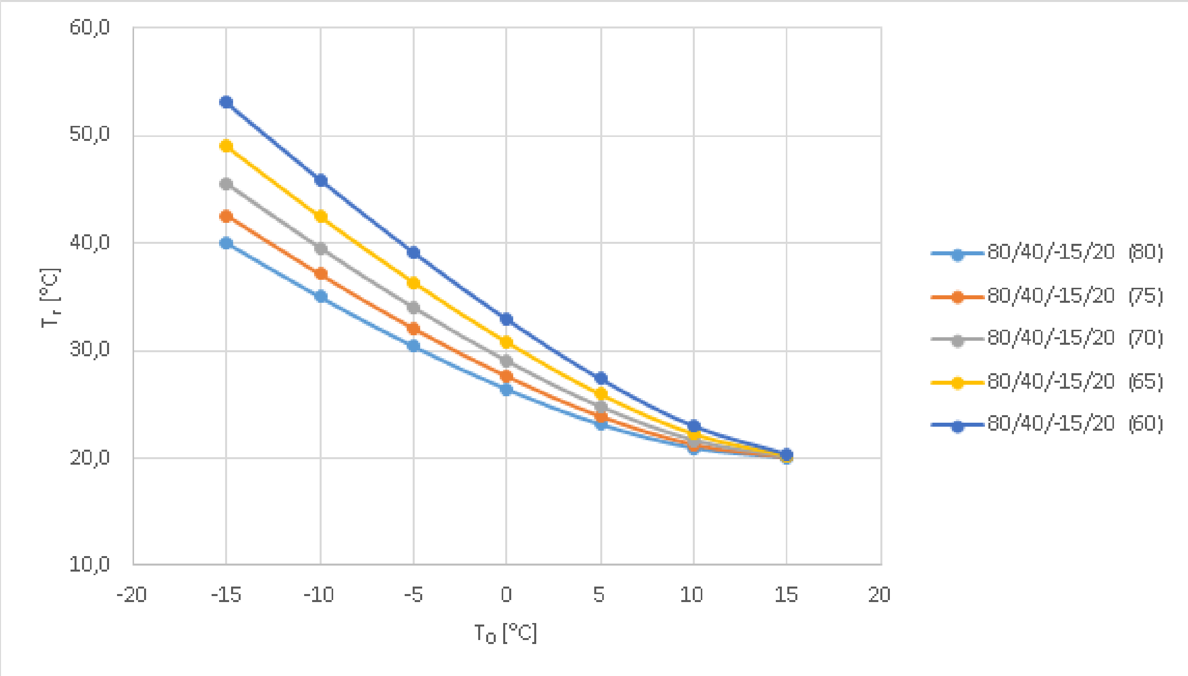

FIGURE 6: Return temperature for 80/40/-15/20 radiator design as a function of outdoor temperature for various supply temperatures (Ts)

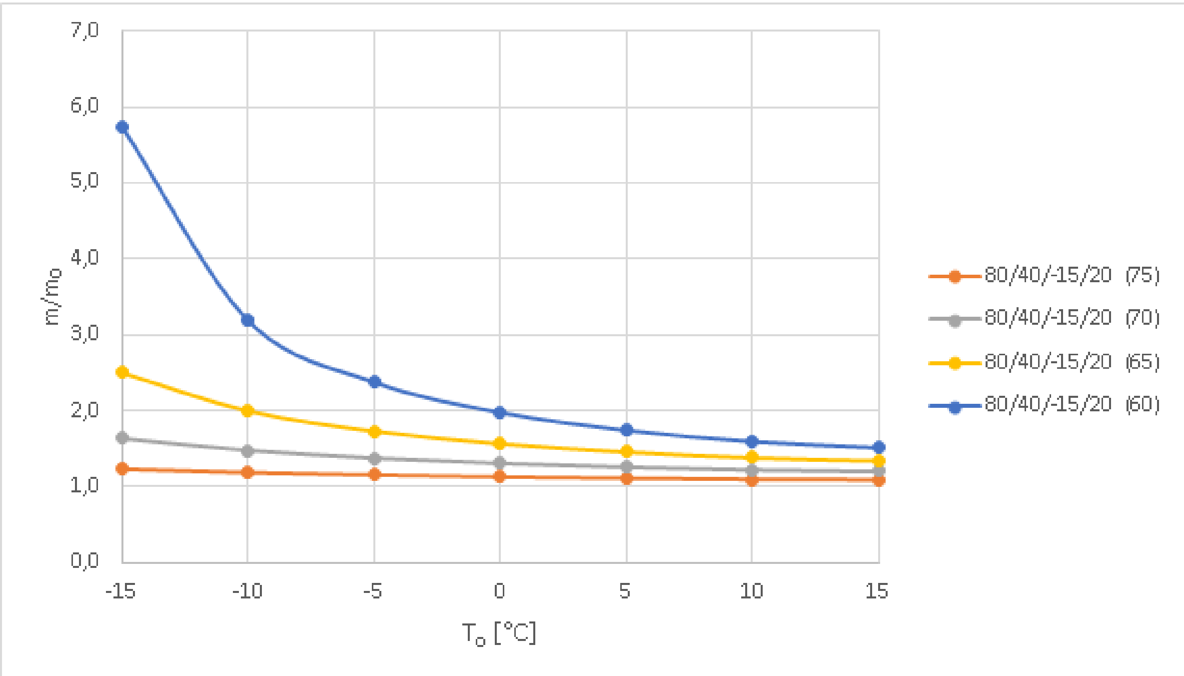

FIGURE 7: Mass flow ratio as a function of outdoor temperature for various supply temperatures, m0 is based on 80/40/-15/20 radiator design

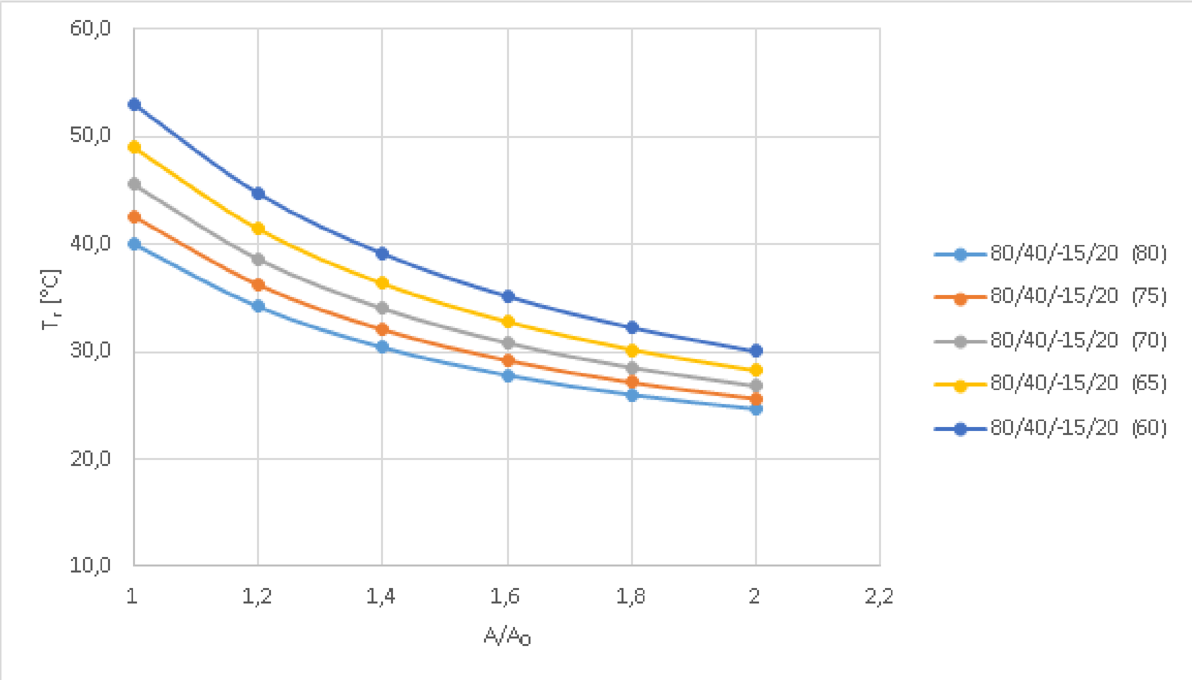

FIGURE 8: Return temperature as a function of area ratio at -15°C outdoor temperature and 20°C indoor temperature, A_0 is based on 80/40/-15/20 radiator design.

3.4 Floor heating systems

Floor heating systems are interesting for geothermal space heating. Such systems can be accommodated with district heating fluid at supply temperature ranging from 40-90°C. Floor heating systems are usually designed with a ΔT ranging from 5-15°C and it is common to have a return temperature from 25-35°C. Floor heating systems can be used alone or in combination with radiators to contribute to reducing further the return temperature.

4. DISTRICT HEATING SYSTEM PLANNING AND DESIGN

District heating end-users usually require energy for space heating and for heating of domestic hot water (DHW). There are two design approaches for the assessment of end-users' power and energy requirements.

The first approach, "microscopic", consists of detailed assessment of the peak demand of each potential end-user. This requires in-depth information of construction components of each building, existing or planned. Since it is extremely difficult and time consuming to compile information in such detail, the normal practice is to assess the overall heat demand of the community by means of key figures. This second approach, also called "macroscopic", is described below.

4.1 Weather data

Space heating loads depend mainly on the building characteristics and on the local weather data. Weather records are usually provided by local weather agency, preferably on an hourly basis, for a period of time as long as possible and are used to draw up the load duration curve.

What we aim at showing with a load duration curve is the number of days/hours per year that have an outdoor temperature lower than a given temperature. The area under this curve is proportional to the number of degree-days required for heating and gives a measure of the amount of energy required for space heating. Figure 9 shows an example of load duration curves for various locations.

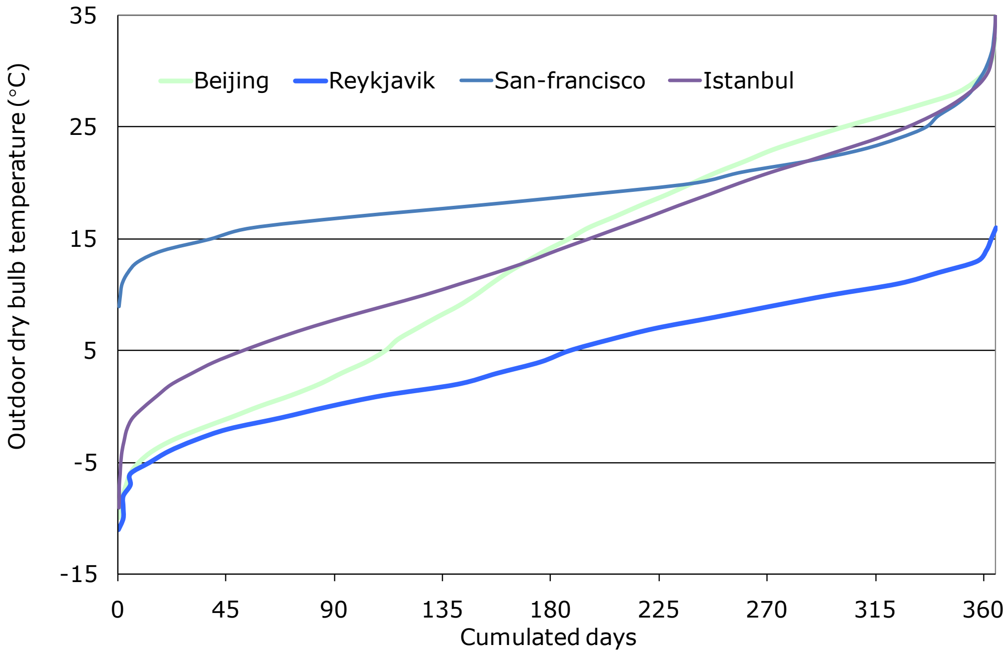

FIGURE 9: Temperature duration curve for various locations

The load duration curve is also used to indicate the heating period and the load factor, an important element of the geothermal district heating economics. Various considerations are taken into account when assessing the heat demand such as local habits and building standards. In western countries, it is quite safe to consider that buildings do not need heating when outdoor temperatures are above 18°C. On the basis of theses premises, space heating would be required in Beijing or in Istanbul about 200 days per year. In Iceland, where summer temperatures are seldom above 15°C, space heating is almost always in use.

On the other end of the load duration curve, severe cold waves are also carefully looked into. Severe cold waves are characterized by their rarity and by their intensity, i.e. much colder temperature than usual. The steep ends of the curves on the left side of figure 2 provide information on the intensity of this phenomenon. If the district heating was to be designed for the coldest weather recorded, it would be run at a partial load most of the time. Since investment costs are proportional to the installed power, installing a district heating system for the coldest weather recorded would not be viable. One of the design premises for district heating is that the indoor temperature might drop to a certain extend below design temperature during the coldest weather conditions. Actually this assumption is quite safe in the case of such systems, as has been shown in various district heating system's behavior studies.

Another phenomena that must be kept in mind is the heat stored in building walls and interiors that tends to dampen out the influence of the cold waves. This dampening effect can often increase the outdoor design temperature by 5-10°C, related to location and building standards.

4.2 Space heating and Domestic Hot Water (DHW) power and energy requirements

The assessment of power and energy requirements is based among other things on data from the local construction standards. With such information, it is possible to assess power requirements for a given type of building. In some cases, it might be necessary to classify buildings in the area considered for district heating according to their type, for instance single house or multiple store buildings. This first step provides key power figures, W/m^2 of indoor building area for instance, for different types of buildings.

In most cases, production of DHW in conjunction with geothermal district heating is possible and recommended (Figure 10). Daily domestic hot water needs are the needs for bathing, washing etc. It is practical to assess the amount of hot water, for instance 60°C, required daily for each user. Domestic hot water is either provided directly by the system or produced indirectly by the district heating system by heating cold water with heat exchanger at the end-users.

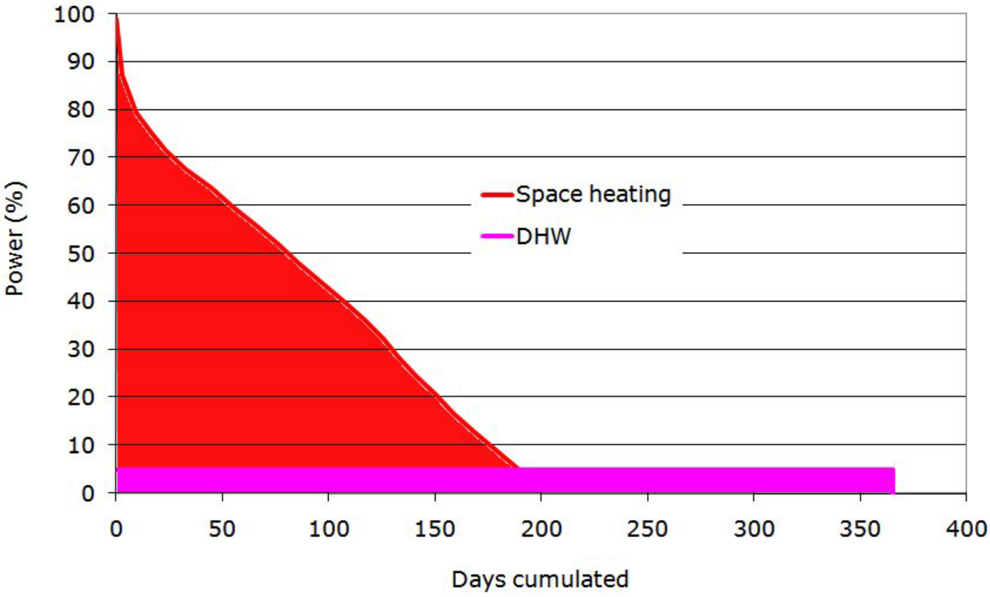

FIGURE 10: Typical load duration curve for space heating and domestic hot water

4.3 Power and energy requirements as seen from the heat central

When load duration curve and power requirements for given types of buildings are known, it is possible to assess the power and energy requirements as seen from the heat central.

4.4 Population and indoor floor area

Size and density of population are important criteria for the design phase. Because a district heating system is expected to be run over decades, one should not only look into the existing facilities to be connected to the system but also into the projected planning development, possibly for the coming 20-30 years.

4.5 Dimensioning the heat central

Although outdoor temperature is one of the major factor for space heating load, all buildings do not require peak power at the same time. Among the elements impacting on the power demand at a given time for a given location are the characteristics of each building envelope of each facility (inertia among other things), internal load, facility orientation and sun load. Also, empty buildings might have been set on spare mode and will require less energy. Formulas have been developed to take these facts into account for the design of a district heating system and a so-called simultaneity factor is generally used.

On top of that, the heat central needs to be able to cover the heat losses in the distribution system depending on the local conditions.

By combining the temperature duration curve and the peak power demand as seen from the heat central we obtain the so-called load duration curve. This curve enables to assess the total energy requirements for the system which is also an important element for the financial analysis because it indicates the energy that can be sold to the end users.

4.6 Geothermal energy production system and peaking facilities

Energy provided by the geothermal reservoir and produced at a peaking facility is the most common combination for a geothermal district heating. These two energy production systems are connected to the heat central where energy is transferred to the distribution system

Provided the geothermal reservoir can provide a sufficient amount of energy, sizing the geothermal production system is in fact a matter of finding the optimal share of peak power to be covered by an additional source of energy as regards to the investment and running costs. Drilling geothermal boreholes is rather expensive but their running costs are rather low (mainly pumping and maintenance costs) and it is generally possible to use them for the basic load, i.e. all year long. On the other hand running costs for peak boiler depend mainly on the additional energy prices and can turn out to be rather high.

Depending on the type of additional energy and on the local conditions (drilling costs among other things), a geothermal district heating system will be optimal from the economical point of view with an installed geothermal power ranging from 40 to 80% of the total peak power. Nevertheless, since geothermal energy is always used for the base load, the share of energy provided by the geothermal system can turn out to be rather high, from 70 to 90%, depending on the shape of the load duration curve. Figure 11 shows how the various sources of energy can combine.

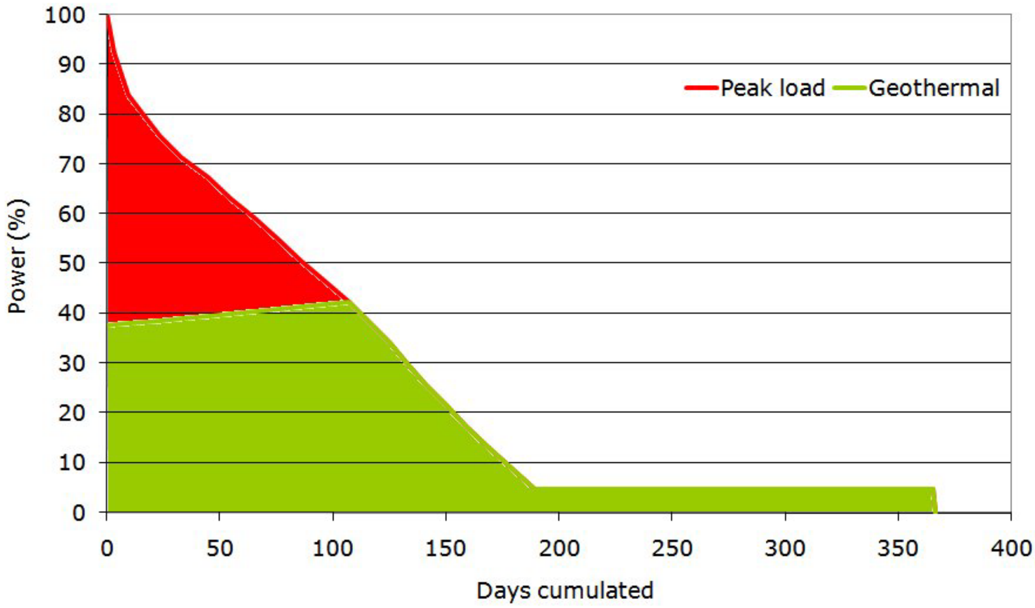

FIGURE 11: Load duration curve for a geothermal district heating system

Sometimes technical design considerations might not be sufficient in themselves to develop a viable geothermal district heating system. As a matter of fact, another important factor for the successful operation of a geothermal district heating system is the design of the metering and tariff systems.

5. METERING AND TARIFF DESIGN

Metering and tariff methods might have a significant impact of the users' energy usage and consumption pattern. It is the author's opinion that special emphasis should be put on the metering methods and design of the tariff system in a geothermal energy heating perspective, as these are a matter of concern for sustainable use of the geothermal resources and the success of the district heating projects.

A good metering method constitutes an incentive that encourages users to reduce energy squandering and energy use, preferably with low cost metering equipment. Poorer metering methods do not form these incentives at all, or with a significantly poorer focus.

Although the metering equipment used for measuring and charging purposes have to function with appropriate accuracy, the main concern when designing a metering and tariff system is to provide an appropriate incentive to use the geothermal resources in a sustainable manner.

Seen from the perspective of a geothermal district heating, good metering and charging methods are important to insure the success of such project. A good metering system provides an incentive to use the energy as sparingly as possible and to use the geothermal resources in a sustainable way. In the context of a geothermal district heating system, metering should:

1) Encourage energy saving behavior;
2) Encourage optimum energy extraction from the district heating water; and
3) Be put up to sell as much as possible, depending on the availability of the heating media.

Issues 1 and 2 are the main sought aims in cases where geothermal energy is extracted from a reservoir with limited potential and is used mainly for heating purposes. In district heating networks, users not only have to pay for their energy consumption, they also have to pay for salaries of staff, peak load energy, and the installation cost of the network. The cost of the heating utility is carried out to the users in form of billing. One has to keep in mind that competition with the heating utility exists, with or without another heating network in the ground. To minimize their energy bill, users could for instance improve the energy efficiency of their building or choose to purchase energy from another cheaper source.

Different metering methods should be used to suit each and one of the conditions above mentioned.

5.1 Structure of a typical charging method

A metering method is a combination of three types of fees:

- One time connection fee: It is a fee that an owner pays for connecting the house to the district heating grid. This fee is used to pay for parts of the installation cost of the heating utility. The remaining installation cost is paid by users with usage fees.
- Fixed annual fee: A fixed annual fee is nearly always used. This can be the only fee, or part of the fee depending on the charging method used. The fixed annual fee often pays for fixed maintenance costs of the heating network.
- Variable fee: A variable fee is used in many types of charging methods. This fee is often related to each users usage, for instance as a proportion of incoming flow or used energy.

The financial fundamental of a heating utility is to get fees to cover for its expenses. Finding a feasible ratio between the one time connection fee and the two types of annual fees is the first decision. When that has been done, a ratio of incomes between fixed and variable annual fees should be chosen carefully.

The metering methods mentioned in the following chapters do not consider the connection fee, but in all of them a ratio between a fixed and a variable annual fee is due consideration.

5.2 Using square meters (m^2) as a metering basis – an insufficient method

When using square meters, the heating area is the main basis for heating. This metering method does not take into account any of the variables of importance with respect to energy savings, i.e. T_{in} ,T_{out}, mass flow or used heat (Q). The results when applying this method could be as follows:

Advantage:

- A simple way of metering which does not require any flow measuring or flow restriction equipment.

Inconvenient:

- Supervision and monitoring is poor as no measures are performed. The system even encourage users to announce incorrect heating area. Furthermore, no information is provided on the performance of the space heating systems.
- The method does not penalize excessive use of heat.
- The method does not support energy savings.
- When heating utility is providing heat to a network of houses, the user with the poorest heating system will complain until his apartment/facility is given enough heat. Other users might have an oversupply of heat and open windows for cooling at these times.

Any mitigation method to compensate for the negative impact of this metering method is rather unrealistic, as the parameter used is heated area. This method is seldom recommended as its impacts on using patterns are unclear.

5.3 Using flow meters as a metering basis – a rather good method

When using flow meters as a metering basis, the consumer is charged for his use of water according to the amount of water used (cubic meters or tons). This metering method is commonly used in Iceland and is presented in Figure 12. A sealed regulating valve might be used to limit the maximum flow into the system. The role of the sealed regulating valve is to prevent unbounded flow into the system. It can be regarded as a safety equipment, for instance, in case of accidental leaks.

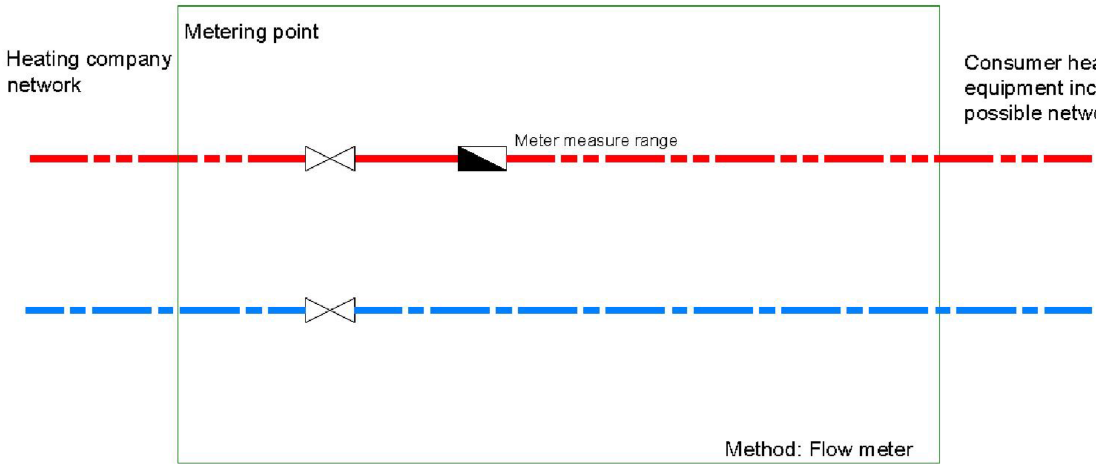

FIGURE 12: Measurement environment of flow meter charging

The method itself does not require a measure on T_{in} or T_{out} although such measurements are often performed on behalf of the user. The results of this metering method on the user could be the following:

Advantage:

- A rather simple and cheap way of metering that requires only flow measuring equipment.
- The method encourages high temperature drop and low flow and hence a good energy utilization of the geothermal resource.

Inconvenient:

- The method does not take into account the temperature of supply water, which can affect the behavior of the radiator system. This can be an issue as colder incoming water makes heating more difficult.

Mitigation:

- A potential mitigation of colder incoming water is to have some kind of compensation for lower incoming temperature. This could be applied to users farthest away from the heat central.
- If the user measures the temperature on his purchasing point, he will effectively check when the temperature goes down and complain to the heating utility.

Metering by flow meters is recommended when the heating utility is using a limited heat source. This method encourages energy savings and is rather applicable to serve as a basis for heat selling when utilizing limited low enthalpy heat sources. In practice, the use of heat will vary with outdoor temperature.

5.4 Using maximum flow as a metering basis – a limited method

Metering house heating by restricting the maximum allowable maximum flow is simple. Each owner negotiates the maximum quantity he can buy and is allowed to use up to that amount anytime. The sought amount is made available by the set up by a flow restrictor (often with a built in orifice), at the users' connection point as shown in Figure 13. This method can be useful when heating needs do not change a lot between seasons, as the maximum flow will stay nearly constant.

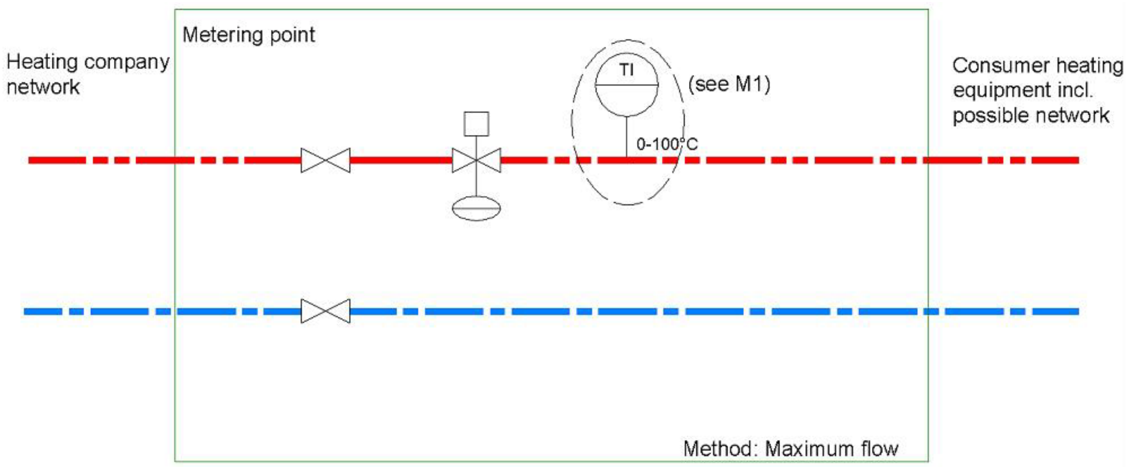

FIGURE 13: Measurement environment of maximum flow charging

Please note that the thermometer M1 is not necessary, but encouraged and mentioned as a possible mitigation method.

Advantage:

- Maximum flow is a simple metering method.
- The method may increase the users' awareness of their heat usage and potentially reduces the peak use as the maximum use is the decisive parameter for the charging amount.
- The heating utility does not have to concentrate as much on delivered temperature and cooling in district networks during summer is a less problem.
- The method tends to make the heat usage more uniform throughout the year.

Inconvenient:

- When the heating usage differs a lot during seasons, the maximum use is in line with the heating need at the coldest day. This means that after the coldest period there is no reason to use hot water sparingly. Thus, where heating loads are periodic, this charging method performs poorly, unless the heating media is in excess.
- This method tends to make the heat usage more uniform throughout the year.
- The method does not encourage energy savings.
- During winter time, but not at peak load, radiators or other heating equipment may be at full load, and temperature control during day is done by opening windows.
- The method does not take into account the temperature of incoming water, which can affect the behavior of the radiator system.
-

Mitigation:

- If the user measures the temperature on his purchasing point, he will effectively check if the incoming temperature goes down and has the possibility to complain to the heating utility.
- The tendency of making the heat usage more uniform throughout the year can either be positive or negative, depending on the heat source. A more uniform use is positive in a few cases: If the heat source is waste heat from a factory, or heat from a producer that has heat in excess, a uniform use might be positive. The same applies when using artesian flow from a natural spring from a natural constant energy source. However, the uniform use of heat over the year often has a negative impact when the source does not provide excessive heat.

Experience of this metering basis is that total annual energy usage is at least 30-40% more compared to situations where flow metering is being used. This method is therefore not recommended for low enthalpy heating utilities with limited water supply as its application will result in more use of water than necessary. On the other hand, when flow from a source is constant and in excess, as might occur with heat from a geothermal power plant, this method may be preferred.

5.5 Using energy meters as a basis for charging consumers – an unsatisfactory method

As shown in Figure 14, the use of energy meters is based on measurements of the flow and the supply and return temperatures (T_{in} and T_{out}). In addition to this, the energy usage is calculated and accumulated in a computer or advanced meter.

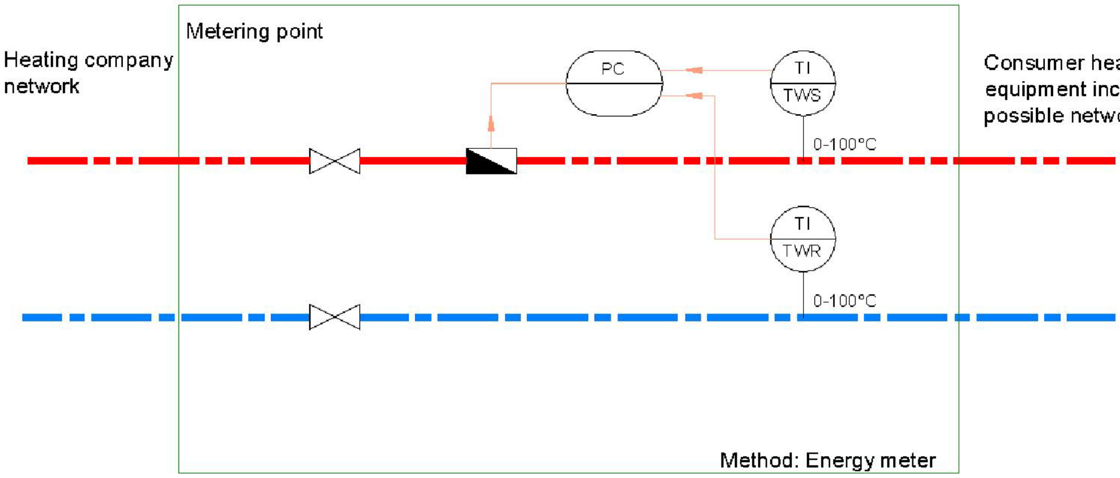

FIGURE 14: Measurement environment of energy meters

Advantage:

- This method measures the energy use exactly. The consequence of that is however not necessarily positive, as heat does not have the same properties as electricity (see chapter on energy availability hereafter).

Inconvenient:

- This kind of metering does not pay any attention to the return temperature or the consumers' temperature usage.
- A small temperature drop in users' heating equipment goes un-penalized. When used wrongly, users may put up extremely small house heating equipment which require large pipes and pumps which are expensive for the heating utility.
- A high return temperature is negative in geothermal heating and will result in wasting energy.

Energy metering is an improvement when the heating utility is based on coal or natural gas burning only, as these methods are less dependent on a low return temperature. The method gives some idea of various buildings' energy usage, and can increase awareness of excessive use in this manner.

5.6 Future meter, energy meter with calculated return temperature

An energy meter with calculated (or fixed) return temperature is a theoretically correct meter, where cooling in district networks may be a problem (Figure 15). This meter charges users equally for the energy that they are provided with from the supply water. The meter uses mass flow and supply temperature as necessary incoming parameters. Outside temperature can be used to calculate the expected return temperature.

This meter does not exist on commercial markets yet, but it would be a quite good meter, especially in geothermal heating networks and would contribute to an equal treatment of customers in rural areas. The meter would typically calculate the energy according to the following formulas:

$$P = F + \dot{m} \cdot (T_s - T_{out*}) \tag{13}$$

where

$$T_{out*} = \begin{cases} f(T_s, T_{outdoors})\ or \\ constant \end{cases} \tag{14}$$

and P = Fee for heat;
F = Fixed annual rate;
T_s = Supply temperature;
T_{out^*} = Acceptable return heat, depending on heating systems;
$f(T_s, T_{outdoor})$ = Return heat according to radiator formulas; and
$constant$ = Constant of acceptable return temperature.

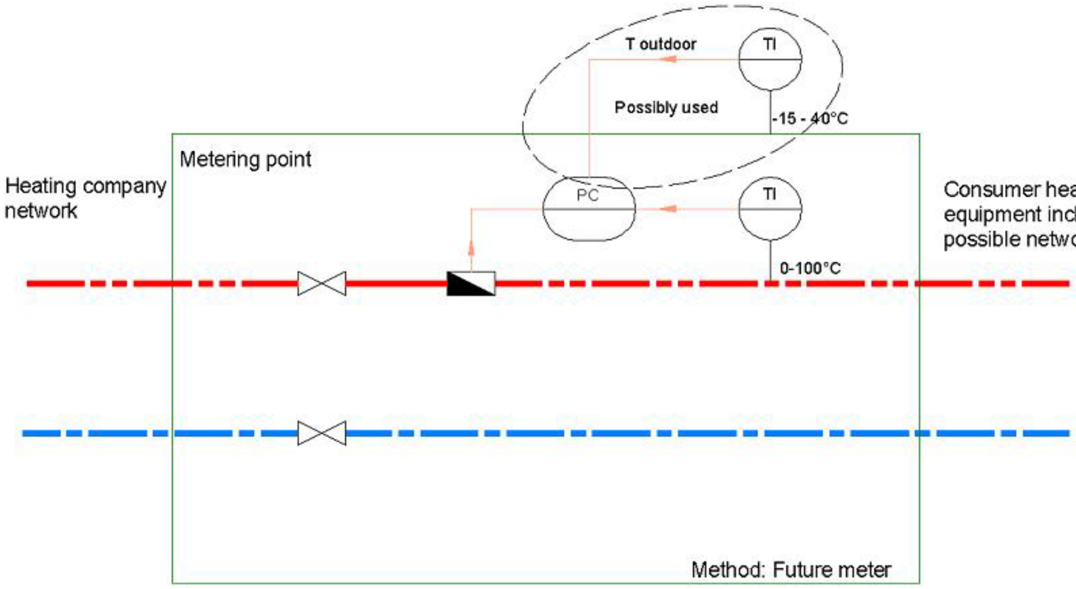

FIGURE 15: Measurement environment of future energy meters

Advantage:

- This method measures use of incoming water temperature with respect to energy availability.
- The meter encourages a good utilization of the geothermal resource.

Inconvenient

- This kind of meter is not a commercial product yet. Ideas of this kind of metering have however been set forth in the recent years.
- Such meters could be difficult for users to understand for the end-users.

This meter would serve well in rural areas, but in dense areas direct flow metering would suit better, as cooling in district networks is not large.

5.7 Comparison

Several energy metering methods exist as shown in Table 3. For instance, another possibility is to have a flow meter and an energy meter, and combine the cost in quite complicated ways. Other methods could be to combine square meters and other methods and so forth.

It is strongly emphasized that simplicity is important in this manner, especially at first stages of exploitation.

TABLE 3: Metering methods

Metering method	Statement	Mitigation possibilities	Rank when used in geothermal heating networks
Area, m^2	Insufficient method	None	5
Flow meter	Rather good method	Many	2
Maximum flow	Limited method	A few	3
Energy meter	Unsatisfactory method	Very few	4
Future energy meter	Future method	Works best in rural heating areas.	1

Choosing an applicable metering method is extremely important to reach the goal of gaining an economical and practical geothermal district heating utility.

6. CONCLUSION

The papers shows that various data are required for a preliminary assessment of a geothermal district heating system. Also the conception of geothermal district heating systems slightly differs that that of conventional district heating systems.

To conclude this paper, the authors would like to emphasize two important elements for the achievement of a successful project:

- Metering and tariff methods; and
- Design criteria for space-heating at end-users.

A metering method of good quality is expected to serve as an active boundary for the conditions in situ with pricing at competitive levels so that all can afford to purchase heat, and do their best to adjust to preferable heating conditions.

In this perspective, space heating at the end-users should be designed for return temperature as low as possible, with 35°C being an ideal and reasonably feasible temperature. In the case of existing buildings, the connection to a geothermal district heating often requires upgrading of the space-heating system to optimize extraction of energy from the district heating water. This element has to be considered from the beginning when developing such project.

REFERENCES

Goldstein, B., Hiriart, G., Bertani, R., Bromley, C., Gutiérrez-Negrín, L., Huenges, E., Muraoka, H., Ragnarsson, Á., Tester, J., Zui, V., 2011: Geothermal Energy. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. (editors), *IPCC special report on renewable energy sources and climate change mitigation*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 401-436. Web: http://srren.ipcc-wg3.de/report

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

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GEOTHERMAL BATHS, SWIMMING POOLS AND SPAS: EXAMPLES FROM ECUADOR AND ICELAND

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ABSTRACT

Geothermal resources have been used for bathing since antiquity in many parts of the world. Selected examples of historical uses are presented along with present day examples from Ecuador and Iceland. While the drive for bathing remains unchanged, bathing practices have evolved into refined cultural traditions and sophisticated therapeutic treatments that rely on modern technology for proper execution.

1. INTRODUCTION

It must be seen as likely that humans started making use of natural hot springs for bathing early on, as there are examples of other primates doing the same in current times. The snow monkey, which is spread over much of Japan, is well known for taking advantage of geothermal springs in Jigokudani Park to keep warm in the winter in the mountains near Nagano city (Aasgaard, 2012). Much like humans, it uses the hot springs for socializing and relaxation, and it does not take a vivid imagination to picture early humans in a similar setting (Figure 1).

FIGURE 1: Japanese macaques (snow monkeys) taking a geothermal bath (SnowJapan, 2014)

Through recorded history, there are various accounts of the utilization of geothermal water for bathing and remnants of such use have been passed on from antiquity. Such bathing has been used for recreation, relaxation, socializing, therapy, and as part of spiritual practices by cultures in many parts of the world (Kępińska, 2003).

In Italy, the Etruscans developed a tradition of bathing in thermal waters (Kępińska, 2003). This tradition was passed on to the Romans who also built on Greek traditions to develop a refined bathing culture that was spread around the empire. Over a thousand thermal baths existed in the capital during the peak period of bathing in the 3rd century A.D. and military camps were built in the vicinity of geothermal springs for massages and healing wounded soldiers (Kępińska, 2003). In the middle of the 1st century A.D., the Romans built a temple by the hot springs in modern day Bath in England and a town, that became known as Aquae Sulis, was gradually built up in the next decades (City of Bath, 2014). The baths from which the modern city draws its name were constructed around 70 A.D. as a grand bathing and socializing complex and are currently one of the best preserved Roman remains in the world (Figure 2), with 1,170 m^3 of 46°C hot water filling the baths every day (VisitBath, 2014). The Greek motto "health through waters" came to be known as "salus per aquis" in Rome and has been abbreviated as *spa* in modern times (Kępińska, 2003).

Wang Ji-Yang (1995), reports that the Huaqing hot spring by the foot of Mt. Lishan close to Xi'an city in China has been utilized for 3000 years. In 747 A.D., the most luxurious imperial palace of the Tang dynasty was built around the spring and the love story of Emperor Tang Xuanzong and his concubine Yang Guifei, who spent much of their leisure time in the hot baths (Figure 2), is well known in China. Aside from recreational activities, the historical use of hot springs in China has mainly been focused on therapeutic treatment (Wang, 1995).

In Iceland, there are several accounts in the literature of early usage of hot springs for bathing and it must be seen as likely that the first settlers started such utilization in the 9th and 10th centuries. In medieval times, the best known example is that of Snorralaug (Figure 2), a geothermal bath believed to have been built by historian, chieftain and saga-writer Snorri Sturluson. A contemporary thirteenth century account mentions Snorri's use of the bath, which is supported by archaeological evidence. Excavations have revealed a circular pool 4 m in diameter and about 0.9 m deep that was fed by a stone conduit from a nearby hot spring (Fridleifsson, 1995). Fridleifsson (1995) suggests that the idea for the conduit was brought from Italy with Icelandic pilgrims.

Kępińska (2003) notes that in Japan, geothermal sources gave birth to the construction and development of many spas visited by noblemen for therapeutic and recreational purposes. Through the centuries, the contribution of different dynasties led to the refinement of practices and in 1710, the first medical books describing baths in hot springs, their curative properties, and the offered treatments were published (Kępińska, 2003). In modern times, the onsen bathing tradition is a popular feature of Japanese tourism.

In South America, the pre-Incan Caxamarca culture built an important city by the hot springs that later became known as Baños del Inca (Inca baths). The place at that time consisted of buildings that were one of the principal residences of the Caxamarca chiefs, who used the hot springs for healing and the worship of water (Figueroa Alburuqueque, 2005). As the Incas gained influence in the region, the baths by Cajamarca became one of the principal residences of Inca chiefs prior to the arrival of the Spanish conquistadors. This is where Inca Emperor Atahualpa first heard of the Spanish invasion of 1531-1532, and some sources say that he was aroused from the baths to receive the news. Kępińska (2003) reports that a great number of Inca palaces and temples were built near natural geothermal ponds and hot springs that were equipped with bathing facilities supplied with hot and cold water through a system of pipelines (Figure 2).

Through time, bathing practices in different parts of the world have evolved into refined cultural traditions (e.g. Japanese onsen and Turkish bath) and sophisticated therapeutic practices (balneology and spa treatments). In this paper, some examples are given of the modern use of geothermal waters for bathing in Ecuador and Iceland, the birth countries of Atahualpa and Snorri Sturluson (both powerful leaders with a common taste for geothermal bathing, meeting their fate at the hands of emissaries of foreign powers).

FIGURE 2: Reconstructions of the Roman Baths in the City of Bath in England (upper left) (VisitBath, 2014), the Crabapple pool built for Lady Yang Guifei by the Huaqing hot spring near Xi'an in China (upper right) (China International Travel CA, 2012), Snorri's pool in Reykholt in Iceland (lower left) (Hurstwic, 2014), and the intact Tambomachay site by Baños del Inca in Peru as passed on to modernity (lower right) (Andean Travel Web Guide to Peru, 2010)

2. EXAMPLES FROM ECUADOR

Today, utilization of geothermal resources in Ecuador is restricted to direct uses, that is, for bathing resorts, balneology and swimming pools. A total installed capacity of 5.16 MWt and an annual energy output of 102.4 TJ/yr has been estimated in 2010 (Beate and Salgado, 2010), with a slight increase in recent years. In general, therapeutic benefits provided by medicinal mineral hot springs have been exploited in most resorts and spas in Ecuador. However, significant alternate uses remain unknown by Ecuadorian society. Currently, several projects for direct use in fish hatchery, greenhouse heating, space heating, and industrial applications are being researched by universities and public research institutions. A map containing the locations of known hot springs in Ecuador is presented in Figure 3.

The following sections describe some of Ecuador's bathing resorts and spas.

2.1 The Aguas Hediondas ecotouristic complex

The Aguas Hediondas ecotouristic complex is located near the border between Ecuador and Colombia. The hot springs come from Chiles Volcano, and feed four geothermal pools, with water temperatures ranging between 40-56°C. The water has a white-yellow appearance due to its high sulphur content, giving rise to its name, which in Spanish means "Smelly Waters". Villagers from Tufiño adduce therapeutic properties among other benefits of bathing in these hot springs. Admission tickets are sold for 1 USD.

Location: 24 km W of Tulcán city, 7 km W of the village of Tufiño
Elevation: 3580 m a.s.l.

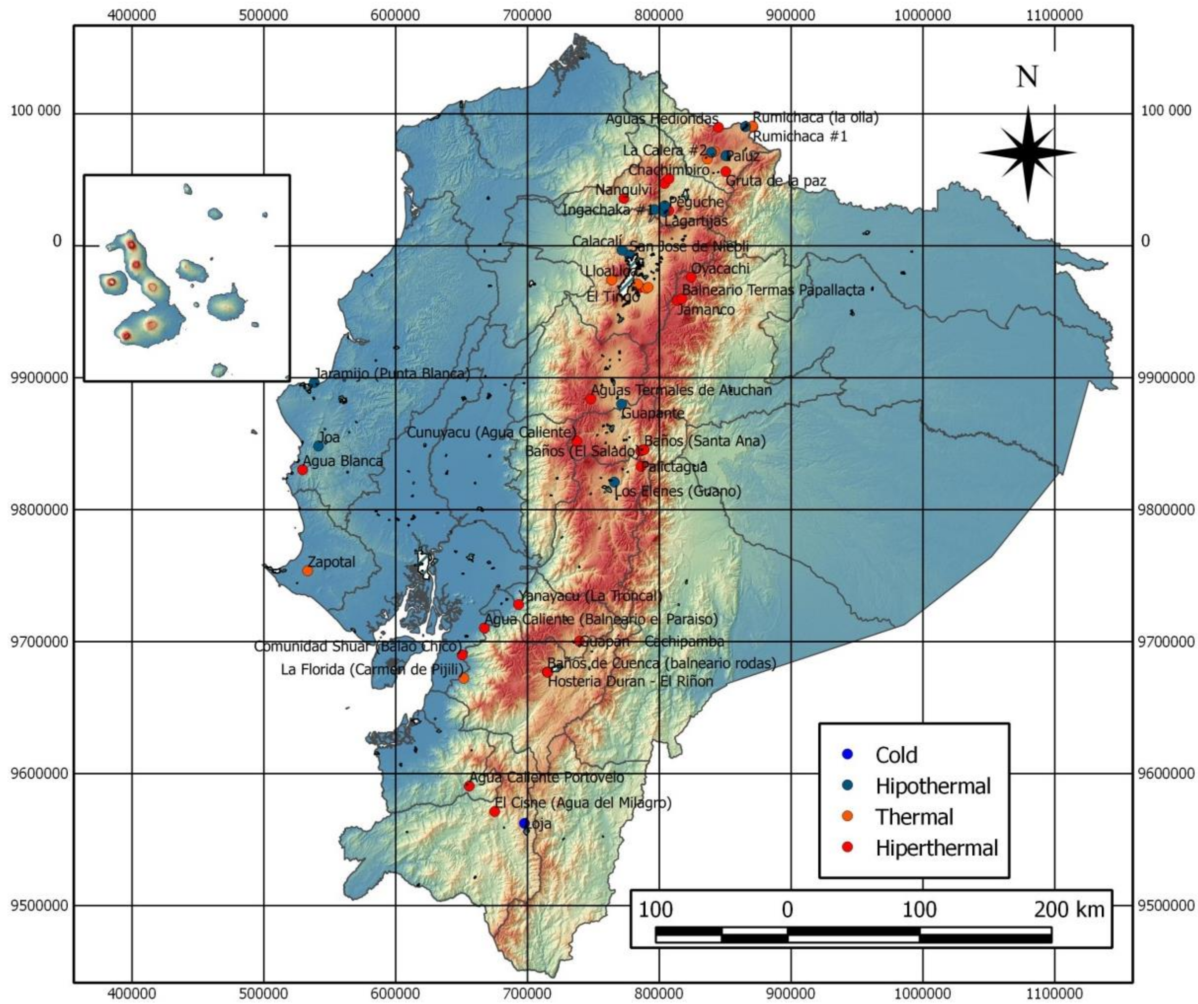

FIGURE 3: Map of geothermal hot springs in Ecuador (Burbano et al., 2013)

Hot spring temperature: 52.5°C
Hot spring type: Sodium – Sulphate (Table 1)

2.2 El Salado hot springs

The city of Baños de Agua Santa, commonly reffered as "Baños" is located in the foothills of Tungurahua Volcano. The city got its name from the hot springs located in the surroundings, and has become one of the most visited places in Ecuador. The hot springs feed five resorts and spas, which offer different low temperature geothermal derived services. The water type is mostly mineralized with sulphate and chlorine contents. Health improvements have been attributed from bathing in these hot springs.

Location: 30 km SW of Ambato city, 2 km E of Baños de Agua Santa
Elevation: 1820 m a.s.l.
Hot spring temperature: 45.6°C
Hot spring type: Chloride – Sulphate – Alkali (Table 1)

2.3 Piedra de Agua hot spring and spa

The Parish of Baños de Cuenca has the hottest springs in the country, which emerge from a side travertine hydrothermal deposit. These springs represent the likely lateral outflow of the Quimsacocha geothermal system, at about 20 km to the SW of Cuenca (Beate and Salgado, 2010). Piedra de Agua is one of the most complete and modern resort and spa in the area, built almost entirely from limestone extracted from the travertine hydrothermal deposit (Figure 4). Unique geothermal derived services are offered to the public, such as volcanic mud baths, steam box bath, and Turkish baths. A detailed description of each service is displayed in the resort´s website. One particularity is the underground thermal baths, which are built inside man made caves. Exploitation of geothermal resources for bathing in the area started in 1928.

Location: 7 km SW of Cuenca city, Baños de Cuenca Parish
Elevation: 2700 m a.s.l.
Hot spring temperature: 74.5°C
Hot spring type: Chloride – Bicarbonate – Alkali (Table 1)

FIGURE 4: Piedra de Agua resort facilities and geothermal bathing pools (Piedra de Agua, 2014)

2.4 Termas Papallacta hot spring and spa

The hydrothermal value of Termas de Papallacta's hot springs comes from the Chacana caldera, which has been persistently active through all the Quaternary period (the last 2-3 million years). The springs are near-neutral alkaline chloride waters with anomalous high concentrations of boron and arsenic, typical of a high temperature water-dominated geothermal system. The Termas de Papallacta resort has five pools for general bathing and private individual pools for hotel guests (Figure 5). It also has a ground source heat pump system that provides space heating mainly in the social areas of the hotel.

Location: 60 km E of Quito city, Papallacta Parish
Elevation: 3300 m a.s.l.
Hot spring temperature: 54.2°C
Hot spring type: Chloride – Sulphate – Alkali (Table 1)

The chemistry of the waters supplying the four resorts is presented in Table 1.

FIGURE 5: Papallacta resort facilities and geothermal bathing pools

TABLE 1: Chemistry of Aguas Hediondas, El Salado, Piedra de Agua, and Papallacta hot springs (Inguaggiato et al., 2010; Burbano et al., 2013)

Name		**Aguas Hediondas**	**El Salado**	**Piedra de Agua**	**Papallacta**
Type		Sodium-Sulphate	Chloride-Sulphate-Alkali	Chloride-Bicarbonate-Alkali	Chloride-Sulphate-Alkali
Location	Longitude	-78,43304	-79,06177	-78,15328	-77,90592
	Latitude	- 1,40618	-2,92243	0,36495	0,80966
Elevation (m.a.s.l.)		3601	1927	2704	3278
pH		4,60	6,40	6,83	7,08
T (°C)		52,5	45,6	74,5	54,2
C.E. (us/cm)		1850	6770	4130,00	2170
Li (meq/l)		0,040	0,093	0,357	0,20
Na (meq/l)		8,75	24,19	28,20	12,28
K (meq/l)		1,03	2,12	1,39	0,16
Ca (meq/l)		4,54	19,60	9,78	8,31
Mg (meq/l)		3,95	66,98	1,98	0,14
F (meq/l)		0,230	0,00	23,72	0,100
Cl (meq/l)		3,49	22,59	23,72	11,32
Br (meq/l)		0,003	0,00	0,032	0,03
SO_4 (meq/l)		16,99	63,24	4,79	7,75
HCO_3 (meq/l)		*0,00	25,60	10,50	1,65
d18O (‰ V-SMOW std)		- 11,7	- 11,7	- 11,4	-11,8
dD (‰ V-SMOW std)		- 87	- 80	- 80	-80
SiO_2 (mg/l)		*126,60	*147,1	*73,55	*0,00

3. EXAMPLES FROM ICELAND

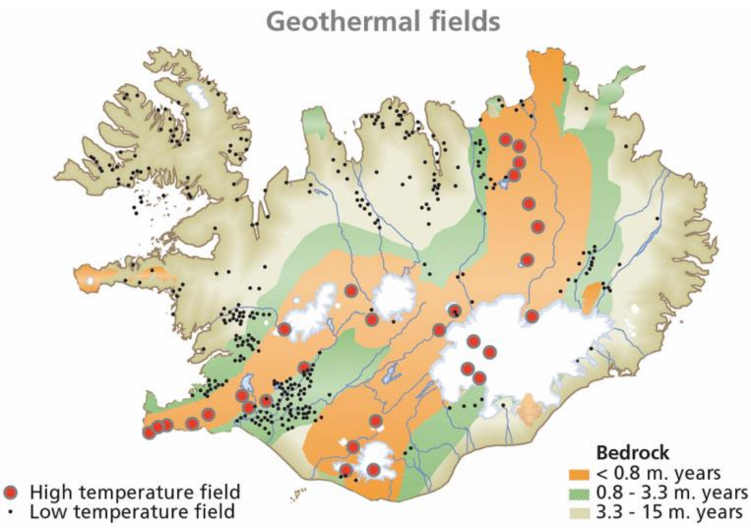

FIGURE 6: Geothermal fields in Iceland (NEA, 2014)

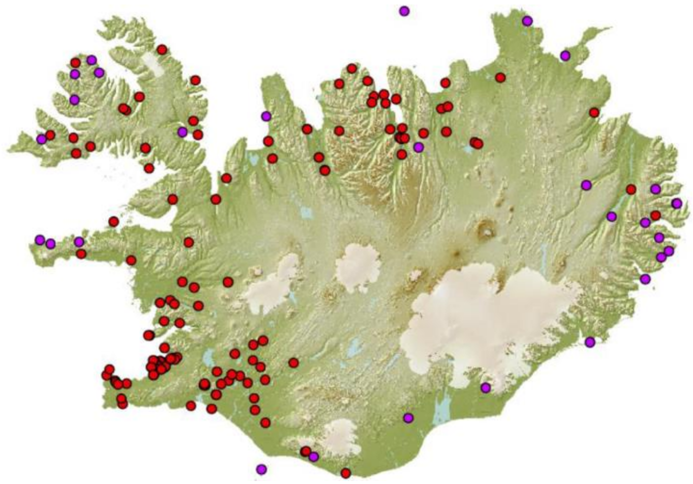

FIGURE 7: Swimming centers in Iceland in 2008 (Haraldsson and Ketilsson, 2010). Red circles indicate geothermal pools, whereas purple circles indicate pools heated by other energy sources (electricity, oil, or wastes)

Iceland is located on top of the Mid-Atlantic Ridge and the resulting volcanism and seismicity give rise to numerous high- and low-temperature geothermal fields (Figure 6). Although some Icelanders made use of geothermal hot springs for recreation, relaxation and bathing since well before the days of Snorri Sturluson, such activity did not become engrained in the culture until the 20th century, when man-made geothermal pools and easier access to natural pools allowed it. Many of the geothermal swimming pools that were constructed in the early part of the century were located in the vicinity of natural hot springs, which called for minimal effort in accessing the resource and water conveyance. Many of these were intended for swimming instruction, which was considered important for a nation reliant on fishing. Over the following decades, the number of man-made pools increased with the establishment of district heating systems around the country, mandatory swimming instruction in elementary schools, improved economic conditions and an increasing appetite for "swimming" among the public. In 2010, there were 163 recreational swimming centers operating in Iceland, out of which 134 used geothermal heat totaling close to 1,400 TJ (Bjornsson et al., 2010; Figure 7). There are also many natural pools in varying conditions to be found around the country (Snaeland and Sigurbjornsdóttir, 2010), a few therapeutic centers and spas, and a geothermal beach was opened by the cold North Atlantic Ocean in 2000. In the following sections, examples are presented of each category.

3.1 Swimming pools – Laugardalslaug

Swimming centers in Iceland are used for mandatory swimming instruction for students, competitive swimming practice, recreation, relaxation, and socializing. They are attended by all age groups in all seasons and have become an important part of Icelandic culture. Although many Icelanders associate health benefits to frequenting the pools, there is not a great focus on water chemistry or balneological aspects among the guests. Access to hot tubs of different temperatures, jaccuzzis and steam baths is highly valued, however.

A regulation is in place regarding sanitary practices in swimming and bathing centers, which defines allowable temperatures, chlorination levels, pH values, water circulation time, cleansing requirements, and the water exchange rate. The temperature of pools used for swimming shall be in the range of 27-29°C, whereas the temperature of thermal pools including childrens' pools should be 30-34°C, and relaxation pools and hot tubs can have temperatures of 34-44°C (MENR, 2010). In accordance with the regulation, swimming centers are placed into three categories depending on sanitation measures. All new swimming pools must fulfill the requirements of category A, which call for an automated control system for all major parameters. Older pools may fall into categories B or C, for which more lenient sanitary requirements are made. According to guidelines published by the Environment Agency of Iceland, all swimming centers need an operation license from the respective health authorities (EAI, 2012).

In a typical modern day setup, the water enters a swimming pool through ducts on the bottom and rises to overflows on the surface edges of the pool, from where it passes through a sand filter and a buffer tank before being recirculated (Figure 8). Heat is added either by mixing district heating water directly into the circulation (open system) or through heat exchangers (closed system). A control system injects CO_2 and chlorination agents as needed to maintain pH values and disinfectant levels within a set range. The sand filter is back-flushed according to need, as indicated by differential pressure measurements.

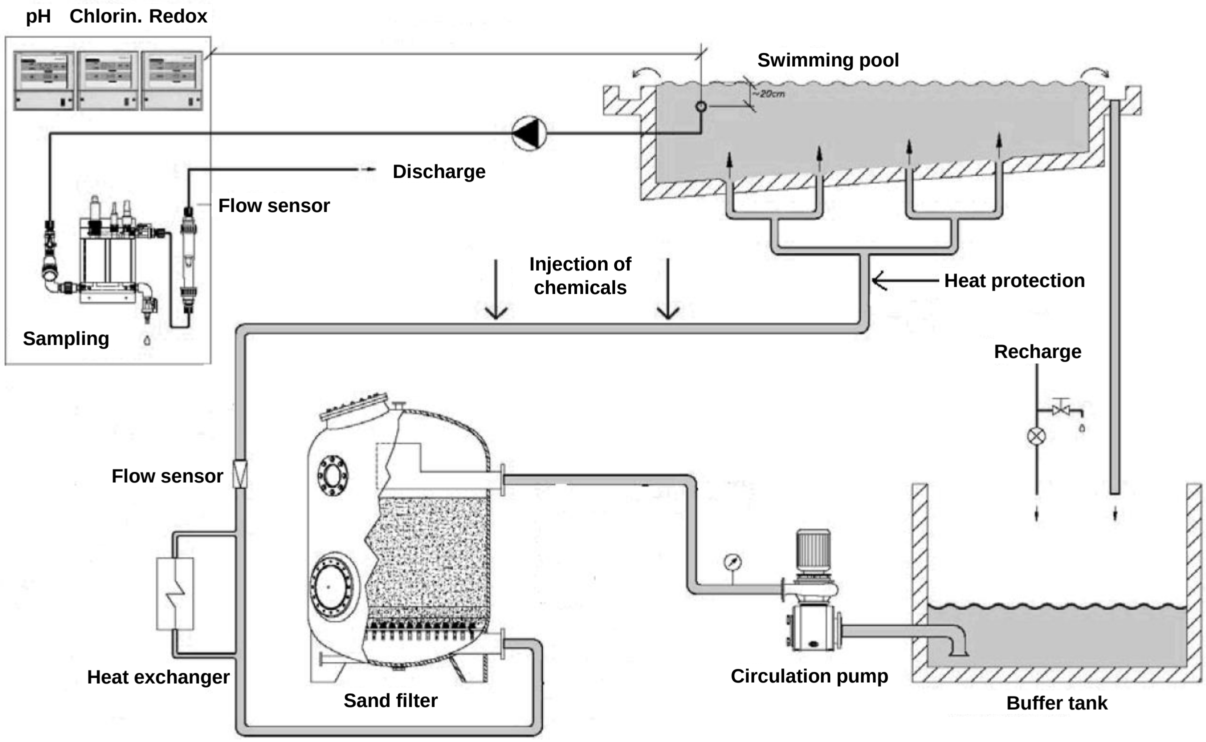

FIGURE 8: Typical setup for a modern day closed circulation swimming pool (modified from Haraldsson and Ketilsson, 2010; Courtesy of Ólafur Gunnarsson)

One of the first man-made swimming pools in Iceland was constructed in the heart of the capital, Reykjavik, in 1907-1908 (City of Reykjavik, 2014a). The Laugardalslaug swimming pool has since grown to become the largest conventional swimming center in Iceland, with large outside and indoor swimming pools designed for training and swimming competitions, a dedicated kids' pool with a water slide, and several relaxation ponds and hot tubs with varying temperatures and massage jet options (Figure 9). One of the hot tubs is filled with brackish water, while "conventional" pool water is used for other tubs and pools. In general, swimming pool water is either water from a district heating system that may have considerable mineral content or heated ground water with low mineral content – or a mix of the two. Table 2 lists the different pools and tubs of Laugardalslaug, and their main defining physical parameters.

FIGURE 9: Laugardalslaug – Laugardalur swimming pool (City of Reykjavik, 2014b)

TABLE 2: Main defining parameters of the pools and tubs of Laugardalslaug (City of Reykjavik, 2014a; Swimming in Iceland, 2014)

	Shape	**Depth (m)**	**Area (m^2)**	**Volume (m^3)**	**Temperature (°C)**	**No. of lanes**
Main pool (outside)	Rect. (L=50m)	0.80-1.76	1,100	2,730	28	8
Kids' pool (outside)	Irregular	0.80	400	320	32	N/A
Relaxation pond (outside)	Circular	0-0.40	15.9		32	N/A
Massage bath (outside)	Irregular		30	17	39	N/A
Hot tub 1 (outside)	Circular		7.0	5.6	38	N/A
Hot tub 2 (outside)	Circular		7.0	5.6	40	N/A
Hot tub 3 (outside)	Circular		7.0	5.6	42	N/A
Hot tub 4 (outside)	Circular		7.0	5.6	44	N/A
Sea tub (outside)	Irregular				40	
Competition pool (inside)	Rect. (L=50m)		1,250			10
Kids' pool (inside)	Rect. (L=25m)	<1 m				4

Outdoor swimming pools in the cold climate of Iceland demand a lot of heat to maintain optimal temperatures and they could hardly be maintained in such numbers if not for the fact that Iceland enjoys the lowest district heating prices in Europe (Haraldsson, 2014). The City of Reykjavik maintains 7 swimming centers that were visited by almost 2 million guests in 2010, out which nearly 800,000 visited Laugardalslaug (Hjaltalín, 2011). By end of year 2011, the estimated operation and maintenance costs for the year amounted to 1,477 million ISK, which translates to 14.3 million USD (adjusting for inflation using the consumer price index as reported by Statistics Iceland and the average exchange rate for February 2014 as reported by the Central Bank of Iceland). The expected income from ticket sales was 567 million ISK (5.5 million USD), meaning that the City would subsidize the total costs by 910 million ISK (8.8 million USD) (Hjaltalín, 2011). This shows clearly the importance attached by many Icelandic municipalities in running swimming centers for public benefit. In 2014, the advertised admission prices were as shown in Table 3.

3.2 Nature pools – Landmannalaugar

There are many natural or semi-natural pools in Iceland. Some have been entirely made by Nature, while most have been touched by man to varying degrees: access has been made easier, facilities constructed, dams raised, ditches dug, water conveyed etc. What these pools have in common is the close connection to Nature experienced by guests.

TABLE 3: Admission prices for swimming centers in Reykjavik (City of Reykjavik, 2014c)

Service	Price (ISK)	Price (USD)
Kids (6-18 years)		
Single ticket	130	1.14
10 tickets	900	7.89
6 months card	6,000	52.59
12 months card	10,000	87.64
Adults		
Single ticket	600	5.26
10 tickets (valid for 36 months)	4,100	35.93
6 month card	16,500	144.61
12 month card	30,000	262.93

Landmannalaugar (People's pools) is an example of a Nature bath in the interior of Iceland that is visited by over 100,000 guests every year (Snaeland and Sigurbjornsdóttir, 2010). Warm brooks originating from a nearby lava field have been dammed to create the pools, which have an elevation of 593 m and are surrounded by colorful rhyolite mountains (Figure 10). The water temperature ranges from 34 to 41°C (Snaeland and Sigurbjornsdóttir, 2010). Despite the lack of facilities for changing clothes and the possibility of parasite attacks, the pools remain popular among Icelanders and foreigners alike.

FIGURE 10: Landmannalaugar (Eskimos, 2014)

3.3 Spas – Blue Lagoon

While Icelanders mostly visit the pools for recreation, relaxation, socializing, and athletic reasons, some geothermal spas are to be found around the country. The most prominent example is without a doubt the Blue Lagoon, which has gained world recognition in the past decades.

The Blue Lagoon was formed in 1976 (Gudmundsdóttir et al., 2010) as effluent geothermal water was discharged from the Svartsengi power plant into the adjacent lava field. In the following years, people suffering from the psoriasis skin disease discovered beneficial effects from bathing in the lagoon. As the word spread, the group of dedicated visitors grew larger, resulting in the construction of the first public bathing facilities and the opening of a special clinic for psoriasis patients in the period 1987-1995 (Blue Lagoon, 2014a). In 1999, the current facility was opened (Figure 11), with enlargement and redesign taking place in 2007 (Gudmundsdóttir et al., 2010). Over the nearly 4 decades since its formation, the Blue Lagoon has grown to become a major Icelandic tourist attraction.

FIGURE 11: The Blue Lagoon with the Svartsengi power plant in the background (left) (Hnefill, 2012) is rich in silica mud which has beneficial effects on the skin (right) (Photo: L.S. Georgsson)

The lagoon fluid is a mixture of sea- and groundwater coming from a depth of 2000 m, where the temperature is around 240°C (Blue Lagoon, 2014b). The fluid is rich in silica, which starts to polymerize and precipitate as the fluid cools and at the 37-39°C water temperature within the bathing section of the lagoon, a white silica mud layer forms on the bottom. The dermatological benefits of bathing in the lagoon are partly attributed to this white precipitate, which guests apply to their skin (Figure 11). Additional benefits derive from photosynthetic blue-green microalgae that thrive in the water (Suryata et al., 2010) – especially in summer when the organisms enjoy near perpetual daylight which can result in the lagoon changing its characteristic blue-white color to green.

TABLE 4: Concentrations of major substances in the Blue Lagoon

Substance	Concentration mg/kg[a]	Concentration meq/kg
SiO_2	251	
Na	7,643	332.3
K	1,117	28.6
Ca	1,274	63.5
Mg	0.60	0.05
SO_4	31.8	0.66
Cl	15,740	443.4
F	0.18	0.01

a: From (Blue Lagoon, 2014c)

Table 4 shows the concentration of major substances in the Blue Lagoon (Blue Lagoon, 2014c). Due to its partial seawater origin, the fluid has a high salinity of 2.5% as evident from the high concentrations of chloride, sodium, calcium, and potassium. This high salinity contrasts with more conventional swimming pool water that has originated as groundwater or from low temperature geothermal reservoirs, as well as with the waters of the 4 hot springs and spas in Ecuador reported on in Table 1 (1 kg of water at 37-39°C is very nearly equivalent to a liter of water at the same temperature). However, the Blue Lagoon has a lower concentration of magnesium, sulphate and fluoride compared to the pools in Ecuador.

3.4 A geothermal beach – Nauthólsvík

In the summer of 2000, a new geothermal beach was opened in Reykjavik (Figure 12). The idea was to elevate the temperature of a small part of the North Atlantic Ocean with discharge water from the Reykjavik district heating system. To this end, two stone barriers were constructed into the Nauthólsvík cove, with a small opening between them to allow water in and out. Geothermal water flows into the lagoon between the barriers, elevating the ocean water

FIGURE 12: The Nauthólsvík geothermal beach (Nordic Adventure Travel, 2014)

temperature by a few degrees, so that the temperature of the lagoon can become as high as 18-20°C in the summer time (Snaeland and Sigurbjornsdóttir, 2010). The combination of warm ocean water and white sand, which has been imported from other parts of the country, allows for the creation of a beach atmosphere reminiscent of more southerly latitudes. The geothermal beach has proved popular with Icelanders, who also take advantage of a geothermal hot tub and a steam bath by the beach.

4. CLOSING REMARKS

The use of geothermal resources for bathing and swimming, for the purposes of personal hygiene, athletic practice and competition, recreation, relaxation, socializing, and therapeutic treatment has deep roots in human history and has evolved in different parts of the world to refined practices that have to some extent been shared in modern times, although different cultures may have certain distinct traditions. In Ecuador, geothermal bathing has mostly been focused on relaxation and therapy, and the country has a great potential for more wide-spread use of geothermal resources for this purpose. In Iceland, a stronger focus has been placed on swimming and recreation, although the other factors are important as well, and attendance to swimming centers is quite wide-spread due to a large-scale build-up of swimming centers in the 20th century. Although the pleasures of bathing in geothermal water have undoubtedly remained much the same through the centuries in all corners of the globe, modern day technology has made it possible for ever greater numbers to enjoy a geothermal bath, in better conditions. Many countries have taken advantage of this, while others have a great potential that awaits application.

REFERENCES

Aasgaard, J., 2012: *Snow monkeys in Jigokudani – Hot springs are not only for humans*. JapanTravel. Website: http://en.japantravel.com/view/snow-monkeys-in-jigokudani

Andean Travel Web Guide to Peru, 2010: Sacsayhuaman and nearby ruins. Website: http://www.andeantravelweb.com/peru/destinations/cusco/sacsayhuaman.html

Beate, B., and Salgado, R., 2010: Geothermal country update for Ecuador, 2005-2010. *Proceedings of World Geothermal Congress 2010, Bali, Indonesia*, 16 pp. Web: http://www.geothermal-energy.org/ pdf/IGAstandard/WGC/2010/0160.pdf

Bjornsson, S., Gudmundsdóttir, I.D., and Ketilsson, J. (editors), 2010: *Geothermal development and research in Iceland*. Orkustofnun – National Energy Authority of Iceland, 39 pp. Web: http://www.nea.is/media/utgafa/GD_loka.pdf

Blue Lagoon, 2014a: *Blue Lagoon history*. Website: http://www.bluelagoon.com/about-us/

Blue Lagoon, 2014b: *Ecology of the Blue Lagoon* (in Icelandic). Website: http://www.bluelagoon.is/blue-lagoon-spa/vistkerfi-blaa-lonsins/

Blue Lagoon, 2014c: *Environmental focus*. Website: http://www.bluelagoon.com/about-us/environmental-focus/

Burbano, N., Becerra, S., and Pasquel, E., 2013: *Aguas termominerales en el Ecuador*. Instituto Nacional de Meteorologia e Hidrologia (INAMHI), technical report 1, 95 pp. http://www.servicio meteorologico.gob.ec/biblioteca/

China International Travel CA, 2012: *Xi'an photo gallery and information page*. Website: http://www. chinatravelca.com/places/xian/

City of Bath, 2014: *Bath timeline*. Website: http://bath.cityofbath.co.uk/history-of-bath/bath-timeline.html

City of Reykjavik, 2014a: *Laugardalslaug swimming pool – General information* (in Icelandic). Website: http://reykjavik.is/thjonusta/laugardalslaug-almennar-upplysingar

City of Reykjavik, 2014b: *Laugardalslaug*. Website: http://reykjavik.is/stadir/laugardalslaug

City of Reykjavik, 2014c: *What does swimming cost?* (in Icelandic). Website: http://reykjavik.is/gjaldskrar/hvad-kostar-i-sund

EAI, 2012: Swimming and bathing centers – Guidebook. Umhverfisstofnun – Environment Agency of Iceland, report UST-2012:13 (in Icelandic), 47 pp. Web: http://www.heilbrigdiseftirlit.is/Innihald_heimasida/Hollustuhaettir/Handbok_Sundstada_2821f.pdf

Eskimos, 2014: Landmannalaugar – The multicolored highland treasure. Website: http://www.iceland. eskimos.is/Viewproduct/landmannalaugar-iceland

Figueroa Alburuqueque, J.R., 2005: *Los Baños del Inca*. Peru Top Tours. Website: http://www.perutoptours.com/index06caincabath.html

Fridleifsson, I.B., 1995: Historical aspects of geothermal utilization in Iceland. *Proceedings of World Geothermal Congress 1995, Firenze, Italy*, 389-394. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/1-fridleifsson.pdf

Gudmundsdóttir, M., Brynjólfsdóttir, Á., and Albertsson, A., 2010: The history of the Blue Lagoon in Iceland. *Proceedings of World Geothermal Congress 2010, Bali, Indonesia*, 6 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/3314.pdf

Haraldsson, 2014: Economic benefits of geothermal space heating from the perspective of Icelandic consumers. Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador, 9 pp.

Haraldsson, I.G., and Ketilsson, J., 2010: *Utilization of geothermal resources for electricity generation and direct applications*. Orkustofnun – National Energy Authority of Iceland, report OS-2010/02 (in Icelandic), 62 pp. Web: http://www.os.is/gogn/Skyrslur/OS-2010/OS-2010-02.pdf

Hjaltalín, D., 2011: *Greatest subsidy on Laugardalslaug* (in Icelandic). Vidskiptabladid (Business Times), 28 December 2011. Website: http://www.vb.is/frettir/68678/

Hnefill, O., 2012: *National Geographic names Blue Lagoon a wonder*. Book Iceland. Website: http:// www.goiceland.is/2012/02/national-geographic-names-blue-lagoon-a-world-wonder

Hurstwic, 2014: *Health, grooming, and medicine in the Viking age*. Webpage: http://www.hurstwic.com/history/articles/daily_living/text/health_and_medicine.htm

Icelandic Ministry for the Environment and Natural Resources, 2010: Regulation on sanitary practices in swimming and bathing centers. Ministry

Inguaggiato, S., Hidalgo, S., Beate, B., and Bourquin, J., 2010: Geochemical and isotopic characterization of volcanic and geothermal fluids discharged from the Ecuadorian volcanic arc. *Geofluids, 10-4*, 525-541.

Kępińska, B., 2003: Geothermal energy in human history, culture, and practices – selected highlights. In: Kępińska, B., *Geothermal resources and utilization in Poland and Europe*. UNU-GTP, Iceland, 3-13. Website: http://www.os.is/gogn/unu-gtp-report/UNU-GTP-2003-02.pdf

MENR, 2010: *Regulation on sanitary practices in swimming and bathing centers*. Icelandic Ministry for the Environment and Natural Resources, regulation no. 814/2010 (in Icelandic). Website: http://stjornartidindi.is/Advert.aspx?ID=d95ce3d0-05db-4dab-aada-c00b50fd64ed

NEA, 2014: *Geothermal – the resource*. Orkustofnun – National Energy Authority of Iceland. Website: http://www.nea.is/geothermal/the-resource

Nordic Adventure Travel, 2014: *Nauthólsvík*. Website: http://www.nat.is/travelguide/ahugav_st_nautholsvik.htm

Piedra de Agua, 2014: *Piedra de Agua - Fuente termal & spa*. Website: http://www.en.piedradeagua.com.ec

Snaeland, J.G., and Sigurbjornsdóttir, Th., 2010: *Thermal pools in Iceland*. Skrudda, Reykjavik, 208 pp.

SnowJapan, 2014: *The snow monkeys of Jigokudani*. Website: http://www.snowjapan.com/the-snow-monkeys-of-jigokudani-nagano

Suryata, I., Svavarsson, H.G., Einarsson, S., Brynjólfsdóttir, Á., and Maliga, G., 2010: *Geothermal CO_2 bio-mitigation techniques by utilizing microalgae at the Blue Lagoon, Iceland*. Proceedings of the Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, California, 8 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2010/suryata.pdf

Swimming in Icealnd, 2014: *Laugardalslaug*. Website: http://www.swimminginiceland.com/reykjavik-and-capital-area/17-laugardalslaug

VisitBath, 2014: *Roman baths*. Website: http://visitbath.co.uk/things-to-do/roman-baths-p25681

Wang, J.Y., 1995: Historical aspects of geothermal energy in China. *Proceedings of World Geothermal Congress 1995, Firenze, Italy*, 389-394. Web: http://www.geothermal-energy.org/pdf/IGAstandard/ WGC/1995/1-wang2.pdf

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GEOTHERMAL ENERGY IN HORTICULTURE

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ABSTRACT

Heating of greenhouses by geothermal energy has been practiced in many countries over a long period of time, especially in Europe. Access to geothermal water makes it possible to keep the climate inside the greenhouses as close to the optimum growth conditions for the plants as possible. In addition to heating, artificial lighting and CO_2 enrichment in greenhouses is common. This makes it possible to keep optimum growing conditions in the greenhouses throughout the year, independent of the outdoor climate conditions. Geothermal energy requires relatively simple heating installations, although modern greenhouses are equipped with advanced computerized installations for controlling the climate inside the greenhouse. The paper describes the activities at the Fridheimar greenhouse farm in Iceland. There, in addition to growing different varieties of tomatoes and other crops in well-equipped greenhouses totalling 4,200 m^2, tourist services play an important role in the daily business.

1. INTRODUCTION

Utilization of geothermal energy in horticulture has a long history, especially heating of greenhouses. Many countries in Europe and other parts of the world are using geothermal energy extensively for commercial production of vegetable, flowers and fruits. Geothermal energy requires relatively simple heating installations, although modern greenhouses are equipped with advanced computerized installations for controlling the climate inside the greenhouse. Where geothermal resources are available for greenhouse heating it has substantial economic benefits compared with alternative energy sources for heating.

The purpose of protected crop cultivation is to keep the climate inside the greenhouse as close to the optimum growth conditions for the plants as possible. The photosynthesis process uses sunlight to convert carbon dioxide and water into building material for the plants such as sugars. Also, each type of plant needs a specific quantity of energy in form of heat. The optimum growing conditions are usually available naturally only a part of the year but geothermal heating and artificial lighting make it possible to keep optimum growing conditions in the greenhouses throughout the year, independent of the outdoor climate conditions (Dickson and Fanelli, 2005).

According to data presented at the World Geothermal Congress in Bali 2010 (WGC2010) the total geothermal energy used for greenhouse heating worldwide increased by 13% in annual energy use in the five year period of 2005-2010, from 20,661 to 23,264 TJ/year. In the same period the total installed capacity for greenhouse heating increased by 10% from 1,404 MWt to 1,544 MWt. A total of 34 countries reported geothermal greenhouse heating compared to 30 five years earlier. The leading countries were Turkey, Hungary, Russia, China and Italy. The main crops grown in greenhouses are vegetables and flowers (Figure 1). A large part of the costs of operating greenhouses is labor costs and this has led to increasing imports of greenhouse products from the developing countries to developed countries. Reliable data for the total area of geothermally heated greenhouses does not exist, but based on the average energy requirement of 20 TJ/year/ha, determined from the WGC2000 data, it can be estimated that about 1,163 ha of greenhouse area was heated by geothermal energy worldwide in 2010. This corresponds to a 16.3% increase since 2005. A few parameters describing the worldwide development in the greenhouse sector during the period 1995-2010 are presented in Table 1 (Lund et al., 2010).

TABLE 1: Greenhouse heating by geothermal energy worldwide (data from Lund et al., 2010)

	1995	**2000**	**2005**	**2010**
Installed capacity (MWt)	1,085	1,246	1,404	1,544
Energy utilization	15,742	17,864	20,661	23,264
Capacity factor	0.46	0.45	0.47	0.48

FIGURE 1: Gerbera production at Espiflöt flower farm, Iceland

2. HEATING SYSTEMS

2.1 Heat loss from greenhouses

Greenhouses are uninsulated buildings where the cover material is in most cases single glass or a plastic cover. This is required since light is an important factor in the cultivation and natural light from the sun must penetrate as easily as possible through the cover material to the plants inside. This is important even if artificial lighting is used in the greenhouse. The heating system is designed to compensate for the heat losses to the environment and keep the air temperature inside the greenhouse close to the optimal temperature for the crops.

Most greenhouses in Iceland have a heating system based on steel pipes transferring the geothermal water in long loops through the greenhouse. Increased use of artificial lighting and more advanced control of the cultivation process has required better control of the heating in greenhouses.

When an artificial lighting of 250 W/m^2 is switched off the heating demand will increase suddenly and a quick response from the heating system is needed. One problem with intensive artificial lighting is that heat emitted from the lamps makes it necessary to open the windows frequently to get fresh air in, with the exception of very low outdoor temperatures. This can cause the top of the plants to be cooled down too much and also create an uneven vertical temperature distribution in the greenhouse which again can slow down the growing rate of the crops. Experiments have been carried out in the Netherlands on cultivation in closed greenhouses where the need for cooling is met by water or air cooling instead of air change by opening the windows. In doing so it should be possible to use the lighting and CO_2 enrichment in a more efficient way to increase the growth.

For a typical greenhouse in Iceland the transfer of heat from the inside of the house to the environment can be divided into different processes as shown in Table 2 and Figure 2.

TABLE 2: Main heat transfer processes in a greenhouse (Ágústsson, 2008)

Outdoor	Forced convection, depending on the wind	60%
	Radiation	40%
Indoor	Convection	38%
	Radiation from the heating pipes	34%
	Radiation from plants and ground plus condensation of water	28

In clear weather the share of radiation in the outside heat transfer can be as high as 60% of the heat loss and as low as 10% when it is cloudy. In addition to this there is a heat loss due to air change in the greenhouse as hot air inside the house is constantly replaced by cold outside air that needs to be heated up. As a design condition for the heating demand of a greenhouse in Iceland it is common to assume that the total heat loss per square meter is given by a U-value of 7.6 W/m^2/°C (Ágústsson, 2008).

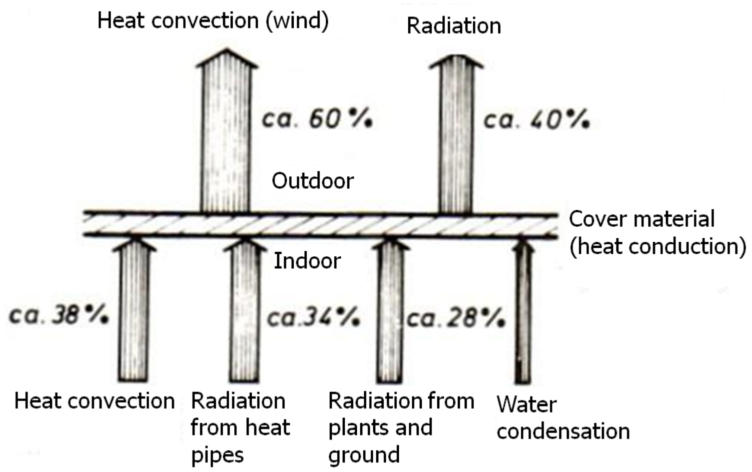

FIGURE 2: Heat transfer processes through a greenhouse cover material

2.2 Heating pipes

Heating pipes in greenhouses can be divided into four main categories. Some of them are more important than others. These are (Ágústsson, 2008):

1. Floor pipes (commonly 40-60% of the heating system);
2. Aerial pipes;
3. Wall pipes;
4. Soil heating.

In general the following requirements are made regarding the heating system in a greenhouse:

a) Keep the desired temperature in the greenhouse;
b) Respond quickly to changes in heating demand;
c) Keep as even a temperature in the greenhouse as possible;
d) Utilize the heat efficiently;
e) Fit into the building and the cultivation system.

The heat transfer processes from the heating pipes to the air inside the greenhouse are mainly of two types, radiation and convection (Figure 3). The radiation can cover up to 50% of the heat transfer, depending on the surface of the pipes. Pipes covered with aluminium bronze and galvanized pipes radiate only about 25% of the heat that is radiated from white painted pipes.

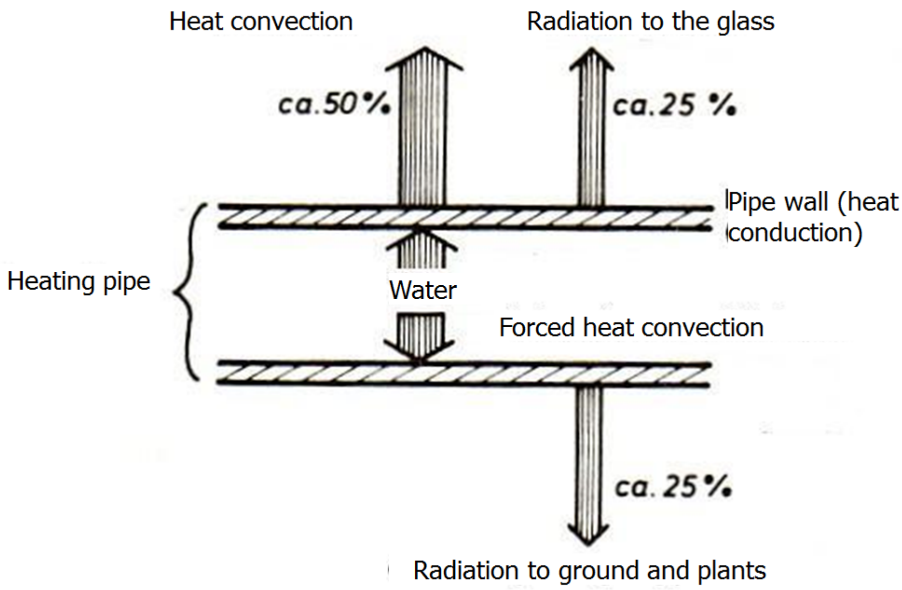

FIGURE 3: Heat transfer from heating pipes in a greenhouse

Floor pipes are the most important part of the heating system for most types of crop cultivation. The purpose of the floor pipes is to make the vertical temperature distribution as even as possible, heat up the lower part of the plants and increase air circulation. They are also used to reduce the humidity of the air by increasing the pipe temperature at the same time as the windows are opened up.

It should be possible to operate floor pipes as a separate heating system independent of other heating systems in the greenhouse. This is because the demand for heating from the floor pipes varies a lot, sometimes there is a need for intensive heating and sometimes not. The floor pipes should be placed at a minimum distance of 10 cm from the floor to ensure a free flow of air around the pipes. The difference between the temperature of the water at the inlet to the heating system and the outlet should preferably be about 10°C to give relatively even heat output from the pipes in the whole greenhouse. The average water temperature in the system is commonly about 60°C and a typical pipe diameter is 50 mm.

Aerial pipes are, as the name indicates, placed relatively high in the greenhouse above the plants. Their main purpose is to heat up the glass and the structural frame of the house and thus reduce the heat radiation from the plants to the glass. This is important since radiation from the plants can cool them down to a temperature considerably lower than the inside air temperature. In addition to being an obstacle to the growth of the plants it can cause dew formation on the plants which again increases the risk of diseases. Heating up the glass also reduces condensation of water on the glass surface which helps to maintain the humidity level and reduces the loss of light due to condensed water on the glass. The aerial pipes should be a separate heating system that can be controlled independent of other heating systems in the greenhouse. They should be placed so that they do not reduce the solar radiation to the plants too much.

Wall pipes are placed along the walls of the greenhouse and can be considered to be a supplementary heating system that is activated when the other systems cannot fulfil the heating demand. The vertical distance between the pipes should not be less than 30 cm to ensure free air flow around the pipes.

The design of heating systems for greenhouses in Iceland is usually based on the experience of the contractor and the wishes of the greenhouse farmer. Commonly between 2 and 5 m of pipeline is required per m^2 floor area depending on the pipe diameter and water temperature (Ágústsson, 2008).

3. GREENHOUSES IN ICELAND

Heating of greenhouses is one of the oldest and most important uses of geothermal energy in Iceland after space heating. Naturally warm soil had been used for growing potatoes and other vegetables for a long time when geothermal heating of greenhouses started in Iceland in 1924. The majority of the greenhouses are located in the south, and most are enclosed in glass. The heating installations are of unfinned steel pipes hung on the walls and over the plants. Undertable or floor heating is also common. It is also common to use inert growing media (volcanic scoria, rhyolite) on concrete floors with individual plant watering. By using electric lighting the growing season is lengthened compared with natural lighting only, which improves the utilization of the greenhouses and increases the annual production per square meter of greenhouse area. Artificial lighting, which also produces heat, has contributed to a diminishing demand for hot water supply to greenhouses. As a consequence of the lengthening of the growing season the need for new constructions is less than before. CO_2 enrichment in greenhouses is common, primarily by using CO_2 produced in the geothermal plant at Haedarendi. Outdoor growing at several locations is enhanced by soil heating with geothermal water, especially during early spring (Ragnarsson, 2010).

The total surface area of greenhouses in Iceland was about 194,000 m^2 in 2012 including plastic tunnels for bedding and forest plants. Of this area, 50% is used for growing vegetables (tomatoes, cucumbers, paprika etc.) and the rest mainly for growing cut flowers and potted plants. The total production of vegetables in 2011 was about 18,000 tons. The share of domestic production in the total consumption of tomatoes in Iceland is about 75% and for cucumbers about 90%.

Most of the greenhouses in Iceland have automatic control of the indoor climate and thus, for example, the temperature can be adjusted to the optimum temperature for different kinds of crops, ranging from 10-15°C in nurseries up to 20-25°C for roses. Also, the temperature is commonly adjusted to follow the optimum daily variations. The main parameters that influence the heat loss from greenhouses and thereby the heating demand are the outdoor temperature, wind speed, greenhouse cover material, indoor temperature, artificial lighting, heating system arrangement and opening of the windows. A study made on energy consumption for heating a group of typical greenhouses in Iceland resulted in an average energy consumption of 3.67 GJ/m^2 in greenhouses with artificial lighting and 5.76 GJ/m^2 in greenhouses without artificial lighting (Haraldsson and Ketilsson, 2010).

4. FRIDHEIMAR GREENHOUSE FARM

Fridheimar is the name of a greenhouse farm located in SW-Iceland. They have their own website, which is the source of information for the description of their activity presented below (Fridheimar greenhouse farm, 2014).

Fridheimar is more than a greenhouse farm since an important part of their activity is the operation of a small restaurant and other tourist services (Figure 4). Fridheimar has specialised in tomatoes which they grow all year round in greenhouses under artificial lighting. Visitors are welcome to see the greenhouses and even taste the crop. They can also buy different kinds of food made from the local production, mainly tomatoes and cucumbers. In addition to the greenhouse farm the owners of Fridheimar are active in horse breeding and tourist services related to that. Different varieties of tomatoes are produced like plum tomatoes, cocktail tomatoes and piccolo tomatoes. The farmers state that the key factors in their production of tasty and healthy tomatoes is the green energy, pure water and biological pest controls. The pest control is based on a bug which devours all the main pests that damage the tomato plants.

FIGURE 4: From the Fridheimar greenhouse farm

The total area under glass is 5,000 m², of which about 4,200 m² are used for cultivation. The plant nursery accounts for 300 m², the atrium for visitors 300 m², and about 200 m² are used for packing etc. The greenhouses were built in the period between 1986 and 2011 and all of them have artificial lighting for year-round cultivation. Fridheimar has about 10,000 plants in their greenhouses that need weekly trimming and picking. The production is about one ton per day.

Seeds are planted in the nursery greenhouse where the plants grow in pots for the first six weeks. Then they are transplanted into the greenhouse and seven to eight weeks later the first tomatoes are harvested. At Fridheimar the tomatoes are cultivated in turf and the plants are renewed twice a year. Young plants are planted in between older plants during the whole growth period. Thus, as the last tomatoes are ready to pick on the older plants the first tomatoes on the young plants are turning red.

Abundant geothermal water for heating the greenhouses is available from a well located about 200 m from the greenhouses. The temperature of the water is about 95°C. In order to maximise sunlight in the greenhouses the glass windows are only 4 mm thick. Thus, a huge amount of hot water is needed for heating or totally about 100,000 tons per year. This amount corresponds to the annual hot water consumption of about 130 single family houses in Iceland. The electricity for artificial lighting in the greenhouses, which is necessary for year round growing, comes from renewable energy sources, partly hydropower and partly geothermally generated electricity. Another important part of the cultivation is enhancing photosynthesis by adding carbon dioxide into the greenhouses. This additional carbon dioxide comes from a factory that utilizes carbon dioxide rich fluid from a geothermal well for their production.

Each greenhouse is equipped with a climate-control computer system for temperature, humidity, carbon dioxide and lighting. The computer is connected to a fertiliser mixer, which waters the crop according to a programmed system. A weather station located on the roof provides data on outdoor temperature and light as well as wind speed and direction. The electrical lighting in the greenhouses is automatically switched on when the natural light goes below a certain limit and switched off again when the natural light has reached the required limit again. The whole control system is connected to the internet which makes it possible for the owners to monitor and adjust the conditions in the greenhouses from anywhere in the world.

REFERENCES

Ágústsson, M., 2008: Lagnir í gródurhúsum (Greenhouse piping). *Lagnafréttir. Newsletter of the Icelandic Society of HVAC Engineers, 36*, 72 pp. Web: http://www.lafi.is/gogn/Lagnafrettir_pdf/ Lagnafrettir-36.pdf

Dickson, M.H., and Fanelli, M. (editors), 2005: *Geothermal energy. Utilization and technology*. Earthscan, New York, NY, United States, 205 pp.

Fridheimar greenhouse farm, 2014: *Horticulture*. Website: http://fridheimar.is/en

Haraldsson, I.G., and Ketilsson, J., 2010: *Utilization of geothermal resources for electricity generation and direct applications*. Orkustofnun – National Energy Authority of Iceland, report OS-2010/02 (in Icelandic), 62 pp. Web: http://www.os.is/gogn/Skyrslur/OS-2010/OS-2010-02.pdf

Lund, J.W., Freeston, D.H., and Boyd, T.L., 2010: Direct utilization of geothermal energy 2010 worldwide review. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 23 pp. Web: http:/www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0007.pdf

Ragnarsson, Á., 2010: Geothermal development in Iceland 2005-2009. *Proceedings World Geothermal Congress 2010, Bali, Indonesia,* 12 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/ WGC/2010/0124.pdf

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GEOTHERMAL ENERGY UTILIZATION AT OSERIAN FLOWER FARM-NAIVASHA

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ABSTRACT

Oserian Development Company Limited (ODCL) is a privately owned farm located in Naivasha next to the Olkaria Geothermal project. The farm has been utilizing geothermal energy for direct use applications since 2003 and for electrical power generation from 2004. For Oserian, the use of geothermal energy has resulted in reduced operation costs, increased productivity, and a large market share due to use of environmentally and eco-friendly practices.

Oserian Development Company heats 50 hectares of rose flower greenhouses using geothermal energy from well OW-101 leased from KenGen in 2003.

KenGen and Oserian entered into a steam supply agreement for supply of steam from wells OW-306 and OW-202 to the two power plants at the Oserian farm. The power generated from the two plants is used for internal operations within the farm.

1. INTRODUCTION

Oserian is located adjacent to the Olkaria geothermal field in Naivasha. It began as a family owned vegetable growing farm in 1969, with a 5 hectare production area and 6 employees. In 1982 they expanded the farm to include cut flower production. Today, Oserian is one of the largest flower producers in Kenya, selling its products to Europe with a 30% share of the cut-flower market (ArGeo C2, 2008). Oserian now stands at the forefront of the industry as a leading force and one of the largest multi–crop, flower farms in Kenya (Figure 1).

In early 2000, the farm initiated a major investment program to utilize the geothermal energy from an early exploration well, well OW-101, leased from KenGen.

2. GEOTHERMAL ENERGY UTILIZATION AT OSERIAN

In early 2000, Oserian decided to move forward with an innovative strategy to harness geothermal energy. Its vision was to develop a technologically advanced growing method based on the full environmental control of its greenhouses and farm operations (Murua 2011). This was in the expectation that the use of geothermal energy for greenhouse heating and electrical power generation using the already available wells (OW-306 and OW-202, leased from KenGen) would significantly reduce the operation cost, improve productivity and increase the market share since geothermal energy is an environmentally benign, cheaper, indigenous and sustainable energy source.

FIGURE 1: Photo showing greenhouses at the Oserian Flower Farm

Oserian constructed a 2.0 MWe binary plant Ormat OEC to utilize fluid from well OW-306. The plant, which is supposed to provide electrical power for the farm's operations, was commissioned in July, 2004. Oserian who grows cut flowers for export is also utilizing steam from a 1.28 MWe well to heat fresh water through heat exchangers, enrich CO_2 levels and to fumigate the soils.

2.1 Direct utilization

Oserian Development Company Limited, ODCL, is the only company in Kenya to utilize geothermal energy for direct use applications on commercial scale. A total of 50 hectares of cut rose flower greenhouses are heated using geothermal energy.

2.1.1 The greenhouse heating system

A low output-cyclic exploration well drilled by KenGen was initially believed to be non-productive and therefore "useless". The well, drilled to a depth of 1617m, encountered a maximum temperature of 278°C with a steam flow rate of 14.7 tonnes per hour and an enthalpy of 1475 kJ/kg. The Oserian Farm however leased the well for use in greenhouse heating. Through a system of loops (Figure 2), hot geothermal fluid heats fresh water which is used as a heat transport medium to the greenhouse. Greenhouse heating assists in controlling relative humidity within the greenhouse especially the early morning hours when humidity tends to rise to about 100%. Reducing relative humidity to below 85% eliminates fungal infection and hence eliminates the use of chemical fungicides. Heated water is also used to sterilise the fertilised water reducing fertiliser wastage and hence reducing cost. Carbon dioxide from the well is piped to the greenhouses in order to enhance photosynthesis.

Heating also enhances growth, increases productivity and saves on fuel costs that would be incurred if heating were to be done using fossil fuels (Hole and Mills, 2003).

FIGURE 2: Oserian greenhouse heating using geothermal energy

Inside a greenhouse, steel pipes are used to distribute the fresh, hot water around in order to attain the desired temperature.

The greenhouse heating system at the Oserian farm comprises various subsystems (Figure 3):

- A geothermal heating circuit located at the well site;
- A secondary fresh water heating circuit to transport heat from the well site to the greenhouse area;
- A large heat storage tank (3.8 million liters) to hold water at 92^{o}Celsius adjacent to the greenhouses;
- A distribution network to supply heat to the individual greenhouses as required; and
- Other secondary utilizFation accessories.

2.1.2 Carbon dioxide enrichment

Hot geothermal fluid comes out of the well and is piped to two plate heat exchangers, where it heats water coming from the 3.8 million litre water tank to about 92°C. The spent geothermal brine is then transported from the plate heat exchangers to a separator from which carbon dioxide is extracted from the top and liquid brine is removed from the bottom, through centrifugal action. The spent brine is then disposed in an environmentally acceptable way while the carbon dioxide is taken to the greenhouses. The fresh water heated inside the plate heat exchangers is taken back into the top of the water tank and mixed, through the use of mixing valves, with the cold water until a temperature of 50°C is attained, after which it is then fed into the greenhouses.

2.1.3 Sterilizing the fertilized water

Over 80 percent of Oserian's crops are grown using a technique known as "hydroponics", which replaces soil with another medium, enabling exactly the right quantities of nutrients to be supplied to the plants. The name "hydroponic" comes from Latin and means "working water". In reality hydroponics is the growing of plants without soil. When most people think of hydroponics, they think of plants grown with their roots suspended directly into water with no growing medium. This is just one type of hydroponic gardening, known as the Nutrient Film Technique (N.F.T.), (Oserian, 2011)

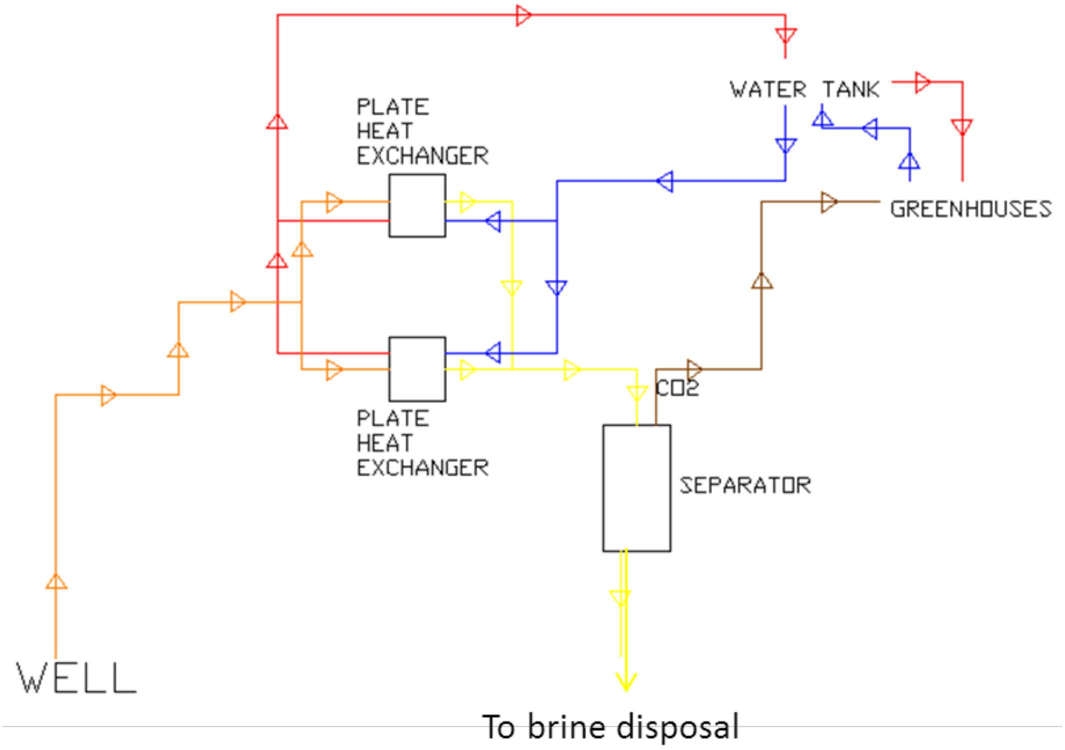

FIGURE 3: Schematic of the geothermal heating system at Oserian (Knight et al., 2006)

At Oserian, the hydroponics is achieved through the use of pumice in pots which supports the plants. Nutrients and water for the plants are in the form of the fertilized water. The excess fertilized water is recycled. To reduce the plants' infection, the recirculating fertilized water is passed through a geothermally heated sterilizer. This technique helps to improves yields and quality, while reducing the quantities of pesticides and fertilizers used as well as enabling water conservation through more efficient irrigation. This has proved to be economical in terms of water and the plants' nutrients.

2.1.4 Integrated Pest Management system

Oserian is also the world's largest Integrated Pest Management (IPM) farm. This activity involves the combination of plant nutrition with bio-control agents, which are biological substances designed to prevent and combat a range of diseases that affect flowers. A 2.5-acre greenhouse is devoted to producing more than 3 million *Phytoseiulus persimilis* parasitic mites that attack spider mites each week. The farm does not use miticides and saves 5 million Euros a year on the chemicals alone (Owles J., 2011). The temperature control in the IPM greenhouse is also regulated using geothermal heat.

Independent assessors from Bristol University have calculated that the carbon footprint of each Oserian rose including air freight is one tenth that of a rose grown in Holland where the greenhouses are artificially illuminated and heated 24 hours a day by electricity and kerosene.

2.1.5 Cooling storage and processing stores

After harvesting, cut flowers are pre-cooled to 3-5°C before they are transported to the market. The pre-cooling helps preservation of the flowers so that they get to the market in the required condition. The temperature in the storage and processing rooms also need to be conditioned. This can be achieved through the use of absorption chillers.

Currently, all cold rooms at the flower farm are air conditioned using electricity. During dry seasons, electricity supply in Kenya is not reliable. The interruptions to electricity supply result in losses, reduction in the quality of stored flowers, or heavy investments in back-up power. Also, due to a high dependence on the dwindling fossil fuels for electricity generation, the cost of electricity in Kenya has increased quite significantly. The firms are therefore incurring hefty costs on pre-cooling bills.

Geothermal energy can be used as a source of heat (Figure 4) and is cheaper and more reliable for cooling storage rooms.

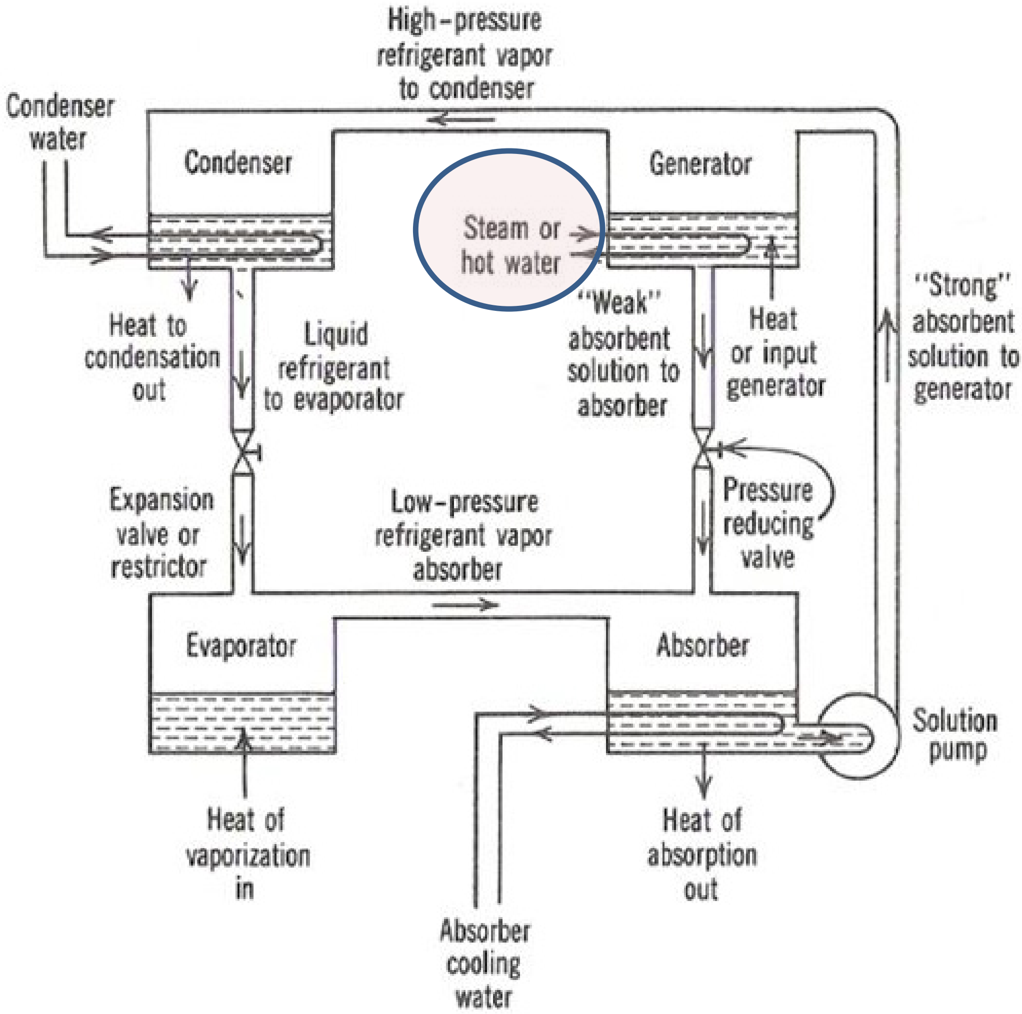

FIGURE 4: Basic absorption refrigeration cycle

3. UTILIZATION IN OTHER FARMS

Greenhouse heating of commercial greenhouses is done at New Mexico State University and at the Masson firm in the State of New Mexico. It has proved to be a viable investment both in the US and in Kenya.

There are more than 20 flower farms with a total of over 600 hectares located at a distance of less than 30 km from the Olkaria geothermal field. Some of these firms have expressed interest in the utilization of the geothermal energy for heating and cooling (Mburu, 2008). Supply of the energy to the farms is technically viable but a study on the economic viability of such a venture needs to be undertaken before implementation.

The greenhouse farms are potential customers for geothermal greenhouse heating but energy supply and brine disposal systems need to be designed and evaluated to ensure that technical, financial and environmental concerns are addressed.

With the drilling of geothermal wells in Menengai, greenhouse farmers in Nakuru also offer a market for geothermal direct use applications. Geothermal Development Company (GDC) is setting up a greenhouse demonstration centre at Nakuru, Menengai geothermal. The greenhouses will be used to showcase greenhouse heating, sterilisation and cold storage.

4. REMARKS

The Oserian Flower Farm is a clear example for utilization of geothermal energy for both electricity generation and direct uses in a small scale. The geothermal resource is enormous in Kenya at about 10,000MW with high potential sites located mainly along the Kenya Rift Valley, which runs from the North to the South of the country. This energy, if utilized for both electricity generation and direct use can go a long way to replacing the use of fossil fuels and hence address global warming and curb overreliance on the diminishing fossil fuel reserves.

Many greenhouses exist and/or have a potential to be implemented at geothermal sites. The greenhouses can utilize geothermal energy to enhance productivity and profitability. An ongoing study has identified greenhouse heating as one of the most viable direct use applications in Kenya (USAID, 2014). From this study, GDC is setting up a 0.25 hectare greenhouse to be used as a marketing tool and to demonstrate the concept.

REFERENCES

Geothermal Development Associates, 2008: Geothermal power at Oserian farms, Naivasha, Kenya. *Presented at ARGeo C2 Conference, Entebbe, Uganda*, 32 pp. Web: http://www.bgr.de/geotherm/argeoc2/docs/sessions/s8_Oserian%20powerpoint.pdf

Knight, B., Hole, H.M., and Mills, T.D., 2006: *Geothermal greenhouse heating at Oserian Farm, Lake Naivasha, Kenya*. United Nations Univesity Geothermal Trainng Programme, Orkustofnun – National Energy Authority, Iceland, 5 pp. Web: http://www.os.is/gogn/flytja/JHS-Skjol/Yearbook2006/Oserian%20Greenhouse.pdf

Mburu, M., 2008: *Feasibility study on direct utilisation of energy from geothermal brine. A case study of Olkaria geothermal power plant, Kenya*. MSc Thesis.

Murua, J., 2011: *Oserian scores a first by introducing geothermal flower farming in the country*. Nairobi Living. Website: www.nairobiliving.com

Oserian: *Factfile*. Web: http://www.oserian.com/eco-friendly-processes.pdf

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ABSTRACT

In a fish farming plant the growth rate of the fish can be increases by 50 to 100% by controlling the rearing temperature. Water quality and disease control are important in fish farming and need to be considered when using geothermal fluids directly. A total of 22 countries reported geothermal uses in aquaculture in 2010. The leading countries were China, USA, Italy, Iceland, and Israel. Tilapia, salmon and trout are the most common species. There are about 70 fish farms in Iceland of which 15-20 use geothermal water. The total production was about 7,000 tons in 2013, mainly salmon and arctic char. An important part of this sector in Iceland is the ongoing development of a fish farm that uses surplus hot water from the Reykjanes geothermal power plant to breed 2,000 tons of Senegalese sole annually.

1. INTRODUCTION

The aim of geothermal aquaculture is to heat water to the optimum temperature for aquatic species. This involves the raising of freshwater or marine organisms in a controlled environment to enhance production rates. The geothermal water is commonly used to heat water in raceways, ponds and tanks. The water temperature depends on the species involved, ranging from 13 to 30°C. By controlling the rearing temperature the growth rate of the fish can be increased by 50 to 100%, thus increasing the number of harvests per year (Figure 1). The heating requirement for a typical outdoor pond in a temperature climate zone can be about 2.5 MJ/hr/m^2 and a 2.0 ha facility might require an installed capacity of 14 MWt. With a load factor of 0.60 the annual heating requirement would be 260 TJ/yr. Water quality and disease control are important in fish farming and need to be considered when using geothermal fluids directly in the ponds (Lund, 2011).

According to data presented at the World Geothermal Congress in Bali 2010 (WGC2010) the total geothermal energy used in aquaculture worldwide increased slightly in the five year period 2005-2010. However, the numbers presented in Bali were lower than previous estimates from 2000 and 2005. In the period 2005-2010 the installed capacity increased by 6% to 653 MWt and the annual energy use increased by 5% to 11,521 TJ. A total of 22 countries reported geothermal uses in aquaculture. The leading countries were China, USA, Italy, Iceland, and Israel. Tilapia, salmon and trout are the most common species, but tropical fish, lobsters, shrimp, and prawns, as well as alligators are also being farmed. Based on data from the USA it has been estimated that the energy demand when using geothermal water in uncovered ponds is 0.242 TJ/year/ton of fish (bass and tilapia). Thus, using the reported energy use of 11,521 TJ/year in 2010 it can be estimated that the total annual production in that year was 47,600 tons. A few parameters describing the worldwide development in geothermal uses in the fish farming sector in the period 1995-2010 are presented in Table 1 (Lund et al., 2010).

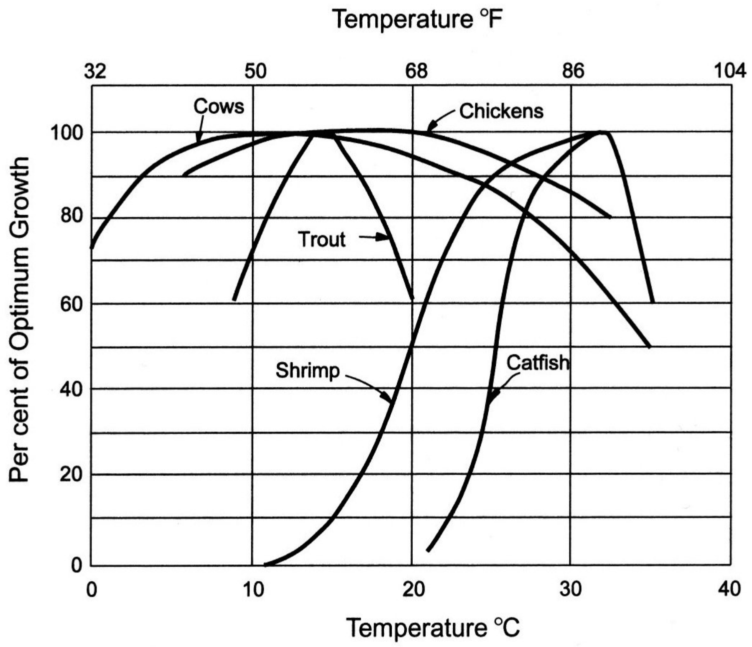


FIGURE 1: Optimum growing temperature for selected animal and aquatic species (Dickson and Fanelli, 2005)

TABLE 1: Geothermal uses in the fish farming sector worldwide (data from Lund et al., 2010)

	1995	**2000**	**2005**	**2010**
Installed capacity (MWt)	1,097	605	616	653
Energy utilization (TJ/year)	13,493	11,733	10,976	11,521
Capacity factor	0.39	0.61	0.57	0.56

2. FISH FARMING IN ICELAND

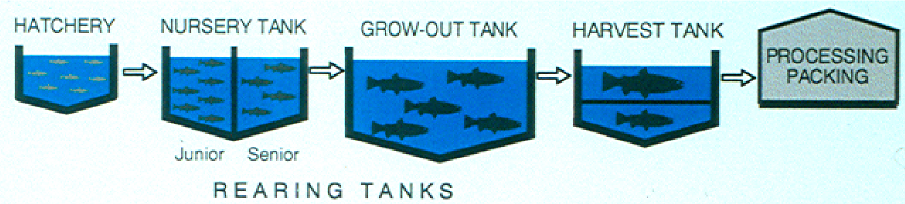
Fish farming has been a slowly growing sector in Iceland for a number of years. After a rapid growth from 2002 the total production reached about 10,000 tons in 2006, mainly salmon. The dominating species are now salmon and arctic char followed by trout. There are about 70 fish farms in Iceland and the total production was about 7,000 tons in 2013. Of these fish farms between 15 and 20 utilize geothermal water. Initially, Iceland's fish farming was mainly in shore-based plants. Geothermal water, commonly 20-50°C, is used to heat fresh water in heat exchangers, typically from 5 to 12°C for juvenile production. The beginning of the 21st century saw growing interest in developing sea cage farming of salmon in the sheltered fjords on Iceland's east coast. Two large farms were established and remained in operation for a few years, but today only two small cage farms are in operation. The main use of geothermal energy in the fish farming sector in Iceland is for juvenile's production (char and salmon). In land-based char production geothermal energy is also used for post-smolt rearing. Geothermal utilization in the fish farming sector is expected to increase in the coming years (Ragnarsson, 2010).

A fish farming plant owned by the company Stolt Sea Farm started breeding warm-water Senegalese sole at Reykjanes peninsula, Iceland, in 2013. It is the first stage of a large indoor land-based plant that is planned. The 22,500 m^2 plant is located close to a 100 MWe geothermal power plant owned by the energy company HS Orka Ltd. The power plant uses a large amount of sea water for cooling and after the cooling process a part of the water, which is then at a temperature of 35°C, flows by gravity to the fish farming plant. There it is mixed with sea water that is pumped from wells and used in the farming at about 21°C, which is the optimum temperature for the fish. The water temperature can be kept constant throughout the year without any influences from the environment. Currently, there are about 1.2 million juveniles in the plant and that number is increasing. They are grown to about 400 g before the Senegalese sole is slaughtered and transported fresh to markets in Europe. The production capacity of the first stage is 500 tons per year, but the planned production after reaching the final stage is 2,000 tons per year. The current number of 14 employees is expected to increase to 60-70 in the final stage.

3. SAMHERJI'S FISH FARMING PLANTS

Samherji is one of the largest fishery and seafood companies in Iceland. Their activity within aquaculture is comprised of most aspects of fish farming, i.e. hatching, juvenile production, the on-growing of marketable fish, harvesting, packaging and marketing of the products. The fish farming operations are situated in several places in Iceland. It is all land-based but not shore-based as is most common in salmon farming. Samherji is among the largest land-based fish farms producing salmon in the world. This has been made possible by using geothermal water (Samherji, 2014).

Íslandslax is the name of Samherji's fish farming plant located at Núpar in South Iceland. There they have juvenile farming and hatchery facilities specially designed to hatch and grow salmon and arctic char from the roe stage until they reach approximately 70-100 g. All the salmon and char roes used in Samherji's farming are hatched at this plant. The farm is situated in a geothermal area with excellent access to high quality water and very stable water temperature. The total fish farming area is about 2,000 m^2 and the total volume about 1,500 m^3. The total consumption of fresh water at 5.5°C is 240 l/s where about one third is pumped from wells and one third flows by gravity to the plant. The consumption of geothermal water is 7-10 l/s of 90°C hot water coming from two wells. A part of the geothermal water is mixed with cold water and used directly in the farming, while another part is used to heat up fresh water in heat exchangers. In spite of the relatively low concentration of oxygen in the geothermal water the experience has shown that it can be mixed with fresh water and thus heat exchangers are not always needed (Haraldsson and Ketilsson, 2010). The water temperature in the juvenile farming is in the range of 6 to 16°C (Figure 2). The growth rate depends strongly on the water temperature and thus the production can be regulated by the temperature. About 300,000 juveniles produced annually at Íslandslax are transported by special trucks to Samherji's on-growing farm called Silfurstjarnan. Then they weigh about 70 g. (Smáradóttir, H., pers. comm., 2014).



ARCTIC CHARR					1 - 2 kg
Temperature °C	6	12	10	9.5	
Salinity ‰	0	0	10	10	
Year	0.4	1.2	1	0.02	

SALMON					2 - 4 kg
Temperature °C	8	10	10	9.5	
Salinity ‰	0	10	10	10	
Year	0.5	1	1	0.02	

FIGURE 2: Breeding of salmon (Georgsson, 2013)

Silfurstjarnan in Öxarfjördur, North Iceland, is an on-growing farm where the bulk of the production is salmon. The farm is ideally situated in an area very rich in geothermal water, close to the sea. This location was chosen after large geothermal exploration efforts in late 1980s to find good sites for fish farming in Iceland with good accessibility to lots of cold and warm water, and also seawater where possible. At the north-eastern border of the Öxarfjördur delta the Silfurstjarnan fish farm was established after exploration had revealed favourable conditions with both fresh water and brackish warm water available in large quantities at very shallow levels and seawater close by at the coast. Many wells on site at Silfurstjarnan and the access to seawater make it possible to use different water temperatures and salinities in different tanks at the same time (Samherji, 2014). They utilize several geothermal wells with different water temperature and salinity. The water from the different wells is mixed to get the appropriate temperature at the given conditions, but the rearing water temperature is about 9-11°C. The total production is about 1,000 tons per year of salmon and about 100 tons per year of arctic char (Figures 3 and 4). The current market price for Silfurstjarnan salmon (in USA) is now at about 6 USD (4.5 USD from factory) compared to general market price of about 4 USD (Georgsson, 2013). Silfurstjarnan operates a harvesting plant on site where all the production is processed and packed (Smáradóttir, H., pers. comm., 2014).

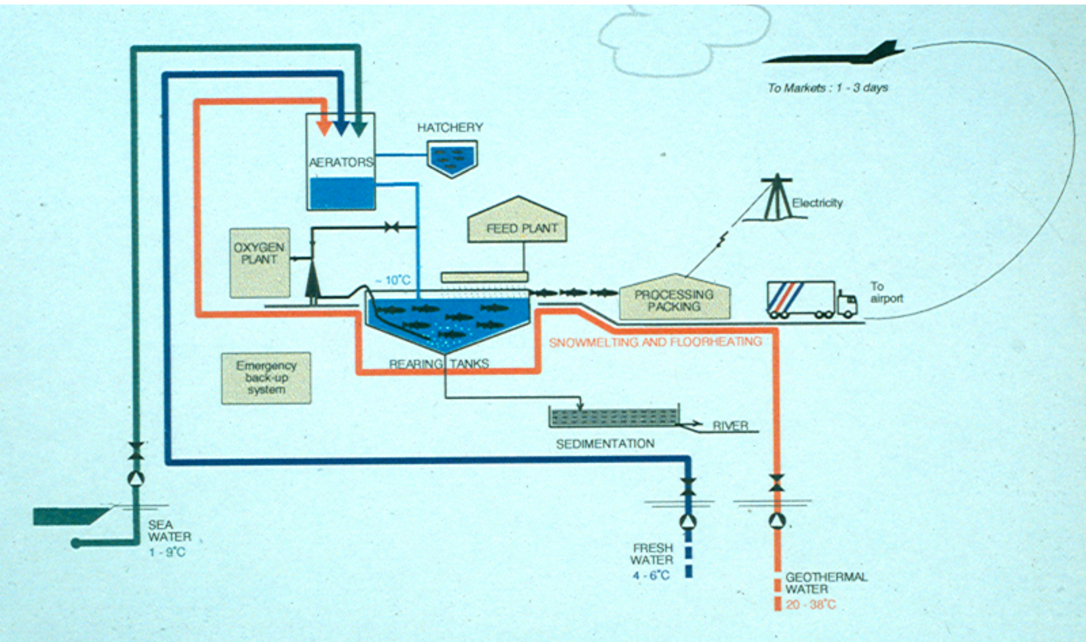


FIGURE 3: Schematic diagram of the main processes at the Silfurstjarnan fish farm, Öxarfjördur, North Iceland (Georgsson, 2013)

FIGURE 4: Silfurstjarnan fish farm, Öxarfjördur, North Iceland (Georgsson, 2013)

REFERENCES

Dickson, M. H., and Fanelli, M. (editors), 2005: *Geothermal energy. Utilization and technology*. Earthscan, 205 p.

Georgsson, S.L., 2013: Geothermal activity, exploration and fish farming in the Öxarfjördur area, NE-Iceland. United Nations University Geothermal Training Programme, Reykjavik, Iceland, lecture notes, 50 pp.

Haraldsson, I.G., and Ketilsson, J., 2010: *Jarðhitanotkun til raforkuvinnslu og beinna nota til ársins 2009 (Geothermal utilization for electricity generation and direct application to 2009)*. Orkustofnun, report OS-2010/02 (in Icelandic), 62 pp.

Lund, J. W., 2011: Development of direct-use projects. *Proceedings of the Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States*, 8 pp.

Lund, J.W., Freeston, D.H., and Boyd, T.L., 2010: Direct utilization of geothermal energy 2010 worldwide review. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 23 pp.

Ragnarsson, Á., 2010: Geothermal development in Iceland 2005-2009. *Proceedings World Geothermal Congress 2010, Bali, Indonesia,* 12 pp.

Samherji, 2014: *Fish farming*. Website: http://www.samherji.is/en

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INDUSTRIAL APPLICATIONS OF GEOTHERMAL RESOURCES

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ABSTRACT

Industrial applications are considered to constitute a huge potential for direct geothermal uses as they often require a source of heat in a range similar to the low to medium temperature geothermal fields. This paper proposes an overview of industrial applications that may resort to geothermal resources instead of other sources. It, however, has to be borne in mind that, due to the nature of the geothermal resources, the industrial application may require a minimum of engineering to avoid potential operational troubleshooting. The paper provides insight on projects in this field.

1. INTRODUCTION

Industrial applications of low and medium geothermal resources encompass a broad scope of uses and there is a huge potential of activities whose energy needs could be matched with medium to low temperature geothermal resources.

For instance, about 25% of US energy use occurs at temperatures < 120°C and most of it comes from burning natural gas and oil (Tester et al., 2013). A large part of this energy is used for industrial applications and such uses should not be neglected when scoping potential exploitation activities for a geothermal field.

2. INDUSTRIAL APPLICATIONS

Industrial applications encompass a rather wide range of industrial activities requiring fluid at low to medium temperature, for instance:

- Process heating;
- Industrial space air conditioning;
- Food processing;
- Food drying;
- Fish drying;
- Pulp and paper processing;
- Washing and dyeing of textiles;
- Leather and fur treatment;
- Fuel production and oil enhancing;

- Chemical production;
- Mineral production: sulphur, gases, salts or other precious metals;
- …and many more.

Typical applications and their temperature range are presented in Figure 1.

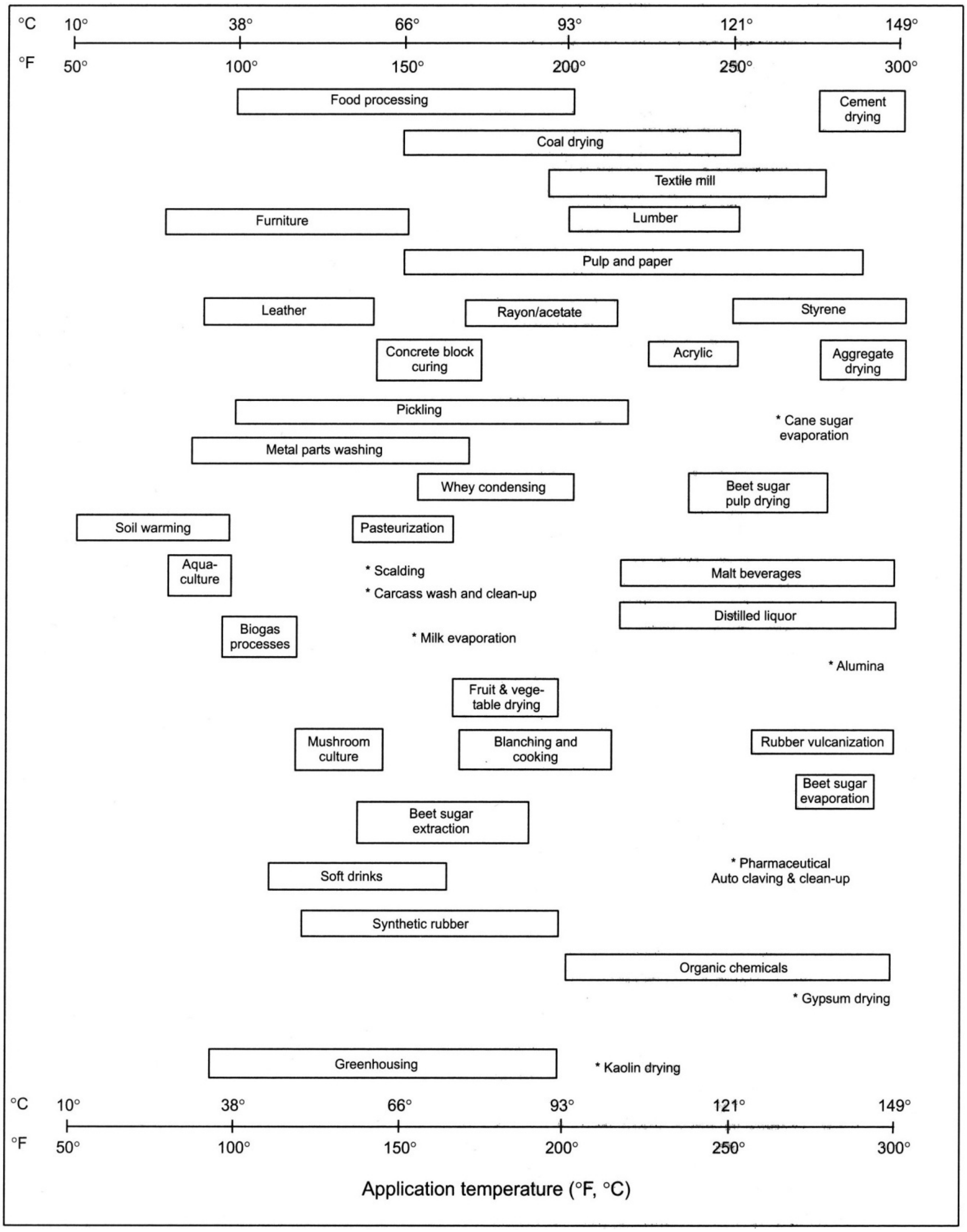

FIGURE 1: Temperature range for some industrial processes and agricultural applications

Conventional industrial processes that utilize fossil fuelled heat can in many cases be transferred to geothermal heat with a minor adaptation, in a technically efficient and economically feasible way.

Typical processes involved in industrial uses of geothermal resources are (Líndal, 1992):

- Drying: Drying can be realised by using air preheated by the geothermal fluid via a heat exchanger or by direct contact. Such a process is commonly used for drying crops or fish.
- Evaporation: The evaporation process is used to concentrate solutions. It is used for instance to obtain salt. The process is also used for water desalination or in any process requiring the vaporization of a solute.
- Distillation: Distillation is the process of separating mixtures based on differences in volatility of components in a boiling liquid mixture. Distillation is a commonly known process in the liquor and hydrocarbon industry.
- Refrigeration: Adsorption heat pumps, using a lithium bromide solution, are well known equipment suitable for realisation of industrial cooling or freezing with geothermal heat.
- Process heating: The process heating can be achieved by pre-heating water in a boiler or with direct heating.
- Industrial space air conditioning might be part of the industrial process in a specific plant where given temperatures are required for the process.
- Other processes such as: extraction, washing and dying, baking, etc.

The use of geothermal resources in industrial applications might, however, not go without challenges due to the peculiar characteristics of geothermal resources that may be richer in minerals than cold groundwater. The equipment selection might be affected by components such as: silica, oxygen, chlorides, calcium, magnesium, hydrogen sulphide and the pH of the fluid. Deposition is not expected to be a major problem in low-temperature utilization compared to high-temperature utilization (calcite, sulphides, silica). For these reasons, industrial projects using geothermal resources will not be able to fully duplicate an already existing solution. The process concept always has to be adapted and engineered to some extent to fit to the specific geothermal resource characteristics.

Depending on the geothermal field characteristics and the industrial application, the benefits of using such a source of energy may be higher than the adaptations that are required to utilize the resource.

3. SHOWCASES

3.1 Nordursalt – a means to process salt

The salt factory Nordursalt (Figure 2) was built in 2012 to 2013 and was officially inaugurated on 17 September, 2013.

The factory uses 36 l/s of 70°C hot waste water from a seaweed factory nearby, which was until then discarded. This water, together with 115°C water from a geothermal well that is useful for regulating the heat, is used to boil the sea into brine and dry down in a salt brine.

FIGURE 2: Salt produced at Nordursalt (Nordursalt, 2014)

A boiling tank and condenser are used to boil the sea and let the water evaporate at 50°C, at sub atmospheric pressure. Pressure is maintained by the injection of cold sea water into the steam in the separator standing by the plant. The salt originates from the sea. The sea is boiled in the boiling tank with titanium tubes where the hot heating water flows. Low pressure superheated sea water is placed in contact with the titanium tube, not directly with the geothermal fluid.

Hot water from the boiling tank is used for drying the salt brine and flakes. Brine is dried in salt pans and the salt is finally dried in the dry chamber, from which the salt passes into the packing containers. The energy that drives the processing plant is thus obtained almost entirely from waste water that was unused until the salt factory was taken into operation, and 115°C geothermal water. Electricity is only used to power pumps, the air blower in ventilation spaces, wrapping and for general use. No pollution is emitted from the factory. The use of the waste water is on the contrary seen as positive as the temperature of the waste water from the seaweed factory decreases considerably from what it was previously.

Figure 3 shows a simplified process concept of the pilot salt factory.

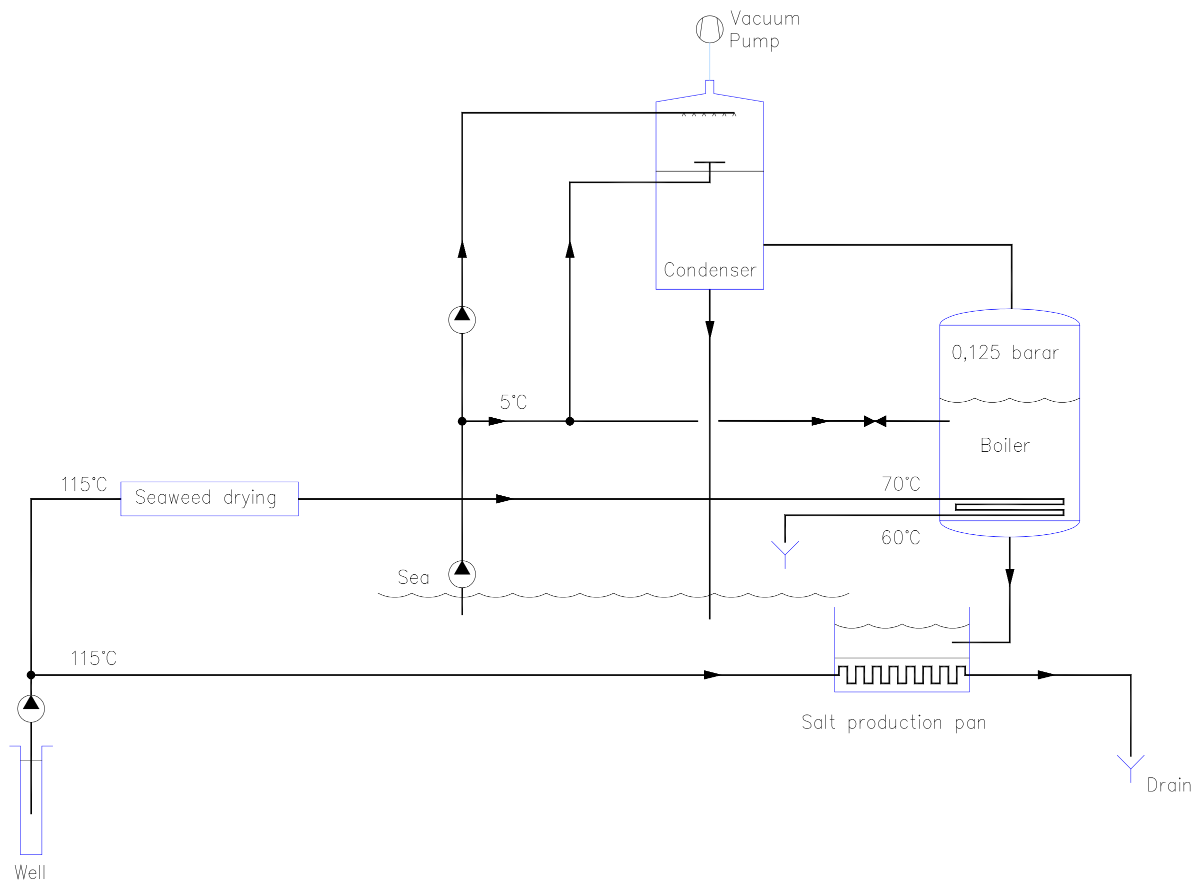

FIGURE 3: Simplified process concept – Pilot salt factory

3.2 Geothermal laundry in Hveragerdi – cleaning and drying

The retirement home Ás in Hveragerdi, Iceland, was founded in 1952 and currently has about 150 residents. In addition, the laundry also provides services to a local health clinic. The laundry, see Figure 4, uses geothermal steam for washing and drying purposes. The energy cost of this "geothermal" laundry is only a fraction of what it would cost to use electricity.

The geothermal laundry was installed in 2006-2007. It uses 150°C geothermal steam from a borehole located nearby. The geothermal steam is directly used to heat up the laundry dryers. Rather important savings in the use of electricity result from the use of the geothermal steam, easily available in the neighbourhood.

FIGURE 4: Laundry dryer

Part of the geothermal steam goes through a heat exchanger used to heat cold water up to 90°C for use in the washing machines. Return water from the dryers, the heat exchanger and from the washing machines is then directed to a cooling tank before it is released back to nature. When at maximum load, the laundry requires about 0.2-0.3 kg/s of geothermal steam. This use of steam for heating enables the laundry to save the electricity normally required for heating and drying.

In addition to using geothermal steam, the laundry also only uses environmentally friendly detergents in the laundry, thus minimising the effects on the environment.

Technical information:

- Geothermal two phase flow from the borehole:
    - 150°C;
    - 0.2-0.3 kg/s at peak load.
- Utilization:
    - Washing machines;
    - Dryers.

Figure 5 presents a simplified process concept for the laundry.

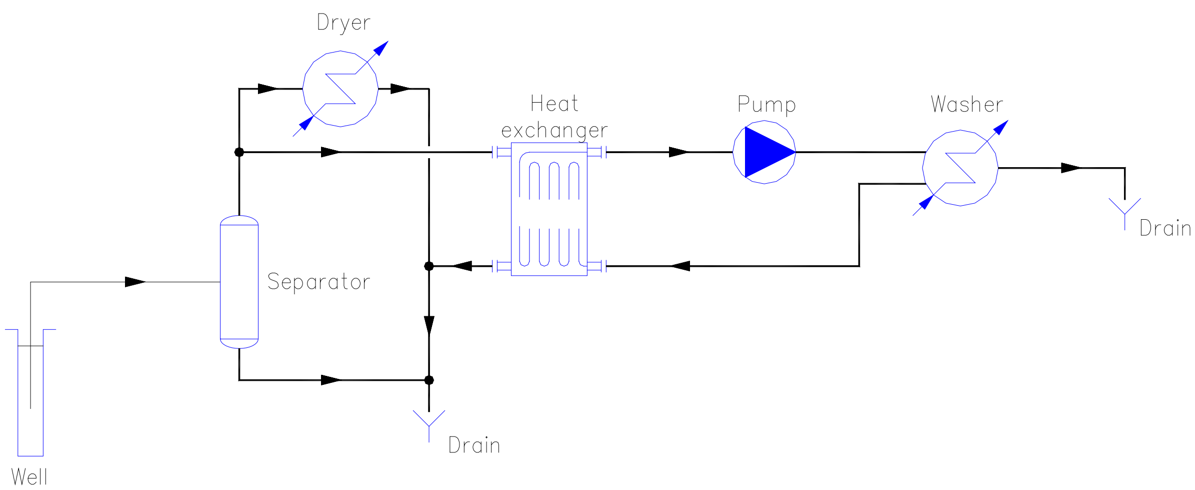

FIGURE 5: Simplified process concept–Laundry in Hveragerdi, Iceland

4. Fish drying in Reykjanes

One of the most successful uses of geothermal resources in an industrial application in Iceland is the fish (head) drying in Reykjanes. The process is rather simple, utilizing high pressure geothermal steam to heat up a closed low temperature (80°C/40°C) water cycle driving the fish drying heater. A low temperature geothermal resources could easily be utilized instead of the steam.

The drying process is done in 2 stages. The first stage is done in a rack cabinet of the conveyor belt drying. The air temperature should be about 18-25°C, relative humidity 20-50% and air velocity 3 m/s.

The duration is about 24–40 h and after that process the water content has gone from 82% down to 55% (Figures 6-8).

The second stage is done with 22-26°C air in a drying container, located on top of an air tunnel. The relative humidity 20-50% and the air velocity 0.5–1 m/s through the drying container. The duration is some 72 h. The water content after drying is lower than 15%.

The total drying time of fish products is in the range of 100–140 h depending on their size and initial water content.

100 kg of fish (heads), with 82% water ends as 21.2 kg of dried fish (heads).

FIGURE 6: Fish products in batch dryer in Reykjanes

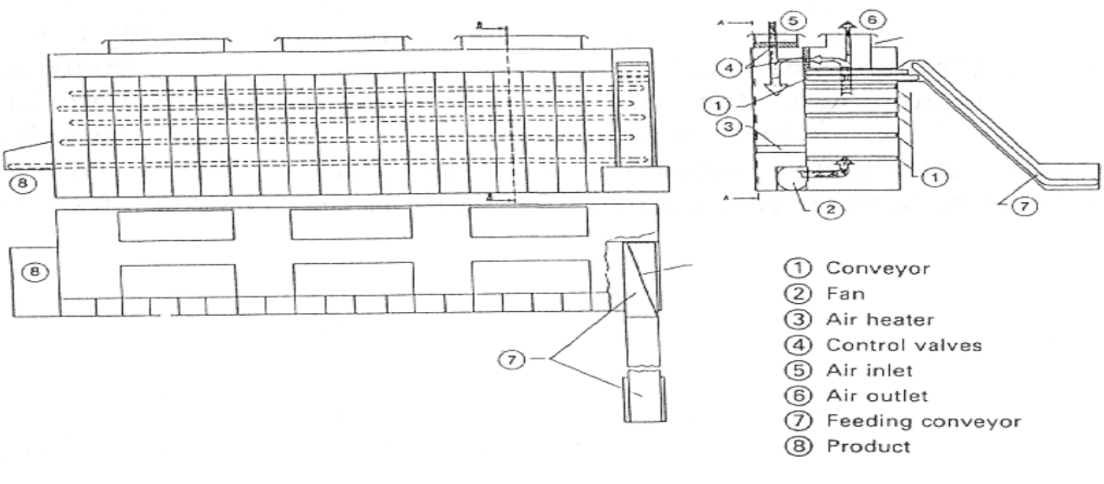

FIGURE 7: Continuous conveyor drying for primary drying

Energy consumption for fish drying is based on the latent heat vaporization for water which is 2,450 kJ/kg, but the design of drying cabinets are normally based on 3,500–5,000 kJ/kg due to heat loss and various other issues.

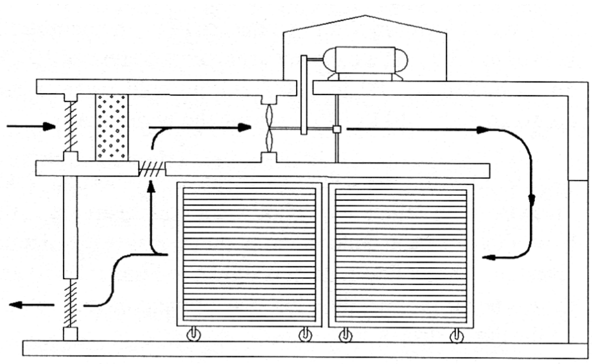

FIGURE 8: Batch dryer for fish drying

5. CONCLUSION

The typical processes involved in industrial uses of geothermal resources require in most cases the use of conventional industrial solutions with minor adaptation taking into account the characteristics of the geothermal fluid and how it may be handled.

Geothermal resources may therefore be directly used for industrial applications in a technically efficient and economically feasible way. Considering the huge potential for industrial applications requiring heat below 120°C, industrial application should systematically be taken into account when scoping potential exploitation activities for a given geothermal field.

The potential value of geothermal resources for direct industrial use is still underestimated. The authors of the paper are convinced that it could be utilised in more situations, should the project developers be more aware of the potential applications and should the industry be less afraid of making the adjustment necessary to be able to use geothermal resources.

REFERENCS

Arason, S., 2003: The drying of fish and utilization of geothermal energy; the Icelandic experience. *Presented at "International Geothermal Conference", Reykjavík, Iceland*, 11 pp. Web: http://jardhitafelag.is/media/PDF/S08Paper076.pdf

Líndal, 1992: Review of industrial applications of geothermal energy and future considerations. *Geothermics, 21-5/6*, 591-604.

Nordursalt, 2014: *The salt*. Website: http://www.nordursalt.com/

Tester, J., 2013: *The potential role of geothermal energy as a major supplier of primary energy in the U.S.* Iceland Geothermal Conference, lecture notes, 61 pp.

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DISTRICT HEAT DISTRIBUTION NETWORKS

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ABSTRACT

This paper treats the mathematics for calculating flow, pressure and temperature in a heat distribution network, when the network has loops. A looped network cannot be calculated directly, and the flow and temperature solution has to be obtained by iteration of the non-linear system equations. Network theory is used to reduce the number of equations which are iterated. The thermal solution of the network is then found without requiring iteration.

An example is given of an analysis of the Balcova district heating network in Turkey.

1. MICROSCOPIC MODELS

The goal is to calculate temperature, heat flow, pressure and water flow for the distribution network. A district heating model has to be able to:

- Calculate water flow in all system elements; and
- Calculate head at all nodes.

Where

- Some elements have known flow; and
- Some nodes have known head.

The unknowns are:

- The element flow; and
- The head at the nodes.

The constraints are:

- Kirchhoff's current law;
- Kirchhoff's voltage law; and
- Elements (branch) relations.

1.1 Kirchhoff's current law

The sum of the mass flows at any node equals 0 at any time. This results in one equation for each node:

$$\sum_{j=1}^{n_n} a_{ij}\ m_j = 0 \tag{1}$$

1.2 Kirchhoff's voltage law

The sum of all voltage (potential) differences along any closed path (loop) in the network is zero. This results in one equation for each loop:

$$\sum_{j=1}^{n_n} b_{ij}\ h_j = 0 \tag{2}$$

1.3 Elements relations

The element relations add one equation for each element, relating flow and head loss:

$$h_j = f\left(m_j\right) \tag{3}$$

This is the so-called resistance formulation, where $f(m_j)$ is a non-linear head loss function. This equation can be inverted in order to give the conductivity formulation:

$$m_j = g(h_j) \tag{4}$$

1.4 Direct mass flow solution

A solution of these two sets of equations will give the flow in all elements. The head change and subsequentially the nodal head can be found from the element relations. The resistance formulation is used here.

$$\sum_{j=1}^{n_n} a_{ij}\ m_j = 0 \tag{5}$$

$$\sum_{j=1}^{n_n} b_{ij}\ f(m_j) = 0 \tag{6}$$

1.5 Direct head loss solution

A solution of these two sets of equations will give the head loss in all elements. The flow and subsequentially the nodal head can be found from the element relations. The conductivity formulation is used here.

$$\sum_{j=1}^{n_n} a_{ij} h^{-1}\left(h_j\right) = 0 \tag{7}$$

$$\sum_{j=1}^{n_l} b_{ij} h_j = 0 \tag{8}$$

1.6 Previous methods

Three linearization and solution methods have been traditionally applied. These are the Hardy – Cross method, the Newton – Raphson gradient iteration and the Wood and Charles linearization (Figure 1).

The Hardy-Cross method is an error correction method. An initial guess value is set for all elements. The head losses are calculated and added along the loops in the system (which is to sum to zero according to Kirchhoff's voltage law), and the error is calculated. Then a flow change in all the loop elements, necessary to make the error zero is found, and a new set of element flows is defined. This is done for all the loops, and repeated until the error vanishes. This method is stable, but requires high number of iterations.

The Newton-Raphson method is a linearization method, the non-linear equations are linearized by the gradient corresponding to the guess value, and a new value calculated according to the solution of the linearized equation system. This method does converge in a few iterations, if it converges at all. A good set of guess values is needed for the method to work. Many commercial programs use Hardy-Cross to obtain a good set of guess values for the Newton-Raphson method.

The Wood and Charles method is as well a linearization method, but the linearization is made by a chord going through origo instead of a tangent as in the Newton-Raphson method. This method converges almost as quickly as Newton-Raphson, but is stable, and can be formulated so, that a set of good initial guess values is generated automatically. The head difference in the pipe branches is usually a quadratic function of the flow. The Newton-Raphson (classical) linearization can give results that cause problems in the iteration, particularly if the flow becomes less than one half of the flow value on which the linearization is based. In that case the head difference will become negative. For the quadratic flow resistance, the slope of the Wood and Charles linearization will be one half of that resulting from the classical linearization. This is indeed a crude approximation, but will result in a robust iteration and have acceptable convergence by averaging two successive iterations.

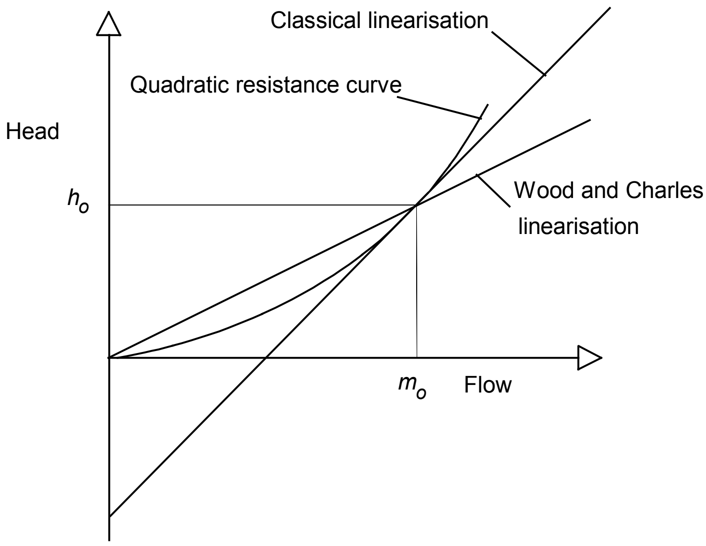


FIGURE 1: Comparison of linearization methods

2. GRAPH THEORY FOR DISTRICT HEATING NETWORK MODELING

In the modelling of district heating network these basic laws have to be fulfilled:

- Conservation of mass;
- Conservation of momentum; and
- Conservation of energy.

The graph theory considers a network to be a composite concept of:

- A set of nodes (x, y, z);
- A set of branches; and
- A connectivity relation (ni, nj).

2.1 Definitions

The general network analysis presented here follows the terminology commonly used in network theory.

Path: A set of branches b_1 ... b_n in the graph G_n is a path between nodes V_j and V_k if consecutive branches b_i and b_i+1 have a common endpoint, no node of G_n is an endpoint of more than two of the branches in the set, and V_i as well as V_j are endpoints of exactly one branch of in the set.
Connected graph: A graph G_n is connected if there is a path between any two nodes of the graph.

Loop: A subgraph G_s is a loop if G_s is connected and every branch of G_s has exactly two nodes of G_s incident at it. Associated with the loop is a direction specified by the direction of a given datum branch in the loop.

Tree: A subgraph G_s of the connected graph G_n is a tree if it is connected and G_s has no loops.

Spanning tree: A subgraph G_s of the connected graph G_n is a spanning tree if it is connected, G_s contains all nodes of G_n and G_s has no loops.

Cutset: A set of branches of a connected graph G_n (not their endpoints) is a cutset if the removal of these branches results in a graph that is not connected, and the restoration of any one of these branches results in the graph being connected again. The cutset can be seen as a border going through the graph. Associated with the cutset is a direction specified by the direction of a given datum branch in the cutset. The separate graphs obtained by removing the branches of the cutset are called components of the graph with respect to the cutset. The net flow over the cutset must be zero in order to conserve the mass in each of the components.

Link: The branches not belonging to a tree T are called links.

Cotree: The set of links in a network with a tree T is named cotree with respect to the tree T.

2.2 Element types

The flow solution of a network has three element types:

p: pipes;
m: flow elements; and
h: head elements.

2.2.1 Pipes

Here the word "pipe" is used in a general sense that is a conduit carrying a fluid from one point in space to another, and can have many elements, pumps, valves, etc. A pipe element is simply a set of serially connected physical element in the network having some relation between flow and head change.

2.2.2 Flow elements

Flow elements have a constant, known flow. They are usually used to define consumption point in the network, and have than one end connected to a datum or zero point.

2.2.3 Head elements

Head elements have a constant, known head difference between the element connection points. They are often used to define a supply point, and have than one end connected to a datum or zero point.

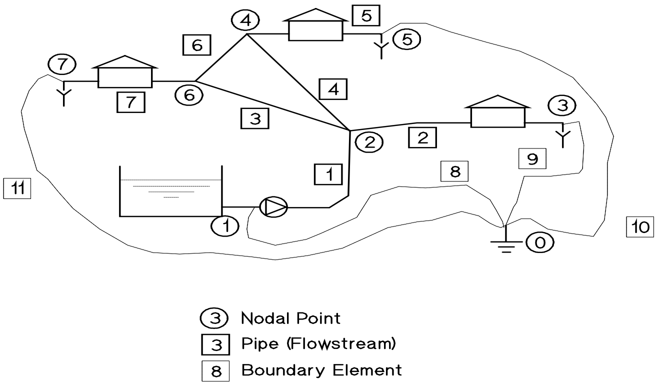
2.3 The connectivity relation

The incidence or connectivity relation relates each branch to a pair of nodes, the node where the branch originates and the node where it ends. A distribution system can be treated as a connected graph, where the pipes correspond to branches and the nodes to points where the pipes divide or are united, or convey the flow to the consumer. In network theory an incidence (or connectivity) matrix must be defined in order to describe the above mentioned connectivity relation for a network with n_n nodes and n_f branches:

Matrix **A** is an $n_n \cdot n_f$ matrix, with entries a_{ij} where:

a_{ij} = 1 if pipe j starts at node i;
a_{ij} = -1 if pipe j ends at node j; and
a_{ij} = 0 otherwise.

The connectivity matrix as defined above has one column for each flow stream in the system, and one row for each node. Each column can only have two non-zero entries, -1 and 1, as the flow stream has to originate somewhere and end at some other location. A simple district heating system, containing typical elements of such a system is shown in Figure 2 along with the associated connectivity matrix.



Boundary Elements

$$\underline{\underline{A}} = \left[\begin{array}{ccccccc|cccc} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 \end{array}\right]$$

FIGURE 2: The connectivity matrix for a simple district heating system

2.4 Continuity equation (Kirchhoff's current law)

Continuity for the mass in a pipe network can be defined by reference to the current law of Kirchhoff: *The sum of the mass flows at any node equals 0 at any time.*

The connectivity matrix has a row for every node in the system. In each row all entries of 1 represent an outgoing flow stream from that node, and entries of -1 an incoming flow stream. The system flow can conveniently be stated by means of a column vector with n_j entries, each stating the flow in the corresponding flow stream. A positive flow indicates flow in the same direction as defined in the connectivity matrix, a minus signs an opposite flow direction. By using the connectivity matrix this becomes:

$$\mathbf{A}\,\mathbf{m} = \mathbf{0} \tag{9}$$

2.5 Momentum equation (Kirchhoff's voltage law)

The node piezometric head is conveniently stated in the column vector $\mathbf{h}_n$ with n_n entries, each stating the head at the corresponding node. As the connectivity matrix contains information on which flow streams connect to each node in the corresponding row, it is possible to calculate the head difference between the ends of all pipes in a vector form:

$$\mathbf{A}^T \mathbf{h}_n = \mathbf{h} \tag{10}$$

2.6 Definition of spanning tree

The choice of a spanning tree is usually based on a certain order of preference in electrical circuit analysis. The following normal tree algorithm can be used to define the spanning tree used for the network calculations:

1. Sort the network branches in the following order:

   h: Head sources;
   p: Pipes; and
   m: Flow sources.

2. Consider the next branch in the sorted list.

3. Check if the new branch will form a loop in the network. (If one and only one node of the new branch nodes is incident at a tree branch, the new branch will not form a loop). If yes, then do not add it to the tree *T*, but to the cotree L. If no, add it to the tree *T*.

Go back to step 2.

Repeat this until all nodes in the network are covered by tree branches.

Note that the check on whether a new branch will <u>not</u> form a loop is specified. This is because that it is not easy to check whether the new branch forms a loop, as specified in the references mentioned. One might expect that if both nodes of a new branch are already incident at tree branches, then the new branch will form a loop. However, this will only be the case when the tree is a connected graph. There is no guarantee that this will be true. It is obvious that if the new branch is not at all connected to the tree, it will be added to it, as it will not form a loop. Then the tree is not a connected graph anymore. The branch that finally connects the components of the tree will have both nodes incident at tree branches, and will therefore be wrongly assumed to form a loop.

The check on the new branches used in the algorithms above assures that the tree will be correctly formed, but assures at the same time that it will be a connected graph at any stage during the selection of the spanning tree.

The tree algorithm assumes that the number of resistors is low compared to the number of pipes, and that no loop will be formed only by resistors, storage tanks and head sources. It is possible to reduce this condition to that of prohibiting only loops composed of head sources, by treating the resistors and the storage tanks in a manner similar to that for the pipes. This will complicate the analysis, and is not relevant to a district heating system, where the majority of elements are pipes. A loop made only of head sources is in violation of the voltage law of Kirchhoff, as the heads around the loop do not necessarily sum up to zero. At least one element in the loop must be such that the head difference is not prescribed in order to fulfill this law.

Cutsets of flow sources are also prohibited. A cutset made up only of flow sources is in violation of the current law of Kirchhoff, as the flow in the cutset branches does not necessarily sum up to zero. Therefore at least one branch in the cutset must be such that the flow is not prescribed in order to fulfill this law.

The graph for the piping system is closed as all boundary points of the physical system are connected with the datum point by some combination of sources and resistors. Therefore, this condition corresponds to requiring that at least one boundary node of the physical system be attached to a head source. That is quite reasonable, because otherwise the pressure level of the network cannot be determined.

The connectivity matrix **A** can be rearranged with respect to a spanning tree T containing n_T branches by splitting it into two sub-matrices $\mathbf{A}_T$ and $\mathbf{A}_L$ in the following manner:

$$\mathbf{A} = \left[\mathbf{A}_T \mid \mathbf{A}_L\right] \tag{11}$$

The sub-matrix $\mathbf{A}_T$ is the $n_n \cdot n_T$ connectivity matrix for the branches of the spanning tree, and the matrix $\mathbf{A}_L$ is the $n_n \cdot n_L$ connectivity matrix for the links, where n_L denotes the number of links. The sum of n_T and n_L is n_f, the total number of branches in the network. As the datum point is not included in the connectivity matrix, and the sub-matrix $\mathbf{A}^T$ is based on a spanning tree, $n_n = n_T$. Therefore $\mathbf{A}^T$ is a square invertible matrix.

2.7 The cutset matrix

A cutset matrix is a matrix with one row for a cutset in the network, and one column for every branch. The entries of the cutset matrix are as follows:

- d_{ij} = 1 denotes that branch j is a member of the cutset i with same direction;
- d_{ij} = -1 that branch j is a member with opposite direction; and
- d_{ij} = 0 that branch j is not member of cutset i.

It follows from the definition of a spanning tree, that every tree branch is member of one and only one cutset, together with some (or no) links, but no other tree branches. Such cutsets are called fundamental cutsets with respect to the spanning tree T. The fundamental cutset matrix **D** is an $n_T \cdot n_f$ matrix, partitioned as follows:

$$\mathbf{D} = \mathbf{A}_T^{-1}\mathbf{A} = \mathbf{A}_T^{-1}\left[\mathbf{A}_T \mid \mathbf{A}_L\right] = \left[\mathbf{I} \mid \mathbf{A}_T^{-1}\mathbf{A}_L\right] \tag{12}$$

As the tree branches are members of and only one fundamental cutset, the tree part of the matrix is the identity matrix. The submatrix $\mathbf{D}_L$ reflects the membership of the links in every fundamental cutset.

2.8 The loop matrix

A loop matrix is a matrix with one row for each loop in the network, and one column for each branch. The entries of the loop matrix are as follows:

b_{ij} = 1 denotes that branch *j* is a member of the loop *i* with same direction;
b_{ij} = -1 that branch *j* is a member with opposite direction; and
b_{ij} = 0 that branch *j* is not a member of loop *i*.

It follows from the definition of a spanning tree, that every link is a member of one and only one loop together with some tree branches, but no other links. Such loops are called fundamental loops with respect to the cotree *L*.

The fundamental loop matrix **B** is an $n_L \cdot n_f$ matrix, partitioned as follows:

$$\mathbf{B} = \left[\mathbf{B}_T \middle| \mathbf{I}\right] \tag{13}$$

As the links are members of one and only one fundamental loop, the link part of the matrix is the identity matrix. The sub-matrix $\mathbf{B}_T$ reflects the membership of the tree branches in every fundamental loop.

2.9 Loop and cutset relations

If the cutset gets into a loop, it has to go out of the loop again. The number of elements common both to the loop and the cutset will thus always have an even number. At one intersection of loop and cutset, the directions will coincide, but be opposite at the other (Figure 3).

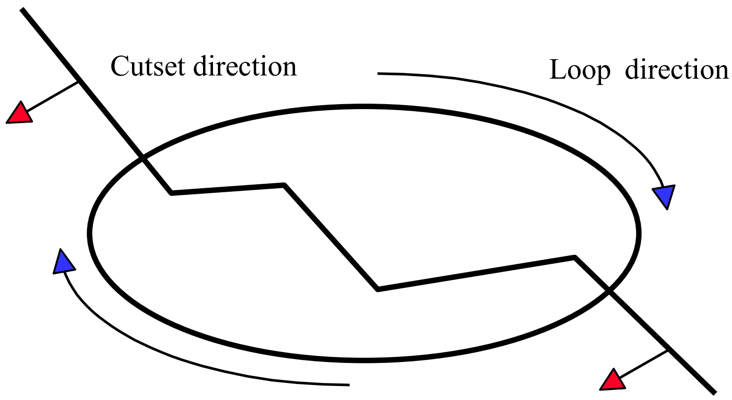


FIGURE 3: The loop and cutset relations

Both the **B** and **D** matrices have one column for every branch in the graph. If both matrices are arranged in the same column order, the following relationship holds:

$$\left[\mathbf{I} \mid \mathbf{D}_L\right]\cdot\left[\frac{\mathbf{B}_T^T}{\mathbf{I}}\right]=\mathbf{0}$$

From this, it can be seen that:

$$\mathbf{B}_T^T = -\mathbf{D}_L \tag{14}$$

Combining this with equation (12), the **B** matrix is calculated as:

$$\mathbf{B} = \left[-\mathbf{D}_L^T \middle| \mathbf{I}\right] = \left[-\left(\mathbf{A}_T^{-1}\mathbf{A}_L\right)^T \middle| \mathbf{I}\right] \tag{15}$$

2.10 Flow elements grouping

The fluid flow vector is divided into four groups. The flow elements, where the flow is known, the head elements, where the head is known, and the pipes, where neither flow nor head is known. All the head elements are members of the spanning tree, and all the flow elements of the cotree. The pipes are divided into tree pipes and cotree pipes.

$$\mathbf{m} = \begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \\ \hline \mathbf{m}_{pL} \\ \mathbf{m}_{mL} \end{bmatrix} \tag{16}$$

The current law of Kirchhoff now looks a little bit different:

$$\left[\mathbf{A}_T \mid \mathbf{A}_L\right]\begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \\ \hline \mathbf{m}_{pL} \\ \mathbf{m}_{mL} \end{bmatrix} = 0 \tag{17}$$

2.11 The partitioned cutset equation

The cutset matrix is calculated from the connectivity matrix. The connectivity matrix can be used to calculate the net flow at every node, which has to equal zero. In the same way, the net flow in every cutset equals zero, and the cutset or connectivity matrices can either be used for establishing the mass conservation in the network. Mass conservation (Kirchhoff's current law) by the cutset matrix is:

$$\left[\mathbf{I} \mid \mathbf{D}_L\right]\left[\frac{\mathbf{m}_T}{\mathbf{m}_L}\right]=\mathbf{0} \tag{18}$$

The cutset matrix is then partitioned into submatrices according to the various branch groups. The partition lines indicate the partitioning between the tree and the cotree as shown in equation (16). Note that there cannot be any flow sources among the tree branches and only pipes and flow sources can occur among the link branches.

$$\underbrace{\begin{bmatrix} \mathbf{I}_{hT} & 0 \\ 0 & \mathbf{I}_{pT} \end{bmatrix}}_{\mathbf{I}} \underbrace{\begin{bmatrix} \mathbf{F}_{11} & \mathbf{F}_{12} \\ \mathbf{F}_{21} & \mathbf{F}_{22} \end{bmatrix}}_{\mathbf{D}_L} \begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \\ \hline \mathbf{m}_{pL} \\ \mathbf{m}_{mL} \end{bmatrix} = \mathbf{0} \tag{19}$$

2.12 The partitioned loop equation

The nodal analysis does not require a specific treatment of the voltage law, as the system heads (pressures) are only expressed at the nodes. The head differences over the loop branches can then be calculated from the nodal heads, and will sum up to zero for any closed path in the network. The voltage law specifies that the sum of voltage (head) differences for any loop in the network shall be zero. This can be written for a pipe network using the fundamental loop matrix as:

$$\mathbf{B}\,\mathbf{h} = \mathbf{0} \tag{20}$$

The loop matrix can then be partitioned into submatrices according to the various branch categories. The partition lines indicate the partitioning between the tree and the cotree as shown in equation (16). The submatrices in the loop matrix tree part are obtained from equation (19) by equation (14).

$$\left[\begin{array}{cc|cc} -\mathbf{F}_{11}^T & -\mathbf{F}_{21}^T & \mathbf{I}_{pL} & \mathbf{0} \\ -\mathbf{F}_{12}^T & -\mathbf{F}_{22}^T & \mathbf{0} & \mathbf{I}_{mL} \end{array}\right] \begin{bmatrix} \mathbf{h}_{hT} \\ \mathbf{h}_{pT} \\ \hline \mathbf{h}_{pL} \\ \mathbf{h}_{mL} \end{bmatrix} = \mathbf{0} \tag{21}$$

2.13 Element relations

The pipes in the network have relation between the head loss and the flow. The matrix notation of the resistance formulation is:

Tree pipe head vector:

$$\mathbf{h}_{pT} = \mathbf{r}_{pT}(\mathbf{m}_{pT}) \tag{22}$$

Link pipe head vector:

$$\mathbf{h}_{pL} = \mathbf{r}_{pL}(\mathbf{m}_{pL}) \tag{23}$$

When an appropriate linearization method has been used, the element relations can be used in order to solve for the network flow. The Wood and Charles linearization changes equations (22) and (23) into linear matrix equations, using a diagonal resistance matrix to relate flow and head loss:

$$\mathbf{h}_{pT} = \mathbf{R}_{pT}\mathbf{m}_{pT} \tag{24}$$

$$\mathbf{h}_{pL} = \mathbf{R}_{pL}\mathbf{m}_{pL} \tag{25}$$

3. BRANCH CHARACTERISTICS – RESISTORS

The resistance function relates the head loss to the flow and the element parameters (diameter, surface roughness etc). The function is defined both for a single pipe (scalar) as *r*(*m,parameters*) and a set of pipes (vector valued function) **r**(**m**,**parameters**). The resistance matrix is then defined by the Wood and Charles linearization as:

$$\mathbf{R} = diag\left(\frac{r_j\left(m_j, parameters_j\right)}{m_j}\right) \tag{26}$$

The resistance matrix is a diagonal matrix, with the linearized resistance factors on the diagonal.

3.1 Pipes

The pipes have a resistance defined by the Darcy-Weisbach equation, which is written as:

$$h = \frac{V^2}{2g}\frac{L}{D}f = \frac{8m^2 Lf}{D^5\rho^2\pi^2 g} \tag{27}$$

The friction factor can be calculated directly from Colebrook - White equation:

$$\frac{1}{\sqrt{f}} = \left(\frac{a}{\mathrm{Re}\sqrt{f}} + \frac{b}{kD}\right)^2 \tag{28}$$

3.2 Valves

$$h = k_L\frac{V^2}{2g} = k_L m^2 = \frac{k_{L\min}}{x}m^2 \tag{29}$$

The factor k_L is a property of the valve or fitting, and is dependent on the valve position when referring to a valve, but is constant for a fitting.

$k_{L\min}$	- loss factor at $x=1$; and
x	- valve position (0…1).

3.3 Pumps

The negative resistance function of a pump can be determined from performance measurements of the pump. A common form of such a function is:

$$h_{pump} = -\left(h_o - k\cdot m^3\right) \tag{30}$$

The factors h_o and k describe pump properties, and depend on the pump speed.

4. STEADY STATE FLOW SOLUTION

4.1 Stepwise solution with back-substitution

The equations which have to be solved together are the cutset, loop and linearized element equations (19), (21), (24) and (25). Recall:

$$\left[\begin{array}{cc|cc} \mathbf{I}_{hT} & 0 & \mathbf{F}_{11} & \mathbf{F}_{12} \\ 0 & \mathbf{I}_{pT} & \mathbf{F}_{21} & \mathbf{F}_{22} \end{array}\right] \left[\begin{array}{c} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \\ \hline \mathbf{m}_{pL} \\ \mathbf{m}_{mL} \end{array}\right] = \mathbf{0} \tag{19}$$

$$\left[\begin{array}{cc|cc} -\mathbf{F}_{11}^T & -\mathbf{F}_{21}^T & \mathbf{I}_{pL} & \mathbf{0} \\ -\mathbf{F}_{12}^T & -\mathbf{F}_{22}^T & \mathbf{0} & \mathbf{I}_{mL} \end{array}\right] \left[\begin{array}{c} \mathbf{h}_{hT} \\ \mathbf{h}_{pT} \\ \hline \mathbf{h}_{pL} \\ \mathbf{h}_{mL} \end{array}\right] = \mathbf{0} \tag{21}$$

$$\mathbf{h}_{pT} = \mathbf{R}_{pT}\mathbf{m}_{pT} \tag{24}$$

$$\mathbf{h}_{pL} = \mathbf{R}_{pL}\mathbf{m}_{pL} \tag{25}$$

The know vectors (inputs) are the head element head vector $\mathbf{h}_{hT}$ and the flow element flow vector $\mathbf{m}_{mL}$. Desired are the vectors of head loss and flow in the pipes, $\mathbf{m}_{pT}$, $\mathbf{m}_{pL}$, $\mathbf{h}_{pT}$ and $\mathbf{h}_{pL}$. The flow element head vector $\mathbf{h}_{mL}$ and the head element flow vector $\mathbf{m}_{hT}$ are of secondary interest, the show only what head is required to keep the input flow for the flow element as well as what flow is needed to keep the input head for the head element.

The tree pipe flow vector is found in the second row of equation (19):

$$\mathbf{m}_{pT} = -\mathbf{F}_{21}\mathbf{m}_{pL} - \mathbf{F}_{22}\mathbf{m}_{mL} \tag{31}$$

The cotree pipe head vector is in the second row of equation (21):

$$\mathbf{h}_{pL} = \mathbf{F}_{11}^T\mathbf{h}_{hT} + \mathbf{F}_{21}^T\mathbf{h}_{pT} \tag{32}$$

Inserting equation (24):

$$\mathbf{h}_{pL} = \mathbf{F}_{11}^T\mathbf{h}_{hT} + \mathbf{F}_{21}^T\mathbf{R}_{pT}\mathbf{m}_{pT} \tag{33}$$

Inserting equations (25) and (26):

$$\mathbf{R}_{pL}\mathbf{m}_{pL} = \mathbf{F}_{11}^T\mathbf{h}_{hT} - \mathbf{F}_{21}^T\mathbf{R}_{pT}\mathbf{F}_{21}\mathbf{m}_{pL} - \mathbf{F}_{21}^T\mathbf{R}_{pT}\mathbf{F}_{22}\mathbf{m}_{mL} \tag{34}$$

Regrouping:

$$\left(\mathbf{R}_{pL} + \mathbf{F}_{21}^{T}\mathbf{R}_{pT}\mathbf{F}_{21}\right)\mathbf{m}_{pL} = \mathbf{F}_{11}^{T}\mathbf{h}_{hT} - \mathbf{F}_{21}^{T}\mathbf{R}_{pT}\mathbf{F}_{22}\mathbf{m}_{mL} \tag{35}$$

and solving:

$$\mathbf{m}_{pL} = \left(\mathbf{R}_{pL} + \mathbf{F}_{21}^{T}\mathbf{R}_{pT}\mathbf{F}_{21}\right)^{-1}\left(\mathbf{F}_{11}^{T}\mathbf{h}_{hT} - \mathbf{F}_{21}^{T}\mathbf{R}_{pT}\mathbf{F}_{22}\mathbf{m}_{mL}\right) \tag{36}$$

Equation (36) has to be solved by iteration. It relates the cotree pipe flow vector to both the input vectors. The real degree of freedom for the network is the cotree pipe flow, so when this vector has been determined, the flow solution has been found. It has one row for every loop in the network, so the number of equations which have to be iterated is reduced considerably compared to the traditional methods. When the iteration has converged, all remaining flows and heads in the network can be found by back-substitution.

This allows all system flows to be calculated in terms of the flows in the flow source elements and the flow in the pipes in the cotree:

$$\begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \end{bmatrix} = -\begin{bmatrix} \mathbf{F}_{11} & \mathbf{F}_{12} \\ \mathbf{F}_{21} & \mathbf{F}_{22} \end{bmatrix}\begin{bmatrix} \mathbf{m}_{pL} \\ \mathbf{m}_{mL} \end{bmatrix} \tag{37}$$

All head losses can now be found from the branch equations (Equations (24) and (25) recalled):

$$\mathbf{h}_{pT} = \mathbf{R}_{pT}\mathbf{m}_{pT} \tag{24}$$

$$\mathbf{h}_{pL} = \mathbf{R}_{pL}\mathbf{m}_{pL} \tag{25}$$

$$\mathbf{h}_{mL} = \mathbf{F}_{12}^{T}\mathbf{h}_{hT} + \mathbf{F}_{22}^{T}\mathbf{h}_{pT} \tag{38}$$

This solution approach has the advantage that the calculation effort within the iteration is kept low. A direct matrix solution may be more interesting, but it will require more effort within the iteration loop.

4.2 Direct matrix solution

Rearrange equations (19) and (21) in order to have only known variables on the left hand side:

$$\left[\begin{array}{cc|c} \mathbf{I}_{hT} & 0 & \mathbf{F}_{11} \\ 0 & \mathbf{I}_{pT} & \mathbf{F}_{21} \end{array}\right]\left[\begin{array}{c} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \\ \hline \mathbf{m}_{pL} \end{array}\right] = -\begin{bmatrix} \mathbf{F}_{12} \\ \mathbf{F}_{22} \end{bmatrix}\mathbf{m}_{mL} \tag{39}$$

$$\left[\begin{array}{c|cc} -\mathbf{F}_{21}^{T} & \mathbf{I}_{pL} & 0 \\ -\mathbf{F}_{22}^{T} & 0 & \mathbf{I}_{mL} \end{array}\right]\left[\begin{array}{c} \mathbf{h}_{pT} \\ \hline \mathbf{h}_{pL} \\ \mathbf{h}_{mL} \end{array}\right] = -\begin{bmatrix} -\mathbf{F}_{11}^{T} \\ -\mathbf{F}_{12}^{T} \end{bmatrix}\mathbf{h}_{hT} \tag{40}$$

Now eliminate the pipe head vectors from equation (40) by equations (24) and (25):

$$\left[\begin{array}{c|cc} -\mathbf{F}_{21}^{T}\mathbf{R}_{pT} & \mathbf{R}_{pL} & 0 \\ -\mathbf{F}_{22}^{T}\mathbf{R}_{pT} & 0 & \mathbf{I}_{mL} \end{array}\right]\left[\begin{array}{c} \mathbf{m}_{pT} \\ \hline \mathbf{m}_{pL} \\ \mathbf{h}_{mL} \end{array}\right] = -\begin{bmatrix} -\mathbf{F}_{11}^{T} \\ -\mathbf{F}_{12}^{T} \end{bmatrix}\mathbf{h}_{hT} \tag{41}$$

The row equations from equations (39) and (41) are:

$$\mathbf{m}_{hT} + \mathbf{F}_{11}\mathbf{m}_{pL} = -\mathbf{F}_{12}\mathbf{m}_{mL}$$

$$\mathbf{m}_{pT} + \mathbf{F}_{21}\mathbf{m}_{pL} = -\mathbf{F}_{22}\mathbf{m}_{mL}$$

$$-\mathbf{F}_{21}^{T}\mathbf{R}_{pT}\mathbf{m}_{pT} + \mathbf{R}_{pL}\mathbf{m}_{pL} = \mathbf{F}_{11}^{T}\mathbf{h}_{hT}$$

$$-\mathbf{F}_{22}^{T}\mathbf{R}_{pT}\mathbf{m}_{pT} + \mathbf{h}_{mL} = \mathbf{F}_{21}^{T}\mathbf{h}_{hT}$$

The three first equations are sufficient to calculate all flows:

$$\begin{bmatrix} \mathbf{I}_{hT} & \mathbf{0} & \mathbf{F}_{11} \\ \mathbf{0} & \mathbf{I}_{pT} & \mathbf{F}_{21} \\ \mathbf{0} & -\mathbf{F}_{21}^{T}\mathbf{R}_{pT} & \mathbf{R}_{pL} \end{bmatrix}\begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \\ \mathbf{m}_{pL} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & -\mathbf{F}_{12} \\ \mathbf{0} & -\mathbf{F}_{22} \\ \mathbf{F}_{11}^{T} & \mathbf{0} \end{bmatrix}\begin{bmatrix} \mathbf{h}_{hT} \\ \mathbf{m}_{mL} \end{bmatrix} \tag{42}$$

or:

$$\begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{pT} \\ \mathbf{m}_{pL} \end{bmatrix} = \begin{bmatrix} \mathbf{I}_{hT} & \mathbf{0} & \mathbf{F}_{11} \\ \mathbf{0} & \mathbf{I}_{pT} & \mathbf{F}_{21} \\ \mathbf{0} & -\mathbf{F}_{21}^{T}\mathbf{R}_{pT} & \mathbf{R}_{pL} \end{bmatrix}^{-1}\begin{bmatrix} \mathbf{0} & -\mathbf{F}_{12} \\ \mathbf{0} & -\mathbf{F}_{22} \\ \mathbf{F}_{11}^{T} & \mathbf{0} \end{bmatrix}\begin{bmatrix} \mathbf{h}_{hT} \\ \mathbf{m}_{mL} \end{bmatrix} \tag{43}$$

The head losses are found by substituting equations (24) and (25). Then the three needed row equations are:

$$\mathbf{R}_{pT}^{-1}\mathbf{h}_{pT} + \mathbf{F}_{21}\mathbf{R}_{pL}^{-1}\mathbf{h}_{pL} = -\mathbf{F}_{22}\mathbf{m}_{mL}$$

$$-\mathbf{F}_{21}^{T}\mathbf{h}_{pT} + \mathbf{h}_{pL} = \mathbf{F}_{11}^{T}\mathbf{h}_{hT}$$

$$-\mathbf{F}_{22}^{T}\mathbf{h}_{pT} + \mathbf{h}_{mL} = \mathbf{F}_{21}^{T}\mathbf{h}_{hT}$$

The head loss matrix equation is then:

$$\begin{bmatrix} \mathbf{R}_{pT}^{-1} & \mathbf{F}_{21}\mathbf{R}_{pL}^{-1} & \mathbf{0} \\ -\mathbf{F}_{21}^{T} & \mathbf{I}_{pT} & \mathbf{0} \\ -\mathbf{F}_{22}^{T} & \mathbf{0} & \mathbf{I}_{mL} \end{bmatrix}\begin{bmatrix} \mathbf{h}_{pT} \\ \mathbf{h}_{pL} \\ \mathbf{h}_{mL} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & -\mathbf{F}_{22} \\ \mathbf{F}_{11}^{T} & \mathbf{0} \\ \mathbf{F}_{21}^{T} & \mathbf{0} \end{bmatrix}\begin{bmatrix} \mathbf{h}_{hT} \\ \mathbf{m}_{mL} \end{bmatrix} \tag{44}$$

or:

$$\begin{bmatrix}\mathbf{h}_{pT}\\\mathbf{h}_{pL}\\\mathbf{h}_{mL}\end{bmatrix}=\begin{bmatrix}\mathbf{R}_{pT}^{-1} & \mathbf{F}_{21}\mathbf{R}_{pL}^{-1} & \mathbf{0}\\-\mathbf{F}_{21}^{T} & \mathbf{I}_{pT} & \mathbf{0}\\-\mathbf{F}_{22}^{T} & \mathbf{0} & \mathbf{I}_{mL}\end{bmatrix}^{-1}\begin{bmatrix}\mathbf{0} & -\mathbf{F}_{22}\\\mathbf{F}_{11}^{T} & \mathbf{0}\\\mathbf{F}_{21}^{T} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{h}_{hT}\\\mathbf{m}_{mL}\end{bmatrix} \tag{45}$$

5. THERMAL SOLUTION

The calculation of temperatures and heat flow in the network is based on the flow solution. Heat is transferred through the pipes of the network by the fluid, so similar methods have to be used to ensure that the conservation of energy for the network is fulfilled, as what was done for the flow solution.

First of all, the connectivity matrix has to be modified. Now the direction of flow in every element does matter, and the connectivity matrix has to be corrected, so that the direction of the elements corresponds with the flow direction. If the connectivity matrix is multiplied from the left hand side with a diagonal matrix containing the sign of the flow on the diagonal, each column in the connectivity matrix will either be multiplied by 1 (if the flow direction is the same as the element direction) or by -1 (if the flow direction is opposite to the element direction). The corrected connectivity matrix is named element flow connectivity matrix:

$$\mathbf{A}_f = \mathbf{A}\cdot diag(sign(\mathbf{m})) \tag{46}$$

The heat flow in a pipe is only dependent on the inflow condition of the fluid. The temperature of the fluid at the inflow end will solely determine the heat flow in the pipe. So a new variant of the connectivity matrix is needed. The element flow origin matrix has the same dimensions as the connectivity matrix. Instead of having two non-zero entries in each column, this matrix has an entry of 1 in the row corresponding to the inflow node into each pipe. The matrix can readily be calculated from the element flow connectivity matrix:

$$\mathbf{E} = \frac{\mathbf{A}_f + \left|\mathbf{A}_f\right|}{2} \tag{47}$$

If a new flow solution is calculated, some flows may have changed direction, and the element flow origin matrix must be recalculated.

5.1 Element types

Three element types are added for the thermal solution. They are:

- *t:* temperature source;
- *q:* heat source; and
- *x:* heat exchanger.

All the element types used in the flow solution are active here, as heat will be transported wit the flowing fluid.

5.2 Pipe heat flow

The heat transported with the flow in a single pipe element is calculated by:

$$q_t = mc_pT_{origin} \tag{48}$$

The origin temperatures for all elements in the network can be found from the nodal temperatures by:

$$\mathbf{T}_{origin} = \mathbf{E}^T \mathbf{T}_n \tag{49}$$

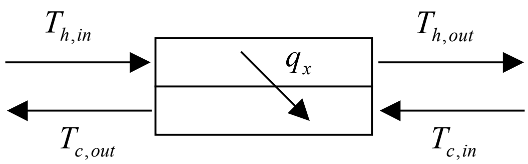
The heat flow for the all the flow elements is then calculated by:

$$\mathbf{q}_t = diag(mc_p)\mathbf{E}^T \mathbf{T}_n \tag{50}$$

5.3 Heat exchangers

Heat exchangers transfer heat from one flowstream to another, without mixing the fluids. They are thus elements with four connection points, as shown in Figure 4.

In order to model the heat exchanger within the network, an equivalent model with two connection points has to be introduced. An equivalent heat transfer coefficient is associated with this simplification. This coefficient is non-linear and dependent on the fluid temperatures, so iteration is necessary for an exact thermal solution. A schematic of the equivalent heat exchanger is shown in Figure 5.



$$\mathbf{q}_x = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln \dfrac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}} AU$$

FIGURE 4: Schematic of a heat exchanger

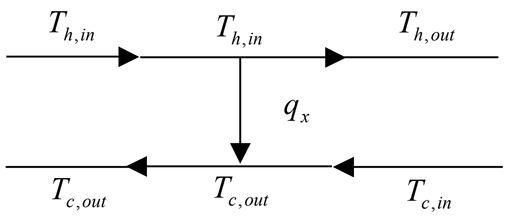


FIGURE 5: Schematic of an equivalent heat exchanger

The heat flow for a heat exchanger elements is then calculated by:

$$q_x = U_{ef}(T_{h,in} - T_{c,out}) \tag{51}$$

In order to relate the heat flow in the heat exchangers to other elements in the network, the heat exchanger connectivity matrix $\mathbf{A}_x$ is defined in the same way as the connectivity matrix. The vector of heat exchanger heat flow is thus:

$$\mathbf{q}_x = \mathbf{U}_{ef} \mathbf{A}_x^T \mathbf{T}_n \tag{52}$$

5.4 Temperature and heat flow elements

These elements are simply treated in the same way as the flow and head elements in the flow solution.

5.5 Steady state thermal solution

The current law of Kirchhoff law for the heat flow in the network is:

$$\begin{bmatrix}\mathbf{A}_f & \mathbf{A}_x & \mathbf{A}_t & \mathbf{A}_q\end{bmatrix}\begin{bmatrix}\mathbf{q}_f\\ \mathbf{q}_x\\ \mathbf{q}_t\\ \mathbf{q}_q\end{bmatrix}=\mathbf{0} \tag{53}$$

By rearranging the equation so that the known vectors are on the left hand side of the equation:

$$\begin{bmatrix}\mathbf{A}_f & \mathbf{A}_x & \mathbf{A}_t\end{bmatrix}\begin{bmatrix}\mathbf{q}_f\\ \mathbf{q}_x\\ \mathbf{q}_t\end{bmatrix}=-\mathbf{A}_q\mathbf{q}_q \tag{54}$$

The pipe heat flow and the heat exchanger heat flow can be calculated as:

$$\begin{bmatrix}\mathbf{q}_f\\ \mathbf{q}_x\end{bmatrix}=\begin{bmatrix}diag(\mathbf{m}c_p) & 0\\ 0 & \mathbf{U}_{eq}\end{bmatrix}\begin{bmatrix}\mathbf{E}_T\\ \mathbf{A}_x^T\end{bmatrix}T_n \tag{55}$$

Equation (55) can now be inserted into equation (54):

$$\begin{bmatrix}\begin{bmatrix}\mathbf{A}_f & \mathbf{A}_x\end{bmatrix}\begin{bmatrix}diag(\mathbf{m}c_p) & 0\\ 0 & \mathbf{U}_{tq}\end{bmatrix}\begin{bmatrix}\mathbf{E}_T\\ \mathbf{A}_x^T\end{bmatrix} & \mathbf{A}_t\end{bmatrix}\begin{bmatrix}T_n\\ \mathbf{q}_t\end{bmatrix}=-\mathbf{A}_q\mathbf{q}_q \tag{56}$$

This equation has the heat flow in the constant temperature elements as unknowns as well as the nodal temperatures. Information required to find this heat flow is entered by adding an additional row to the equation.

$$\left[\begin{array}{c|c}\begin{bmatrix}\mathbf{A}_f & \mathbf{A}_x\end{bmatrix}\begin{bmatrix}diag(\mathbf{m}c_p) & 0\\ 0 & \mathbf{U}_{tq}\end{bmatrix}\begin{bmatrix}\mathbf{E}_T\\ \mathbf{A}_x^T\end{bmatrix} & \mathbf{A}_t\\ \hline \mathbf{A}_t^T & 0\end{array}\right]\begin{bmatrix}\mathbf{T}_n\\ \mathbf{q}_t\end{bmatrix}=\begin{bmatrix}-\mathbf{A}_q\mathbf{q}_q\\ \mathbf{T}_t\end{bmatrix} \tag{57}$$

T

his additional row enters information about the value of the temperature of the constant temperature elements (inputs). Expanding the terms in this equation in order to obtain a more readable result:

$$\begin{bmatrix}\mathbf{A}_f diag(mc_p)\mathbf{E}_T+\mathbf{A}_x\mathbf{U}_{eq}\mathbf{A}_x^T & \mathbf{A}_t\\ \mathbf{A}_t^T & 0\end{bmatrix}\begin{bmatrix}T_n\\ \mathbf{q}_t\end{bmatrix}=\begin{bmatrix}-\mathbf{A}_q\mathbf{q}_q\\ T_t\end{bmatrix} \tag{58}$$

The nodal temperatures and constant temperature heat flow are now found by:

$$\begin{bmatrix}T_n\\ \mathbf{q}_t\end{bmatrix}=\left[\begin{array}{c|c}\mathbf{A}_f diag(mc_p)\mathbf{E}_T+\mathbf{A}_x\mathbf{U}_{eq}\mathbf{A}_x^T & \mathbf{A}_t\\ \hline \mathbf{A}_t^T & \mathbf{0}\end{array}\right]^{-1}\begin{bmatrix}-\mathbf{A}_q\mathbf{q}_q\\ T_t\end{bmatrix} \tag{59}$$

6. PRACTICAL EXPERIENCE AND CONCLUSION

The microscopic models presented here are just one of many kinds of network calculation models. These models have proven to be powerful, and as they give insight into the mathematics behind the model, the enable a skilled user to do very detailed and accurate analysis. The method is as well very flexible, because the terminology enables the user to adapt these models relatively easily to new fields of application.

6.1 Industrial usage

The Dutch energy company NUON in Arnhem, the Netherlands, has been using these models as their main tool for district heating design and operation since 1995. The main benefit they saw in these models was the flexibility and easy adoption to other systems or for new application. The author has developed the analysis package Pipelab in cooperation with NUON, running under the numerical environment Matlab. This package is not commercial, but is used for research purposes both in academia and industry.

6.2 A sample study from Turkey

Adil Caner Şener, at the Izmir Institute of Technology Geothermal Energy Research Development Test and Education Centre did as well aproject at the United Nations University – Geothermal Training Programme in Reykjavik in 2002. The title of the report was: "Modelling of Balçova geothermal district heating system".

His study analyzed the system, pinpointing various problem areas in the present operation of the system. Optimization of the geothermal supply system was studied, as well as time series methods for load forecasting.

The microscopic models were used for calculation of flow and head loss in the distribution system. Figure 6 is a diagram from the report, showing the head both in the supply and return network as a function of the distance from the supply point.

The thermal solution method was then used to obtain the temperatures in the supply network. Figure 7 is a diagram from the report, showing the temperature as a function of the distance from the supply point.

It is apparent from the diagram, that unacceptable cooling is in a few of the pipes in the network. There were reports from the operation on heating problems by a few of the consumers.

In Figure 8, the distribution system is shown, and the problem areas indicated.

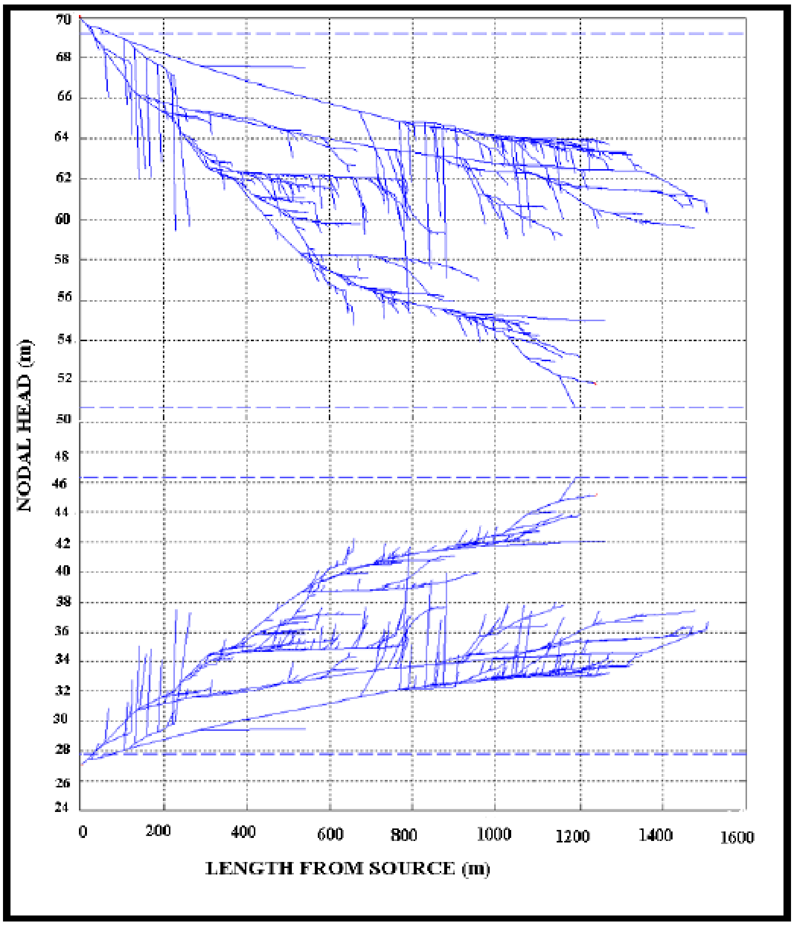


FIGURE 6: Length from source vs. head loss diagram for the Balcova distribution system

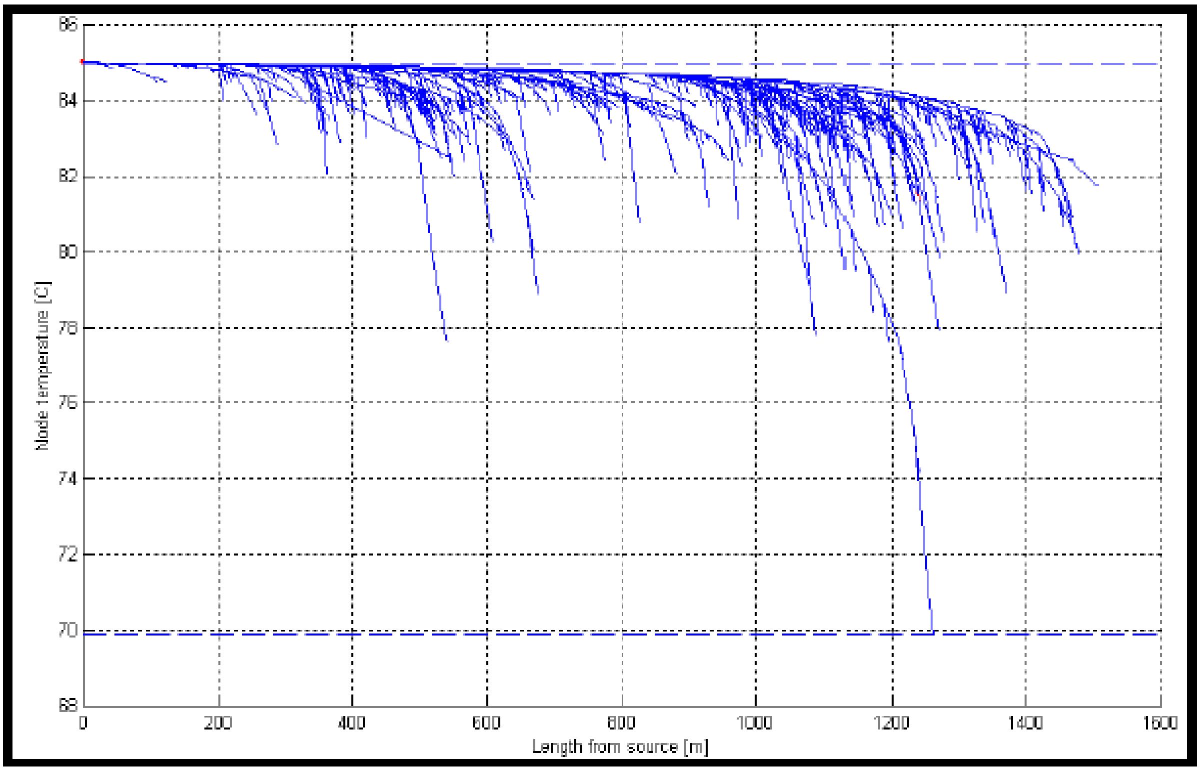


FIGURE 7: Length from source vs. node temperature diagram for the Balcova distribution system

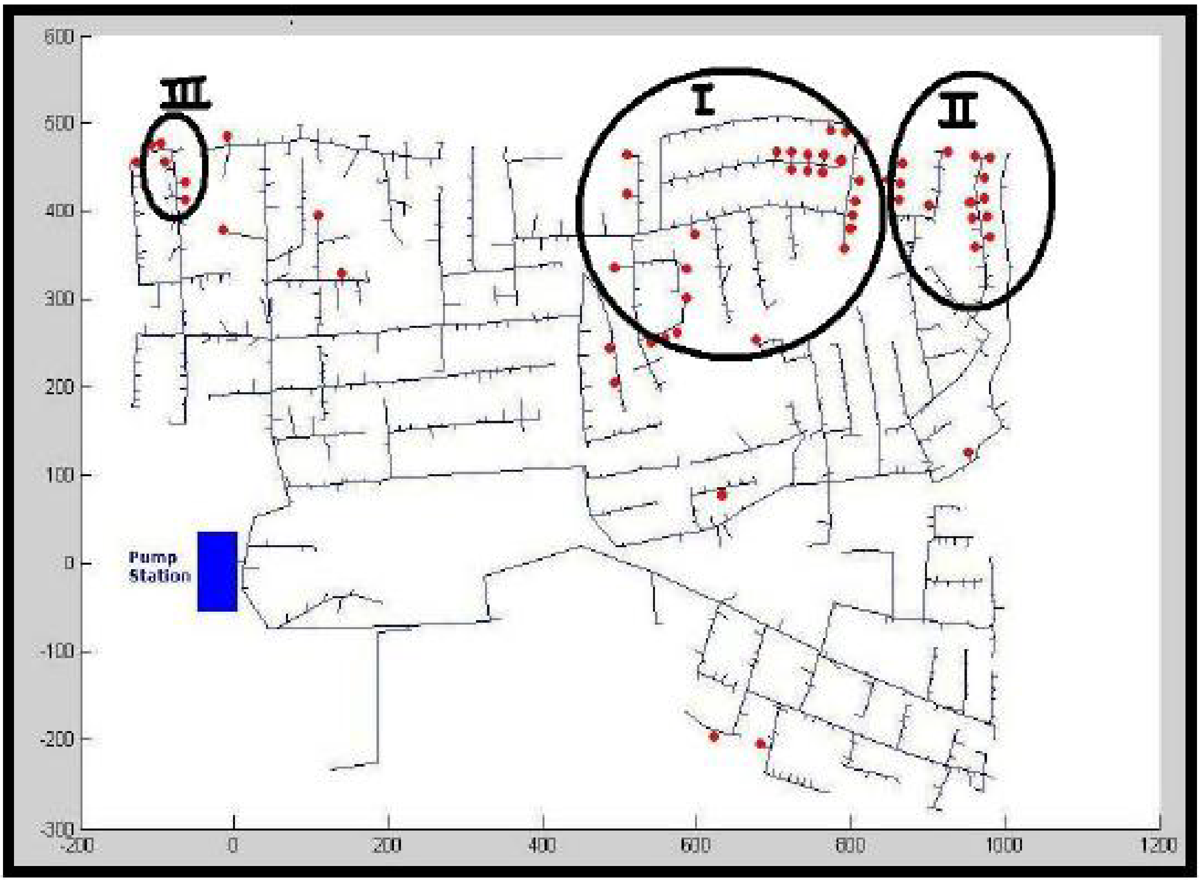


FIGURE 8: Buildings with heating problems

The analysis did show, that the problem areas were related to pipes with abnormally high head loss per unitary length. The problem areas are indicated in Figure 9.

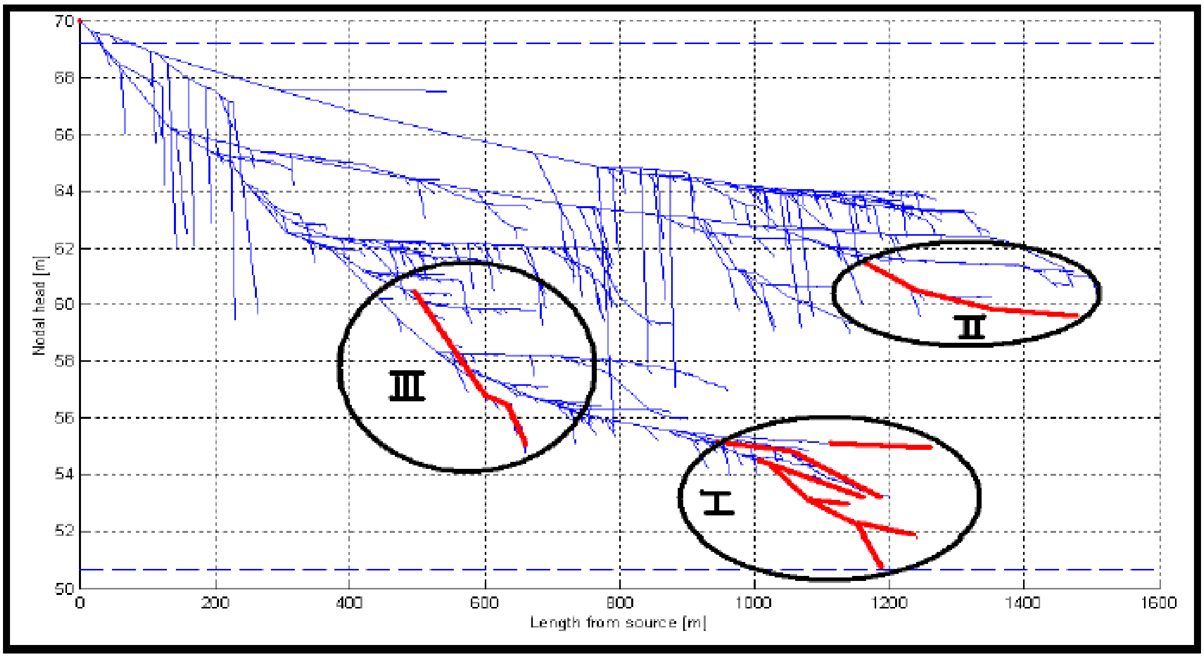


FIGURE 9: Presentation of regions with heating problems in h-l diagram of supply network

Similarly, the area with the high cooling in the supply system was one of the problem areas (Figure 10).

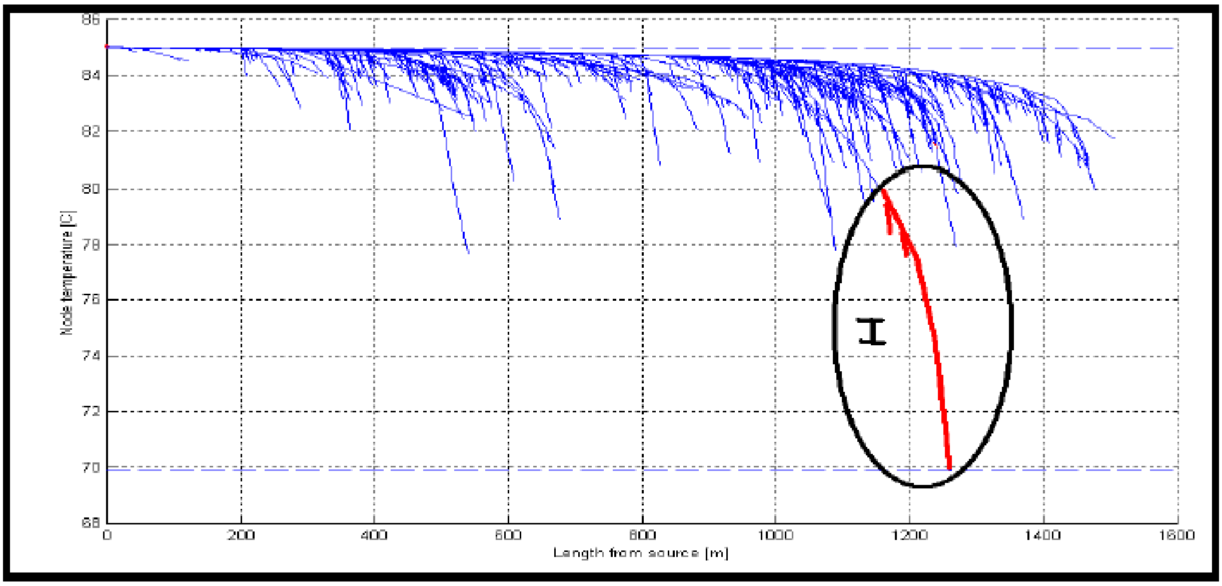


FIGURE 10: Presentation of regions with heating problems in T-l diagram of supply network

The conclusion is, that a microscopic analysis is necessary for safe and good design, operation and troubleshooting of pipe networks.

7. FINAL WORDS

I do sincerely hope that this presentation of the mathematics behind a thorough analysis of district heating networks will give the reader a new insight into this fascinating area of research and design.

NOMENCLATURE

Scalars

A	Heat transfer area (m^2)
a_{ij}	Connectivity matrix entry (-)
C	Heat capacity of house (J/°C)
c_p	Water heat capacity (J/(kg °C))
g	Acceleration due to gravity (m/s^2)
G_n	Graph
G_s	Subgraph
k_i	PI-control parameter (kg/(s^2 °C))
k_l	Building heat loss factor (W/ °C)
k_p	P-control parameter (kg/(s °C))
L	Cotree (the set of links)
m	Water mass flow (kg/s)
m_0	Reference water mass flow (kg/s)
m_{avg}	Average mass flow
n_L	Number of links (-)
n_n	Number of nodes (-)
n_q	Number of constant heat flow elements (-)
n_t	Number of constant temperature elements (-)
n_T	Number of tree branches (-)
q	Heat flow (W)
Q	Heat duty (W)
Q_0	Heat duty at reference conditions (W)
Q_{loss}	Heat loss (W)
Q_{net}	Net heat (W)
q_q	Constant heat flow (W)
Q_{supp}	Heat supply (W)
q_t	Heat flow in constant temperature element (W)
q_x	Heat exchanger duty (W)
R_c	Capacity ratio
T	Temperature (°C)
T	Tree
T_1	Pipe inlet temperature (pumping station) (°C)
T_2	Return temperature at pumping station (°C)
Tc,in	Cold fluid inlet temperature (°C)
Tc,out	Cold fluid outlet temperature (°C)
T_g	Ground temperature (°C)
Th,in	Hot fluid inlet temperature (°C)

Th,out	Hot fluid outlet temperature (°C)
T_i	Indoor temperature (°C)
T_{i0}	Reference indoor temperature (°C)
$T_{i,set}$	Desired indoor temperature in dynamic modelling (°C)
T_o	Outdoor temperature (°C)
T_{o0}	Reference outdoor temperature (°C)
T_r	Return water temperature (primary network) (°C)
T_{r0}	Reference return water temperature (primary network) (°C)
T_{rs}	Return water temperature in secondary network (°C)
T_s	Water supply temperature (primary network) (°C)
T_{s0}	Reference water supply (primary network) (°C)
U	Heat transfer coefficient (W/(m2°C))
Ueq	Equivalent heat transfer coefficient (W/°C)
U_p	Pipe heat loss factor (W/ °C)
y	Variable
z	Variable

Greek symbols

ε	Heat exchanger effectiveness
τ	Pipe transmission effectiveness
τ_0	Pipe transmission effectiveness at reference conditions
ΔT_m	Logarithmic mean temperature difference (°C)
ΔT_{m0}	Logarithmic mean temperature difference at reference conditions (°C)

Vectors and matrices

$\mathbf{A}$	Flow elements connectivity matrix (-)
$\mathbf{A}_f$	Flow connectivity matrix (-)
$\mathbf{A}_L$	Cotree connectivity matrix (-)
$\mathbf{A}_q$	Constant heat flow connectivity matrix (-)
$\mathbf{A}_T$	Tree connectivity matrix (-)
$\mathbf{A}_t$	Constant temperature connectivity matrix (-)
$\mathbf{A}_x$	Heat exchanger connectivity matrix (-)
$\mathbf{D}$	Cutset matrix (-)
$\mathbf{E}$	Element flow origin matrix (-)
$\mathbf{I}_{hT}$	Tree head source identity matrix
$\mathbf{I}_{pT}$	Tree pipe identity matrix
$\mathbf{I}_{pL}$	Cotree pipe identity matrix
$\mathbf{m}$	Flow vector (kg/s)
$\mathbf{m}_{hT}$	Tree head source flow vector (kg/s)
$\mathbf{m}_{mL}$	Link flow source flow vector (kg/s)
$\mathbf{m}_{pL}$	Link pipe flow vector (kg/s)
$\mathbf{m}_{pT}$	Tree pipe flow vector (kg/s)
$\mathbf{F}_{ij}$	Submatrix of the cutset matrix
$\mathbf{q}_f$	Vector of heat flow in flow elements (W)

$\mathbf{q}_q$	Constant heat flow vector (W)
$\mathbf{q}_t$	Vector of heat flow in constant temperature elements (W)
$\mathbf{q}_x$	Heat exchanger duty vector (W)
$\mathbf{T}_n$	Node temperature vector (°C)
$\mathbf{U}_{eq}$	Heat exchanger transfer matrix (W/°C)

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HEAT PUMPS AND GEOTHERMAL SPACE COOLING

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ABSTRACT

This paper is an introduction to the heat pump technology applied to geothermal space cooling. It provides a brief overview of the theoretical background related to the heat pump cycle, available technology and presents the main parameters impacting the technology of geothermal space cooling.

1. INTRODUCTION

Geothermal ground source heat pumps are currently the most widespread form of geothermal utilization. Geothermal heat pumps for decentralized applications are rather common in Europe.

As the cycle on which the heat pumps are based is reversible, they can be applied for both heating and cooling purposes. During winter time the ground source delivers heat into the heat pump and the sink is the space to be heated. During summer time the ground source is the sink and the space delivers heat into the heat pump.

Geothermal heat pumps for cooling purpose is something completely different. Instead of using electricity for the heat pump compressor, like in a normal cooling machine or a refrigerator, the heat from a geothermal resources is used as the driving energy in an absorption heat pump, often named geothermal absorption chillers.

2. MARKET PROSPECTS

The projection to 2040 by the EIA for residential space cooling energy consumption indicates a steady increase in space cooling energy use worldwide of about 1.5% annually, from 0.85 PJ 2010 to 1.25 PJ. Electricity is currently the most common source of energy used for driving traditional space cooling machines. Rising electricity prices and the search for low CO_2 emission energy makes geothermal absorption heat pump an interesting option.

Cooling degree days give an indication on the measure of how much, and for how long, the outside temperature was above that of the base temperature.

Table 1 below gives an indication on potential cooling demand in various places in South-America.

Such information could be combined with information on potential geothermal resources to give an indication about the places where geothermal space heating could be applied.

TABLE 1: Cooling degree days for various locations (BizEE Software Limited, 2014)

Cooling Degree Days **For a base temperature of 22°C**	**Celsius based** **5 year average**
Santiago, Chile	317
Baranquilla, Colombia	2145
Guayaquil, Ecuador	1387
Fortaleza, Brazil	1725

When a site for a space district cooling system has been selected, more detailed weather and load studies should be applied, similar as is done when geothermal district heating is designed.

Space cooling loads depend mainly on the building characteristics and on the local weather data. Weather records are usually provided by the local weather agency, preferably on an hourly basis, for a period of time as long as possible and are used to draw up the load duration curve.

The aim is to show with a load duration curve the number of days/hours per year that have an outdoor temperature lower or higher than a given temperature. The area under this curve is proportional to the number of degree-days required for heating or cooling and gives a measure of the amount of energy required for space conditioning. Figure 1 shows an example of load duration curves for various locations.

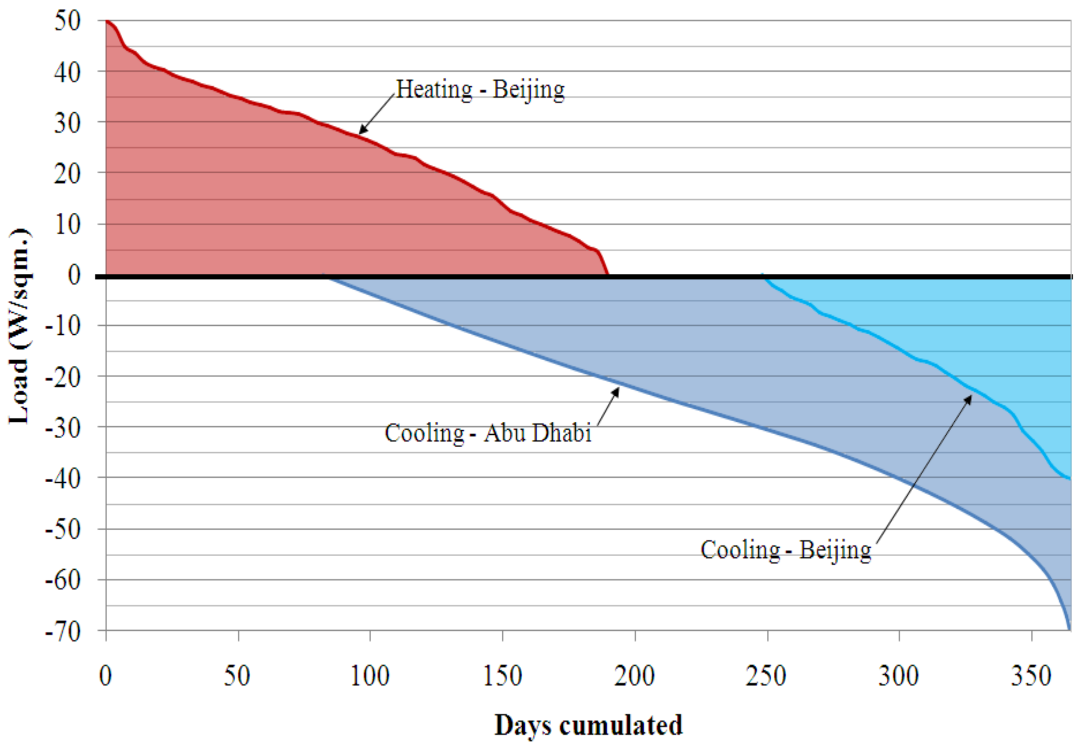

FIGURE 1: Heating/cooling load factors in various locations

Heating and cooling load factors are summarized in Table 2 below.

TABLE 2: Heating/cooling load factors

	Cooling load	Heating load
Abu Dhabi	2.650 h/year @ 25°C	-
	2.850 h/year @ 22°C	
Beijing	1.250 h/year @ 25°C	2.400 h/year @ 18°C
Reykjavík	-	4.300 h/year @ 20°C

3. COOLING TECHNOLOGY

3.1 Heat pumps

The heat pump's theoretical cycle proceeds from the Carnot cycle. Heat pumps are reversible machines that transfer heat by absorbing heat from a cold space and releasing it to a warmer one, and vice-versa. The heat is transferred by a working fluid media and requires additional energy input as shown in Figure 2.

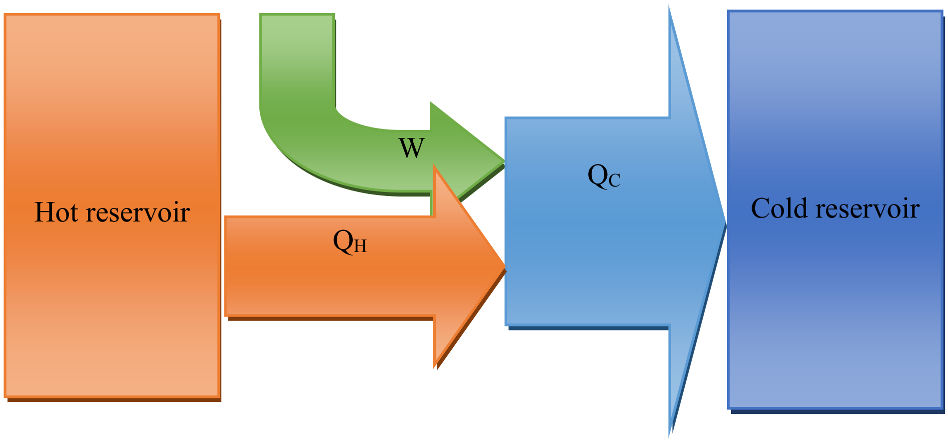

FIGURE 2: Heat pump – heat flow principle

Heat pumps are characterized by a coefficient of performance (COP) corresponding to the number of units of energy delivered to the hot reservoir:

$$COP = \frac{Q_C}{W} = \frac{Q_C}{Q_C - Q_H} \qquad (1)$$

where Q_C = Heat released to the cold reservoir, cooling capacity (W);
W = Work consumed by the heat pump (W); and
Q_O = Heat extracted to the hot reservoir (W).

3.2 Heat pumps – various technologies for geothermal utilization

The most common applications of heat pumps are refrigerators and freezers. Heat pumps are also very common as chillers for space heating and cooling. Table 3, below, proposes an overview of the most common cooling methods.

TABLE 3: Overview of the most common cooling methods

Chiller type	**Compression**	**Absorption**
Compression type	Mechanical	Thermal absorption loop
Energy source	Electric power	Heat energy 85°C–150°C
Refrigerant agent	Halons, chlorinated CHC, Chlorine free hydrocarbons	Water with lithium bromide as an absorption agent
COP	4-6	0.6–1.0

A few machines that can be applied to geothermal space cooling are briefly introduced below.

3.2.1 Conventional compressor driven chiller for space cooling

The compression cycle requires an electrical energy supply. Figure 3 proposes a schematic view of the process.

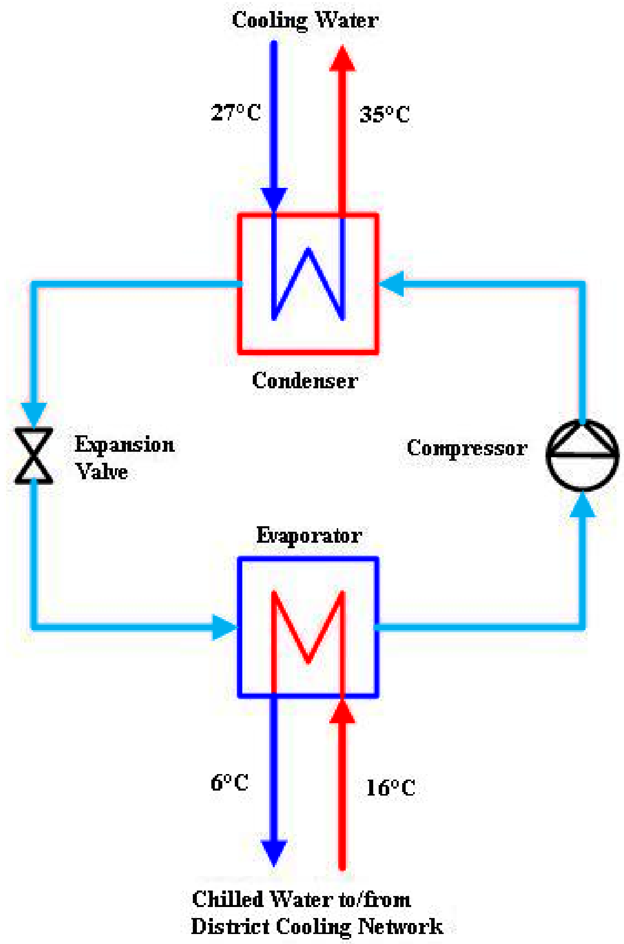

FIGURE 3: Compressor driven chiller – typical working process

The typical operation range for compressor driven chillers is:

- Electricity.
- Cooling water: 27/35°C, i.e. from cooling tower.
- Chilled water: 16/6°C, used for space cooling.
- Working fluid.
- COP: 4–6.

3.2.2 Absorption chiller machine

Absorption chillers present various advantages. They are cost effective with a high efficiency, long lifetime and low operation and maintenance costs. The investment cost of such equipment is, however, rather high, or about twice the investment cost required for a compressor driven chiller.

Absorption chillers can easily be operated by geothermal energy as they are driven on a heat source with a broad temperature range of 85°C–150°C. It is furthermore to be noted that such equipment is much more silent than the conventional compressor driven chillers.

Typical operation range for absorption chillers is:

- Driving heat: 95/60°C.
- Cooling water: 27/35°C.
- Chilled water: 16/6°C.
- Coefficient of performance: 0.7 single stage, 1.2 double stage.
- Cost: 20–50% more expensive than a standard compressor machine.

Figure 4 proposes a schematic view of the process.

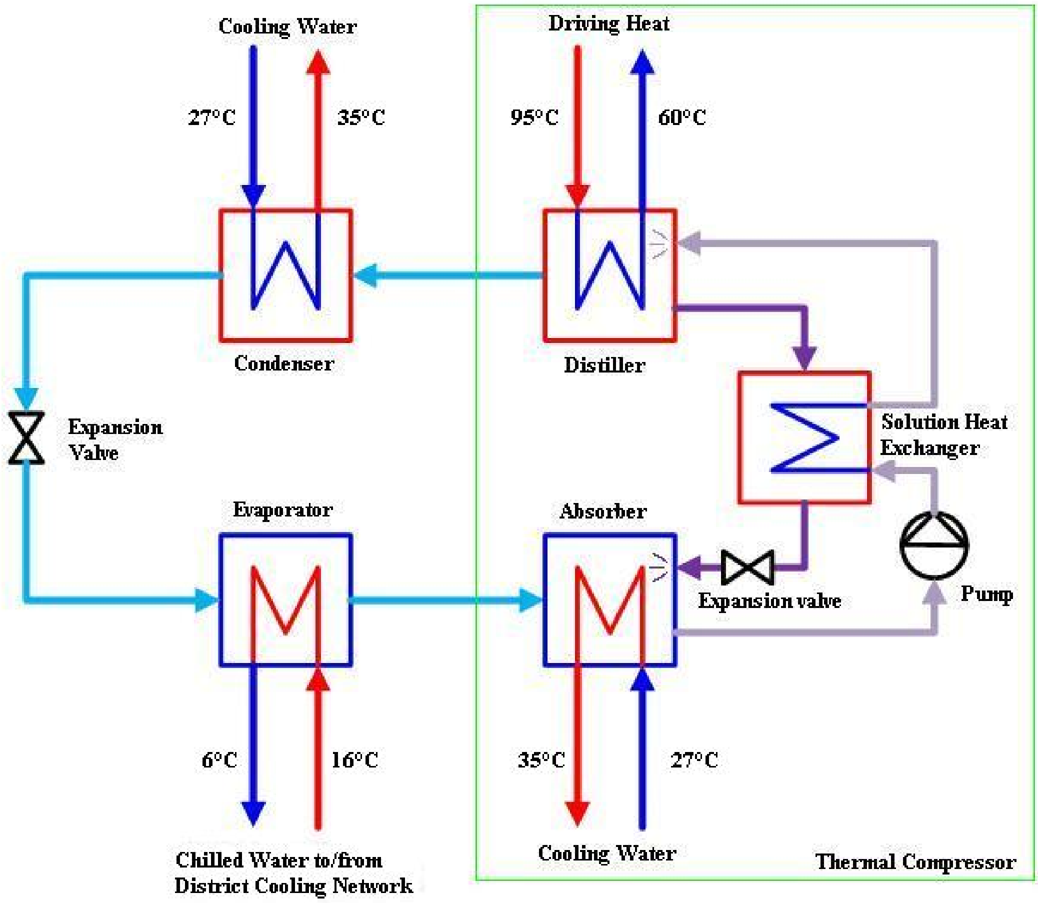

FIGURE 4: Absorption chiller – typical working process

An absorption chiller does not use an electric compressor to mechanically pressurize the refrigerant. Instead, it uses a heat source to evaporate the refrigerant. The absorption cooling cycle can be described in three phases:

- Evaporation: the liquid refrigerant evaporates in a low partial pressure environment, thus extracting heat from its surroundings.
- Absorption: the gaseous refrigerant is absorbed – dissolved into another liquid - reducing its partial pressure in the evaporator and allowing more liquid to evaporate.
- Regeneration: The refrigerant-laden liquid is heated, causing the refrigerant to evaporate out. It is then condensed through a heat exchanger to replenish the supply of liquid refrigerant in the evaporator.

Lithium bromide is commonly used as the carrier fluid and water as refrigerant. Unlike CFCs and HCFCs, the working fluid used in absorption chillers is environmentally friendly and non-toxic. Lithium bromide can be easily transported, as white odorless salt, and stored.

4. THE USE OF GEOTHERMAL ENERGY AND HEAT PUMPS FOR COOLING

4.1 District cooling

A district cooling system distributes thermal energy in the form of chilled water or other media from a central source to multiple buildings through a network of underground pipes for use in space and process cooling. The cooling or heat rejection is usually provided from a central cooling plant, thus eliminating the need for separate systems in individual buildings. Figure 5 presents the main components of a district cooling system.

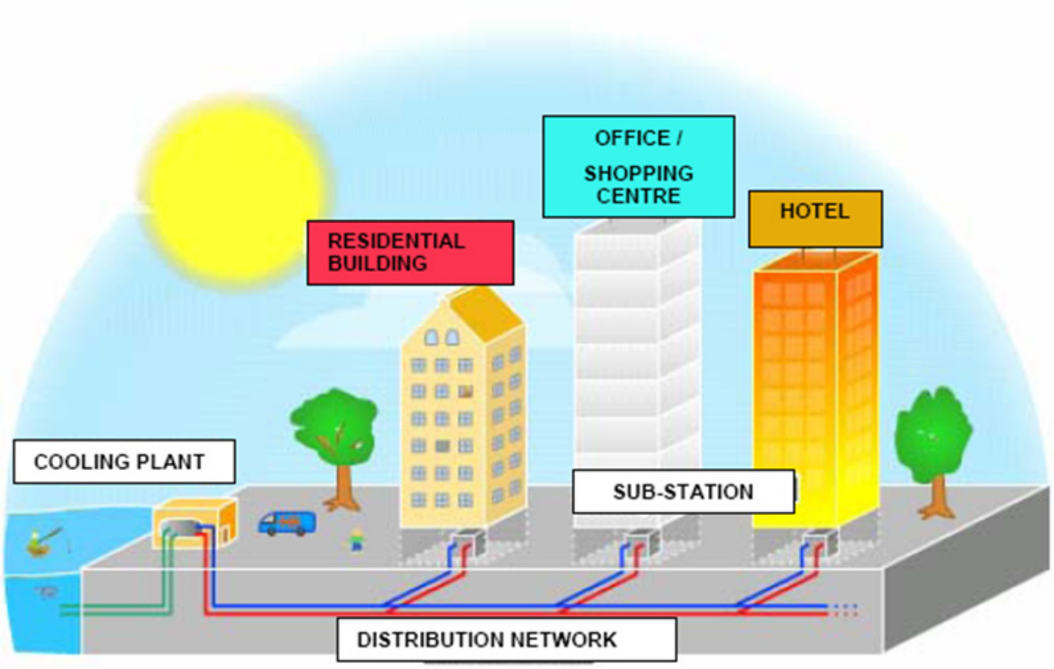

FIGURE 5: Main district cooling components

The main components of a district cooling system are further listed below:

- Cold Sink:
    - Cooling tower for air cooled systems.
    - Water for water cooled system: e.g. sea water, lake or a river.
- Cooling Plant producing chilled water at 6- 8°C:
    - Compressor driven chiller, with electricity as an energy source, or absorption chiller requiring heat as energy source.

    - Storage tanks, accumulators and other typical equipment for district systems.
- Water distribution network: usually consisting of supply and return pipes.
- Consumer's substation.
- HVAC systems in buildings:
    - Forced air ventilation system.
    - Free cooling with panels.

District cooling systems are competitive systems and present various benefits. Their energy performance is significantly better than individual, decentralized, systems and a district system often contributes to a maximized cost effectiveness. Furthermore, the investment costs for the users are significantly reduced. Finally, such systems enable space to be saved for the users allowing them to allocate space in the buildings to other activities than for the installation of space demanding equipment.

From the environmental point of view, a district cooling system will contribute to reducing sound pollution and is expected to have less impact on the environment than many individual systems producing the same cooling effect.

Geothermal district cooling systems use geothermal resources as a source of energy instead of primary energy sources such as oil or natural gas. They are therefore expected to contribute to a significant cut of CO_2 emissions in addition to contributing to reducing dependency on fossil fuel exports.

Last but not least is the efficiency and flexibility of such systems. Large industrial equipment are by far more efficient than commercial equipment. They are furthermore flexible as different energy sources may be used, e.g.:

- Electricity;
- Natural gas;
- Waste heat;
- Solar; and
- Geothermal energy.

4.2 Energy efficiency considerations

Although an absorption chiller as a much lower COP than a compression driven chiller, it might be more efficient than the latter if the whole production process is taken into account. Table 4 proposes a comparison of the energy output for compressor driven chiller and geothermal heat driven absorption chiller with the same initial energy input, i.e. to produce electricity or from the geothermal field.

TABLE 4: Energy output vs. energy input

Machine	COP	Energy source	Initial energy input at the chiller	Output
Compressor driven chiller	5	Electricity	0,2 kWh to deliver 1 kWh chiller effect	1 kWh
Absorption chiller	1	Geothermal hot water, 120°C	1 kWh heat to deliver 1 kWh at the chiller. No losses are expected to occur between the well and the chiller	1 kWh
Electricity		Geothermal hot water, 120°C	2 kWh heat from geothermal used to produce 0.2 kWh electricity (10% thermal efficiency)	0.2 kWh

An absorption heat pump driven with hot geothermal driving fluid might deliver 2 times more cooling energy than a compressor chiller, driven with electricity produced with the same geothermal fluid.

5. CONCLUSION

Geothermal space cooling is technically and in many cases a commercially competitive solution compared to space cooling from conventional sources of energy. It presents various advantages, the main ones being the cut of CO_2 emissions, and the reduction of dependency on fossil fuel exports. When utilized in a district system, efficiency and cost effectiveness will be enhanced.

REFERENCES

BizEE Software Limited, 2014: *Degree days – Weather data for energy professionals*. Website: www.degreedays.net/

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GEOTHERMAL TRAINING PROGRAMME

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HYBRID POWER PLANT USING THREE ENERGY RESOURCES AT THE SAN VICENTE GEOTHERMAL FIELD, EL SALVADOR

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ABSTRACT

A conceptual design of a 10 MW power plant (3HS+ORC), where energy comes from hybridization of geothermal water, solar irradiation and biomass heat sources (3HS), is proposed to generate electricity by a conventional organic Rankine cycle (ORC) with isopentane as a working fluid. The power plant performance is preliminarily assessed by integrating the amount of these renewable energies available in the northern boundary of the San Vicente geothermal field.

1. INTRODUCTION

Global energy crisis demands many countries to change or diversify their energy matrix. This is done mainly by reducing fossil consumption and opening up to technologies that use renewable energy as indigenous energy resources. During the 70's and this century's worldwide crisis, El Salvador began to assess solar, small hydro, wind and biomass renewable energies to add them to its energy matrix, which is composed mainly of imported oil, large hydro from Lempa River and high enthalpy geothermal resources.

A political frame to develop electricity generation projects based on renewable energy has existed since 2009 in El Salvador. For instance, tax incentives for projects up to 20 MW size and a long term strategy (2015-2025) are applied to meet electrical demand considering natural gas and renewable energy such as geothermal, photovoltaic, small hydro, wind and biogas technologies.

Power plant technology based on hybrid systems like geothermal-thermosolar or geothermal-thermosolar-biomass should be developed by the generator sector to take advantage of the cheaper indigenous energy, and therefore the country should be ready for the electricity demand and environmental obligations beyond 2020.

In Ahuachapán (Alvarenga, et al. 2008) and Berlin (Handal and Alvarenga, 2010) geothermal fields, LaGeo has demonstrated that thermosolar concentration and geothermal residual water can be combined to produce saturated steam to drive steam turbines, without scaling or corrosion problems in the solar field, however, low availability factor was an issue because of the duration of the solar day.

To improve the availability and capacity factors of an ORC power plant using isopentane as a working fluid as well taking advantages of low to medium geothermal resources existing in El Salvador became the reasons to assess and discuss the 3HS+ORC hybrid power plant concept.

2. 3HS+ORC POWER PLANT CONCEPT

Figure 1 shows a diagram of the 3HS+ORC power plant concept. It consists of a thermosolar field including thermal storage tanks, a biomass boiler, heat exchangers and a power block.

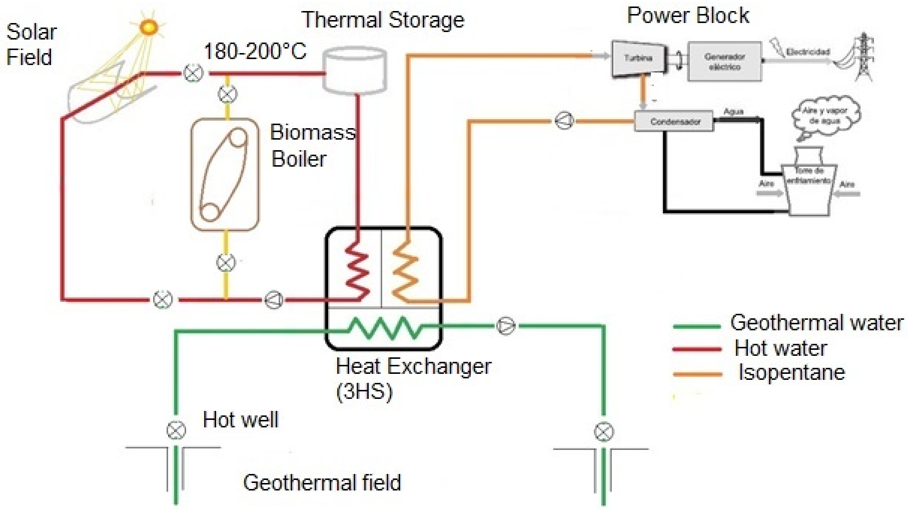

FIGURE 1: 3HS+ORC hybrid power plant concept

The organic Rankine cycle uses isopentane as a working fluid for driving the turbine in the power block side. The heat to process the isopentane is supplied by hotter water flowing through the heat exchangers.

The hot water flow can be originated in a liquid dominated and low to medium enthalpy geothermal reservoir or can be conducted from separated liquid into a flash process of a high temperature geothermal field, which feeds steam power plants. Also, water flow can gain heat into a thermosolar field that during sun's peak hours can save energy in the thermal storage tanks. This stored energy can be utilized during cloud coverage or some hours after sunset. In the case of low or lack of solar irradiation, water can be heated through the boiler that can generate hot water by forestry biomass combustion.

The nominal capacity of the hybrid power plant depends on the amount of energy resource on the site and governmental regulations to make use of the tax incentives, which in El Salvador establishes an upper limit of 20 MWe.

3. SITE PROPOSAL FOR THE POWER PLANT

As can be seen in Figure 2, both the sites for the 3HS+ORC hybrid power plant and the solar field are proposed to be located at the northern part of the San Vicente Geothermal production wells. Pipelines for less hot reinjection water would cross the border of solar field supplying separated water to the 3HS+ORC system. The terrain, currently used for sugar cane plantation with 13.5% S-N slope is appropriate for deploying the solar field of 1 km^2 size and has access to unpaved roads to transport forestry biomass from nearby plantations.

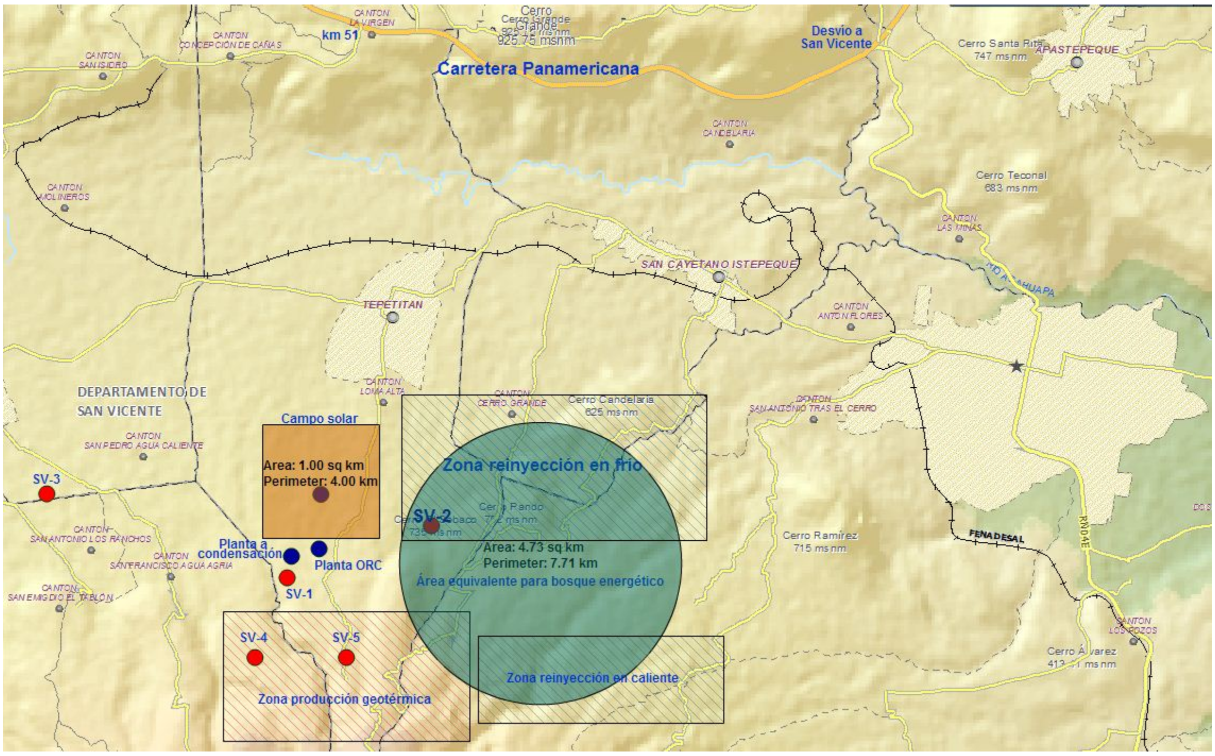

FIGURE 2: Site proposal for developing the 3HS+ORC hybrid power plant and solar field

4. OUTPUT

The power output of the 3HS+ORC hybrid power plant is based on the ORC efficiency and assessment of the renewable energy resources, which is available in the surroundings and also considered in this proposal, i.e. geothermal, solar and biomass.

5. GEOTHERMAL POTENTIAL

The geothermal energy that will supply a portion to drive the 3HS+ORC hybrid power plant would come from the enthalpy in the mass flow of the separated water in the process to get steam for the planned single flash power plant in the San Vicente geothermal field.

The available water mass flow can be derived from the size of the single flash power plant, steam fraction of 25% and a consumption factor of (2.0 kg/s)/MW. The installed capacity for the single flash power plant is estimated by applying the well-known volumetric calculation method with Monte Carlo simulation. According to Sarmiento and Steingrímsson (2011), the volumetric method calculates the thermal energy in the rock and the fluid that could be extracted based on volume and temperature reservoir as well as in the final or abandonment temperature, which is 170-180 ºC for steam power plants. Considering that San Vicente geothermal reservoir is a liquid dominated type, the total thermal energy stored in that reservoir is:

$$Q_t = A\, h\, [\, \rho_r\, C_r\, (1-\varphi) + \rho_w\, C_w\, \varphi\,]\, (\, T_i - T_f\,) \tag{1}$$

The power plant size (P) to be supported by that resource results as:

$$P = \frac{Q_t \, R_f \, C_e}{t \, P_f} \tag{2}$$

As shown in Table 1, all the quantities in the above equations are in IS units. Besides, area (A), thickness (h), porosity (φ) and reservoir temperature (Ti) are considered here as random variables with triangle and normal log probability distributions. Some properties as density (ρr) and heat capacity (Cr) of the reservoir rocks are taken as uniform or constant distributions. Additional properties like abandonment temperature (Tf), recovery factor (Rf), conversion efficiency (Ce), economic life in years (t) of the project and power plant factor (Pf) are of a reasonable constant value.

TABLE 1: Values and probability distributions for the variables of the volumetric method

Variable	**Symbol**	**SI units**	**Min**	**Most likely**	**Max**	**Probability distribution**
Area	A	km^2	4	6	12	Triangle
Thickness	h	m	700	1500	2000	Triangle
Temperature	Ti	°C	230	240	250	Triangle
Abandonment temperature	Tf	°C		180		Constant
Porosity	φ			0.06		Normal Log SD=0.02
Rock specific heat	Cr	kJ/kg °C		0.85		Constant
Water specific heat	Cw	kJ/kg °C		4.6		Constant
Rock density	ρr	kg/m^3		2500		Constant
Water density	ρw	kg/m^3		806		Constant
Recovery factor	Rf			0.20		Constant
Conversion efficiency	Ce			0.12		Constant
Plant factor	Pf			0.95		Constant
Economic life	Years			30		Constant

Figure 3 shows the results of 100,000 iterations using the Monte Carlo simulation. The available geothermal potential, with 90% of certainty, is between 21 and 58 MWe. The cumulative probability curve indicates that there is 80 to 90% of probability for extracting about 27 MWe of reserves existing in the San Vicente geothermal area.

If 27 MWe are going to be developed in a single flash power plant, the total steam consumption would reach 54 kg/s and therefore hot separated water at 180 ºC available for the 3HS+ORC hybrid power plant would be 162 kg/s.

6. FORESTRY BIOMASS

The thermal energy that will be the second portion to drive the 3HS+ORC hybrid power plant, would be heat obtained through water, while both native Gliricidia Sepium (locally known as Madre Cacao) and imported Eucaliptus Camaldulensis trees will be used to burn into a conventional boiler.

The chemical energy (Bridwater, A., 1996 and Nogués et al., 2010) contained in this biomass forestry type depends on their chemical constituents and moisture present in these trees. Table 2 summarizes the chemical composition of each tree as well as their higher heating value (HHV) dry base and lower heating value (LHV), with 30% wet base.

Those heating values are related with the following equation and the plot in the Figure 4 indicating that the LHV decreases linearly with the moisture content.

$$LHV_{(wet)} = HHV_{(dry)} \left(1 - \frac{w}{100}\right) - 24.49 \, (w + 9H) \left(1 - \frac{w}{100}\right) \tag{3}$$

where w and H are the moisture ratio and dry base hydrogen fraction, respectively.

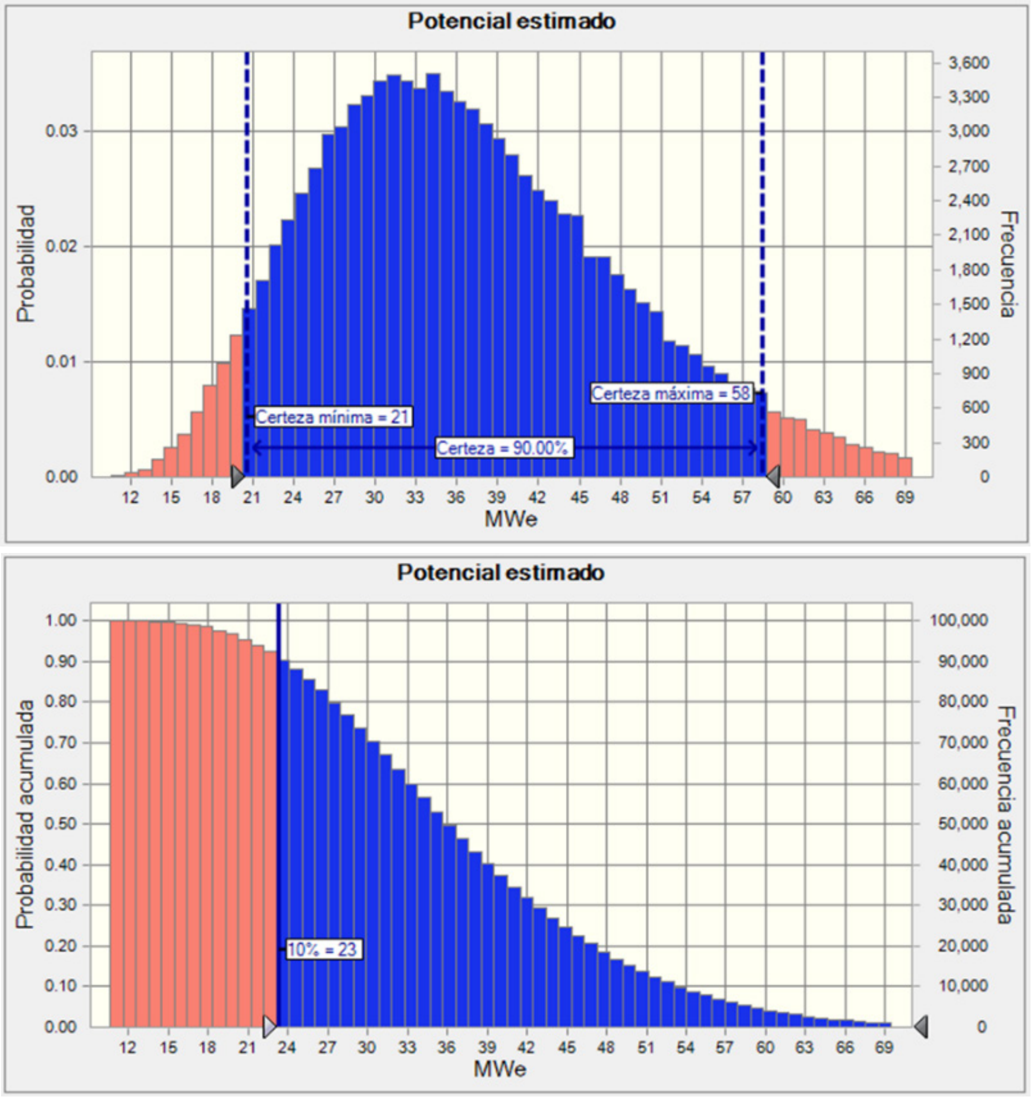

FIGURE 3: Relative frequency histogram and cumulative probability curve of the volumetric reserves estimation for the San Vicente geothermal field

TABLE 2: Chemical content and heating values for the Gliricidia Sepium and the Eucaliptus Camaldulensis biomass forestry type.

Chemical content and physical properties	**Gliricidia Sepium**	**Eucalyptus Camaldulensis**
	% weight	
C	45.22	48.68
H	5.91	6.20
N	1.06	0.24
S	0.00	0.00
O	46.26	44.86
CL	0.03	0.03
ASH	1.52	0.00
$HHV_{(dry)}$ (kJ/kg)	18380.00	20100.00
$LHV_{(wet)}$ (kJ/kg)	11219.46	12378.72

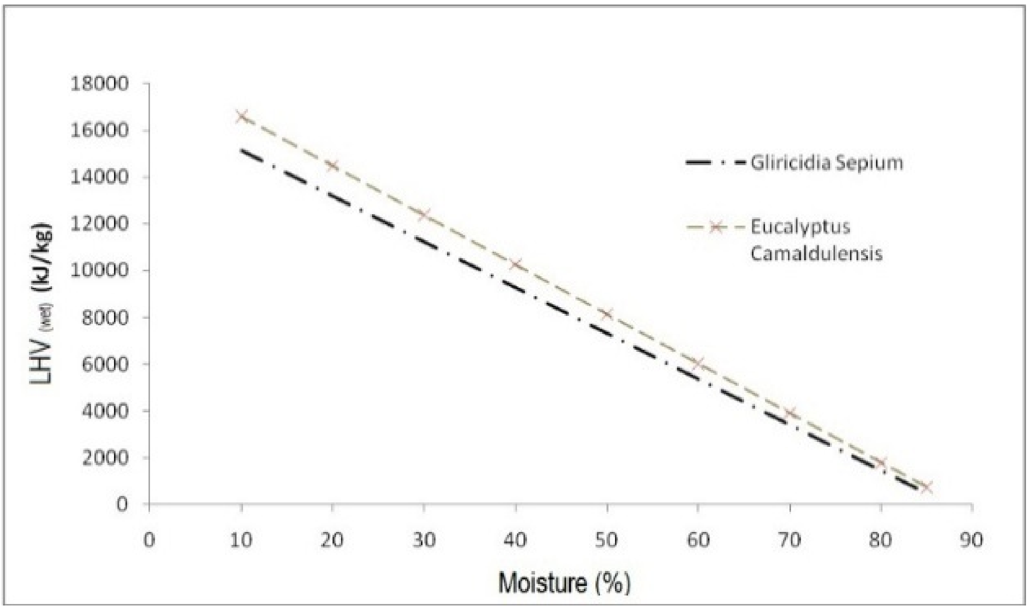

FIGURE 4: Low Heating Value versus moisture content

If "M" ton/year of biomass, 30% wet, is transformed into thermal energy by biomass combustion in the boiler, with thermal efficiency η_{th}, during "t" hours per year, the available thermal power (P_{wet} in MW_{th}) is calculated as follows:

$$P_{wet} = \frac{M(LHV_{wet})}{3600\ t}\ \eta_{th} \tag{4}$$

If the total amount of biomass is 1000 ton/month and the thermal efficiency of the boiler, working 8000 hours/year is 70%, the thermal power P_{wet} becomes 3.40 MW as it can be easily deduced from Table 3.

TABLE 3: Available thermal power from biomass

Forestry biomass	M (ton/month)	M (ton/year)	LHV wet (kJ/kg)	P wet (MW)
Gliricidia Sepium	600	7200	11219.46	2.80
Eucalyptus Camaldulensis	400	4800	12378.72	2.06
Total	1000	12000		3.40

Hence, if water temperature flowing into the boiler changes from 140 to 200°C, then 13.5 kg/s of water flow will obtain sensible heat caused by the available 3.40 MW thermal power.

7. SOLAR ENERGY

The last portion of thermal energy to drive the 3HS+ORC hybrid power plant would be heat gained by water circulating into a concentrated solar power field.

For IEA-ETSAP and IRENA (2013) and Kalogirou, (2009), concentrating solar power (CSP) plants use mirrors to concentrate sunlight onto a receiver, which then collects and transfers the solar energy to a heat transfer fluid that can be used to supply heat to generate electricity through conventional steam turbines. CSP plants can be equipped with a heat storage system for electricity generation at night or when it's cloudy.

There are four CSP variants: Parabolic trough, Fresnel reflector, solar tower and solar dish, which differ depending on the design, configuration of mirrors and receivers, heat transfer fluid used and whether or not heat storage is involved (Kalogirou, 2009 and Chen, 2011). Despite of the parabolic trough which is commercially the most developed technology, the solar tower mode with a heat storage system seems to be appropriate to deploy in the San Vicente area mainly because of its adaptability to non-flat terrain, neglected thermal losses, ability to operate at high pressure to heat water and its cost will be competitive by the years 2020-2025 to the conventional power plants.

The solar tower configuration, shown in Figure 5, is estimated to consist of 400 heliostats deployed in a circular shape to optimize 1 km^2 land size. Because of the terrain topography, the southern semicircle of the solar field will have more heliostats than the northern semicircle. Thus, considering 12m x10m per heliostat size, the total aperture area will be 48,000 m^2. Each heliostat will track the sun along the azimuthal and elevation solar position, resulting on continuous solar concentration.

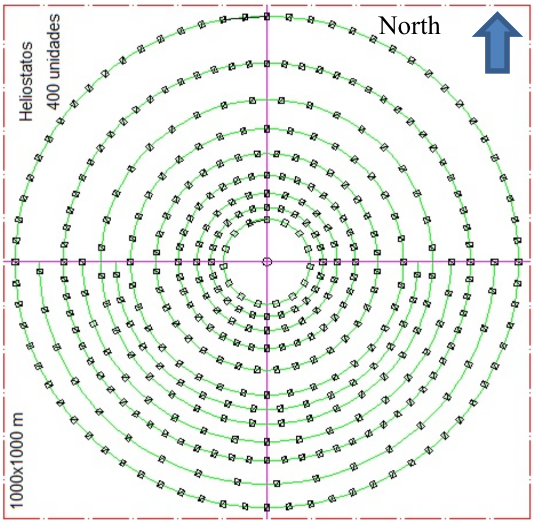

FIGURE 5: Heliostat solar field

At 100 m height, above the center of the heliostat circle, a tubular cylinder type boiler will receive concentrated sunlight to heat deionized water. This boiler or heat receiver should be installed next to the 3HS+ORC hybrid power plant to reduce energy consumption when pumping hot water to the heat exchanger of the hybrid power plant.

The lower elevation land to the north of the San Vicente geothermal production wells could have an annual global irradiation, characteristic of the world solar belt, which according to LaGeo solar monitoring in "15 de Septiembre" hydropower dump, is almost 2000 KWh/m^2.year equivalent to 5.0 to 5.5 kWh/m2 day.

If design irradiance is taken as 800 W/m^2 during 7 hours/day and solar field global efficiency is 44%, the solar power input would reach almost 38 MW and the water flowing into the receiver would gain approximately 17 MWth. These quantities are summarized in Table 4.

TABLE 4: Thermal power from the solar field

Solar power input, efficiency and thermal power output	**Value**
Solar irradiance (W/m^2)	800
Solar power input (MW)	38.4
Solar field global efficiency	44%
Thermal power absorbed by water (MW)	16.9

Therefore, if the working pressure in the receiver is 20 bar-g, the water mass flow that changes temperature from 140 to 200ºC when it has absorbed 17 MWth, results on about 68 kg/s.

8. INTEGRATING THREE HEAT SOURCES AND THE ORC CYCLE (3HS+ORC)

From the three previous analysis, the available water mass flow in the hot water/isopentane heat exchanger is around 243 Kg/s, which is the result of 162 kg/s separated geothermal water at 180ºC/10 bar, 13 kg/s biomass at 200ºC/20 bar and 68 kg/s thermosolar at 200ºC/20 bar.

Because of heat and pressure losses along the hot water transportation, the 243 kg/s hot water side of the water/isopentane heat exchanger would flow at least at 10 bar and 180ºC, respectively.

Figure 6 shows a linear correlation (Estevez (2012) among ORC turbine gross power output and both geothermal water at 184ºC and isopentane mass flow rates. This linear tendency matches data for a 9 MW binary cycle power plant installed in the Berlin geothermal field.

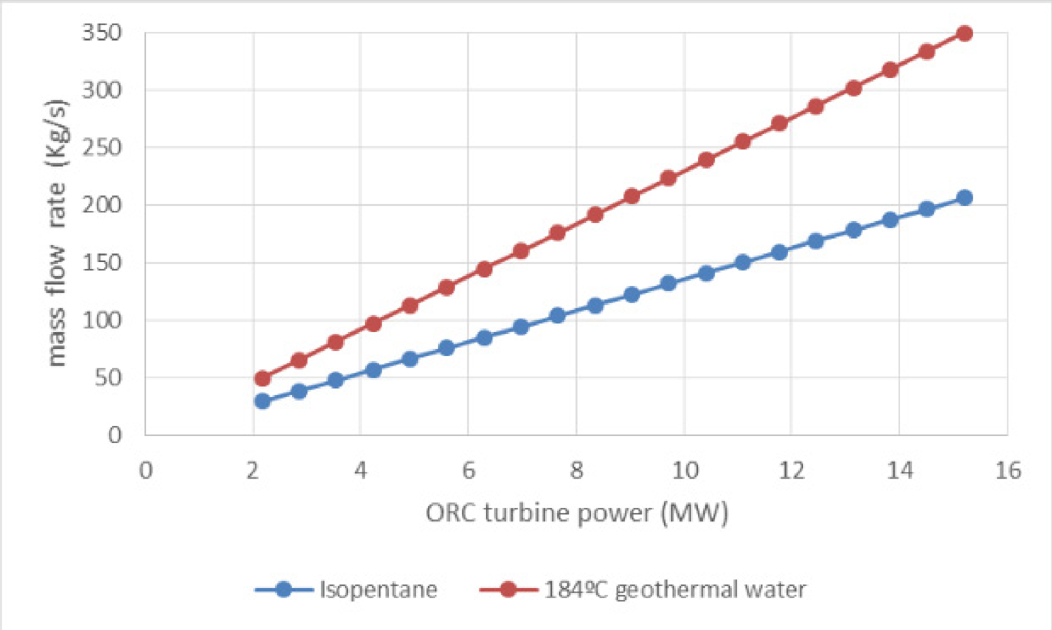

FIGURE 6: ORC turbine gross power output versus mass flow rates (Estevez, 2012)

If that approach is conservatively applied not to the available 243 kg/s but to 231 kg/s hot water at 180ºC, results presented in Table 5 come close to 10 MWe install capacity.

The geothermal hot water flow ensures the highest contribution to the 10 MW ORC gross electrical power, hence, the geothermal portion should be taken as basis source of energy while the rest sources should be on line according they are either naturally available or stored in the synthetic oil, which conveniently can be use later to generate electricity.

TABLE 5: Water flow and heat source breakdown for 10 MWe 3HS+ORC hybrid power plant

Heat source (3HC)	Water flow (kg/s)	ORC power (MWe)
Geothermal	158	6.9
Solar	63	2.7
Biomass	10	0.4
Total	231	10.0

The breakdown heat source contribution to generate 10 MWe during sunny and cloudy days is outlined in Figure 7. For days with clear sky or dry season, input thermal energy from 7 to 17 hours will be of the three types of resources, utilizing them for electrical generation and stored heat in the synthetic oil tank. During cloud coverage or wet season, the solar irradiance decreases partially or totally allowing the biomass boiler balances the reduction of hot water mass flow. In both scenarios, from 17 to 21 hours, sensible heat stored in the synthetic oil will be released to supply heat to hot water/isopentane heat exchanger. The subsequent 10 hours, the 3HC + ORC hybrid power plant will operates to very low demand.

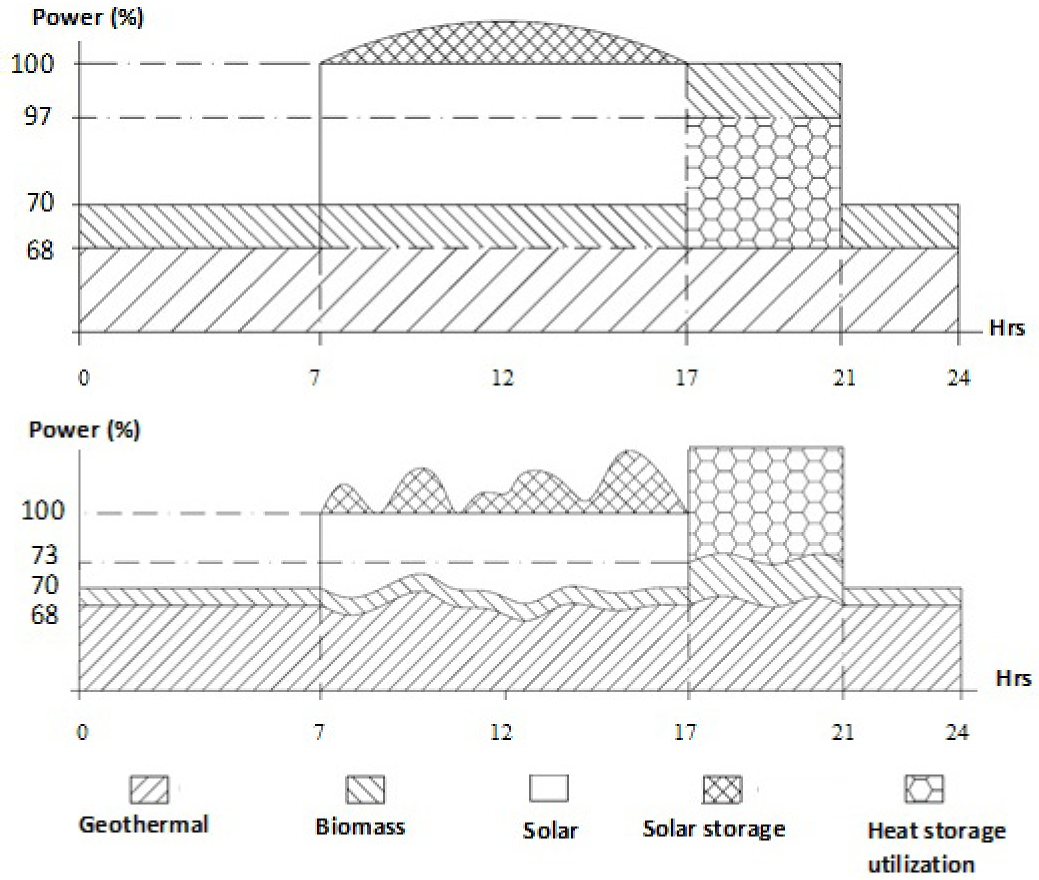

FIGURE 7: Heat sources input breakdown for 10 MWe ORC gross power generation.
On the top sunny days and below cloudy days.

9. HIGHLIGHTS

It seems that the 3HS + ORC hybrid electrical power plant conceptual approach offers an alternative to take advantage of the coexistence in a particular area of geothermal, solar and biomass energy renewable resources. Nevertheless, site solar monitoring, direct lab measurement of biomass heat content and determining available geothermal power should be completed to demonstrate whether or not the project is viable to be implemented by 2020-2030.

The thermodynamic conditions needed to drive the ORC hybrid electrical power plant can be those of either separated hot geothermal water from flash geothermal fields or hot geothermal water from low to medium temperature geothermal wells. In any case, scaling chemical potential studies should be included to define the optimum temperature to cool down the geothermal water.

Solar energy concentration and biomass combustion are well known methods to produce hot water or steam at thermodynamic conditions to drive any Rankine cycle and so they can be used for running the 3HS + ORC hybrid electrical power plant concept.

It seems that San Vicente geothermal area is suitable to develop at least 10 MWe of the 3HS + ORC hybrid electrical power plant type. That electrical power could be higher because:

a) Separated hot geothermal water mass flow could be increased if the flash geothermal plant becomes larger than 27 MWe;
b) Hot water mass flow from biomass combustion could be larger if a forest of Gliricidia Sepium (locally known as Madre Cacao) or Eucalyptus Camaldulensis can be planted in nearby zones to exceed 1000 ton/month of biomass feedstock; and
c) Additional plantation of biomass near the San Vicente geothermal field with similar or higher heat content than the Gliricidia Sepium or Eucaliptus Camaldulensis could exist there to increase hot water mass flow.

Design of the solar field still needs a topographic, soil property, ground water, geological risk and environmental studies to optimize civil works, risk management and water supply for thermosolar field and biomass boiler.

The logistics of transport, chips manufacturing, dry process and other costs need to be studied to determine biomass feasibility.

REFERENCES

Alvarenga, Y., Handal, S., and Recinos, M., 2008: Solar steam booster in the Ahuachapán geothermal field. *Geothermal Resources Council Transactions, 32*, 395-400. Web: http://pubs.geothermal-library. org/lib/grc/1028355.pdf

Bridwater, A., 1996: Thermal Biomass Conversion and Utilization – Biomass Information System. Energy and Research Group, University of Aston, Birmingham, United Kingdom, 185 pp.

Chen, C.J., 2011: Physics of solar energy. John Wiley & Sons Inc., Hoboken, NJ, United States, 352 pp.

Estévez, J.R., 2012: Geothermal power plant projects in Central America: Technical and financial feasibility model assessment. University of Iceland, School of Engineering and Natural Sciences, MSc thesis, UNU-GTP, report 4, 76 pp. Web: http://www.os.is/gogn/unu-gtp-report/UNU-GTP-2012-04.pdf

Handal, S., and Alvarenga, Y., 2010: Thermosolar power from geothermal fluids in El Salvador geothermal fields. Renewable Energy Conference, Yokohama.

IEA-ETSAP and IRENA, 2013: Concentrating solar power. International Energy Agency Energy Technology Systems Analysis Programme and International Renewable Energy Agency, 32 pp.

Kalogirou, S.A., 2009: Solar Energy Engineering: Processes and Systems. Elsevier Inc., Academic Press, Burlington, MA, United States, 744 pp.

Nogués, F.S., Galindo, D.G., and Rezeau, A., 2010: Energía de la biomasa. Volumen I. Prensa Universitaria de Zaragoza.

Sarmiento, Z., and Steingrímsson, B., 2011: Resource assessment I: Introduction and volumetric assessment. Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants, organized by UNU-GTP and LaGeo in Santa Tecla, El Salvador, 15 pp. Web: http://www.os.is/ gogn/unu-gtp-sc/UNU-GTP-SC-12-28.pdf

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GEOTHERMAL DIRECT APPLICATIONS IN CENTRAL AMERICA AND MEXICO

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ABSTRACT

Central America and Mexico are rich in geothermal resources; however, only a small portion has been developed for electricity generation and few for direct applications. Worldwide direct applications use medium and low temperature geothermal resources, which are abundant in the region, to supply the heat required in several processes.

This paper is a review of direct application of geothermal energy in Central America and Mexico. In general, the main uses are thermal swimming pools for local tourism, which utilizes natural discharge of hot water.

1. INTRODUCTION

Countries with geothermal reservoirs use the heat of the hydrothermal fluids for power generation, as well as for direct application. High enthalpy reservoirs with temperatures above 150°C are used for power generation, where the process consists of separating the mixture of fluids in the surface by means of a cyclone separator; the steam then goes to the turbine for electricity generation, while the hot water has three different options: production of steam at low pressure in a flasher process, utilization of heat for a binary plant, and the hot reinjection (DiPippo, 2005).

Medium to low temperature geothermal resources (below 150°C) are mostly used for direct application, where several studies have been carried out. The Lindal Diagram (Figure 1) shows a large number of uses of heat over a temperature range of 20 - 200 °C, for example space heating, agribusiness processes, and others (Armstead, 1983). Waste fluids from the power plant (steam, hot water and condensate) have a residual energy ("heat"), which could be used in direct application.

2. GEOTHEMAL DIRECT APPLICATION

High temperature geothermal resources for electricity production are few compared with medium and low temperature resources, which brought about many applications for direct use.

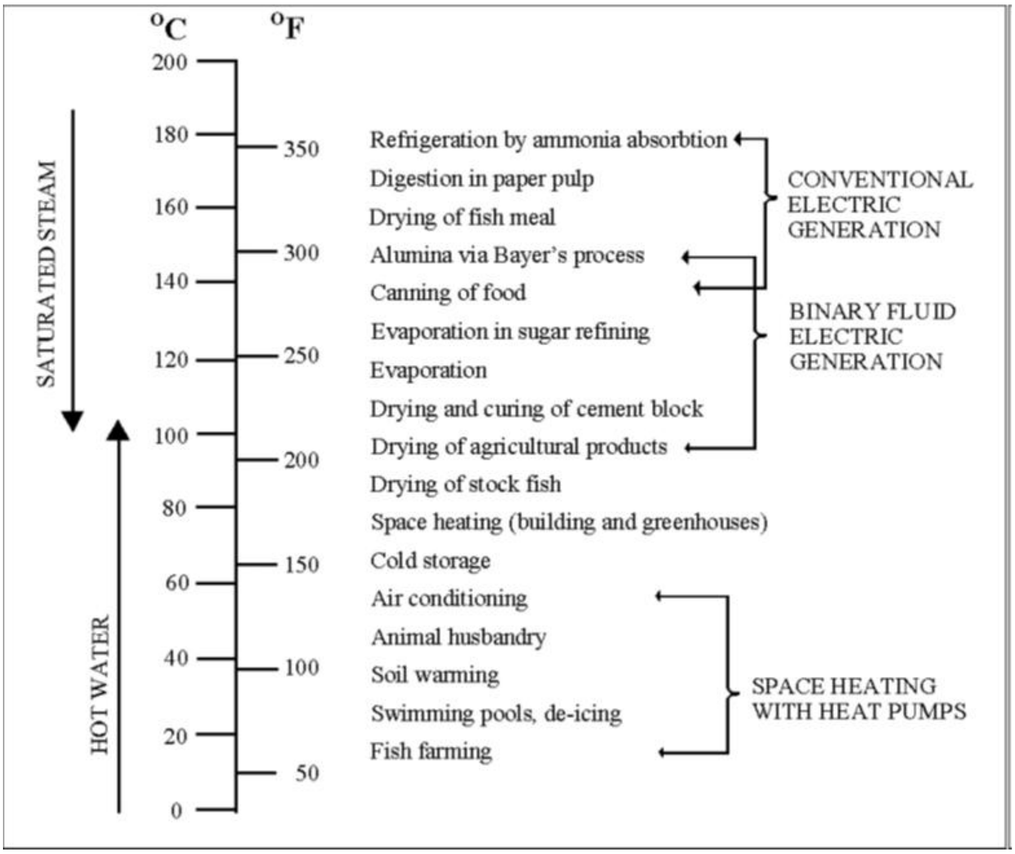

FIGURE 1: Lindal diagram with approximate temperature requirements of geothermal fluids for various applications (Armstead, 1983)

Direct application or direct use of geothermal resources consists of the utilization of the heat in the extracted fluid from the reservoir ("heat source"), or the energy stored in subsurface ("thermal energy storage") (Norden, 2011). It can be divided in four categories (Armstead, 1983):

- Space heating and cooling (hot water supplies, geothermal heat pumps, etc.);
- Agribusiness applications (greenhouse, aquaculture, drying fruit and vegetables, etc.);
- Industry processes (evaporation and crystallization processes, drying of timber, pasteurizing milk, pulp and paper processing, etc.);
- Miscellaneous applications (swimming pools, bathing and balneology, scenic attractions, snow melting, etc.).

3. EQUIPMENT REQUIRED

The process consists of the extraction of the hot fluid to the surface, where it passes into a heat exchanger for heating a secondary fluid, which is used in the main process. The reason for that is to avoid salt deposits or corrosion in the main process equipment.

Direct use systems (Figure 2) are typically composed of three main components (USDOE-OGT, 1998):

- A production well to bring the hot water to the surface;
- A mechanical system (piping, heat exchanger, controls, etc.) to deliver the heat in the process;
- A disposal system (injection well, storage pond or river) to receive the cooled geothermal fluid.

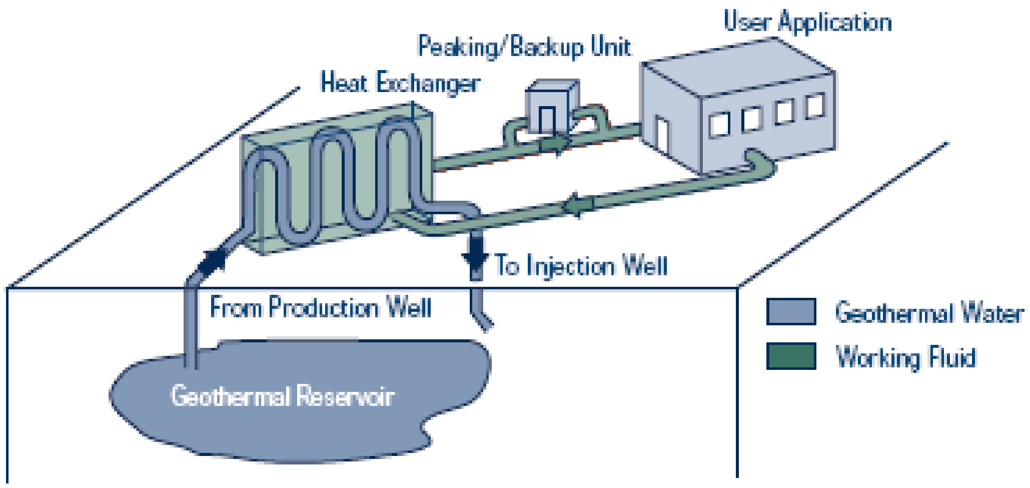

FIGURE 2: Direct use systems main components (USDOE-OGT, 1998)

With respect to the heat exchanger (Figure 3), shell and tube heat exchanger or a plate heat exchanger could be used, depending on the mass and energy requirements of each process (Norden, 2011).

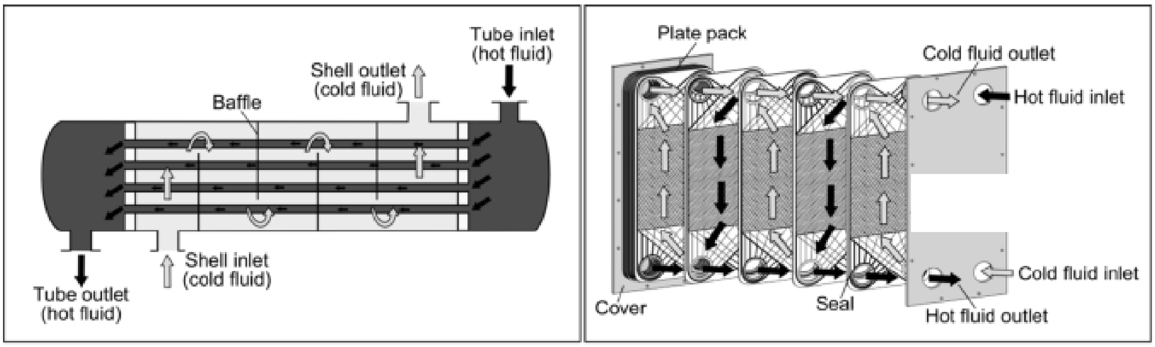

FIGURE 3: Illustration of a shell-and-tube heat exchanger (left) and a plate heat exchanger (right).

If the production well cannot discharge on surface, a submersible pump (Figure 4) could be used to extract the hot water, or a downhole heat exchanger to extract heat by means of a secondary fluid. The basic design is a U-tube as shown in Figure 5.

4. GEOTHERMAL HEAT PUMP

Geothermal heat pumps are very popular and widely used, mainly in cold countries, where it uses the thermal energy stored in the underground for heating and cooling space. In colder weather, the pump uses the earth as a heat source, and in hotter temps, it can actually pump heat into the ground (essentially creating a heat sink in the ground under the house or building).

A heat exchanger into the underground is used in a closed loop (horizontal or vertical, Figure 6), and for that reason, the geothermal heat pumps are sometimes called "geoexchange systems" or "ground source heat pumps".

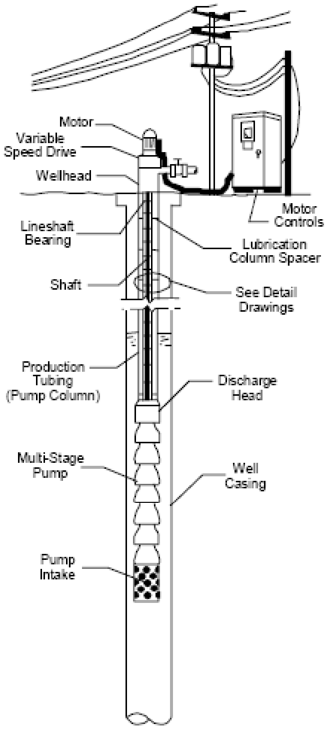

FIGURE 4: Submersible pumps into production well (Lund, 2003)

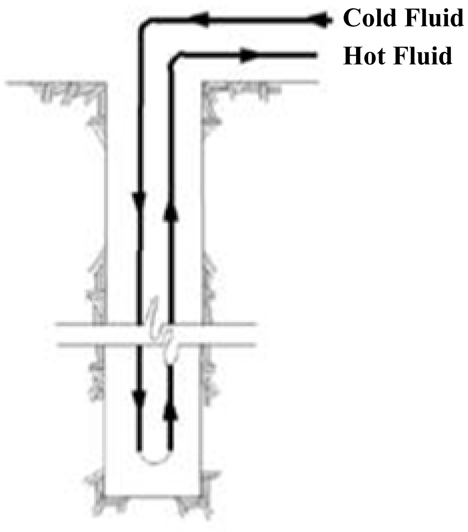

FIGURE 5: Down hole heat exchanger into production well (Modified from Culver and Lund, 1999)

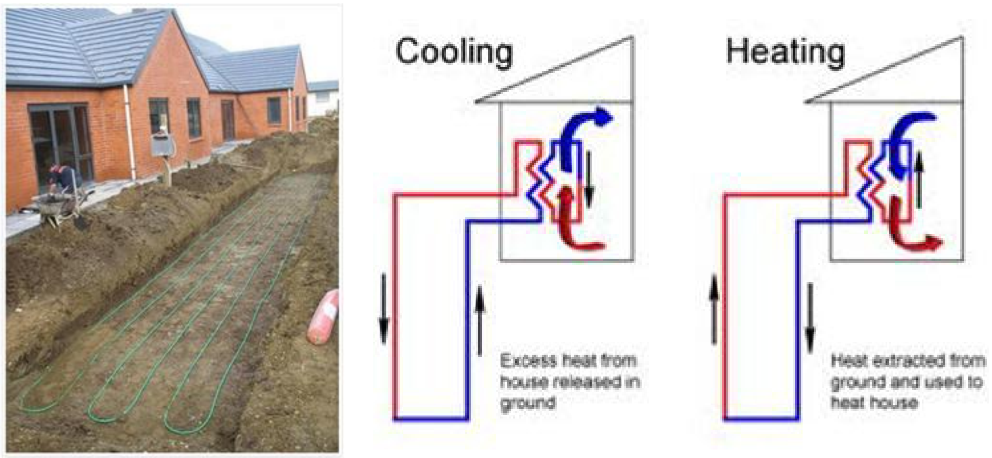

FIGURE 6: Geothermal heat pump cooling and heating process
(Picture from http://www.geothermalheatingandcoolingreview.com/geothermal-heat-pump)

5. ABSORPTION REFRIGERATION SYSTEMS

Besides using the heat for space heating or industrial processes, geothermal energy can also be used for providing low temperature heat needed for refrigeration called "Absorption Refrigeration Systems", which uses a mixture consisting of a refrigerant and an absorbent as working fluid in a system with an evaporator, a condenser, a generator, an absorber, a solution heat exchanger, a solution pump and throttling valves (Rafferty, 1998).

Absorption systems are commercially available today in two basic configurations. For applications above 32°F (mainly air conditioning), the cycle uses lithium bromide as the absorbent and water as the refrigerant. For applications below 32°F, an ammonia/water cycle is employed with ammonia as the refrigerant and water as the absorbent.

Figure 7 shows a diagram of a typical lithium bromide/water machine (Li Br/H2O). The process occurs in two vessels or shells. The upper shell contains the generator and condenser; the lower shell, the absorber and evaporator.

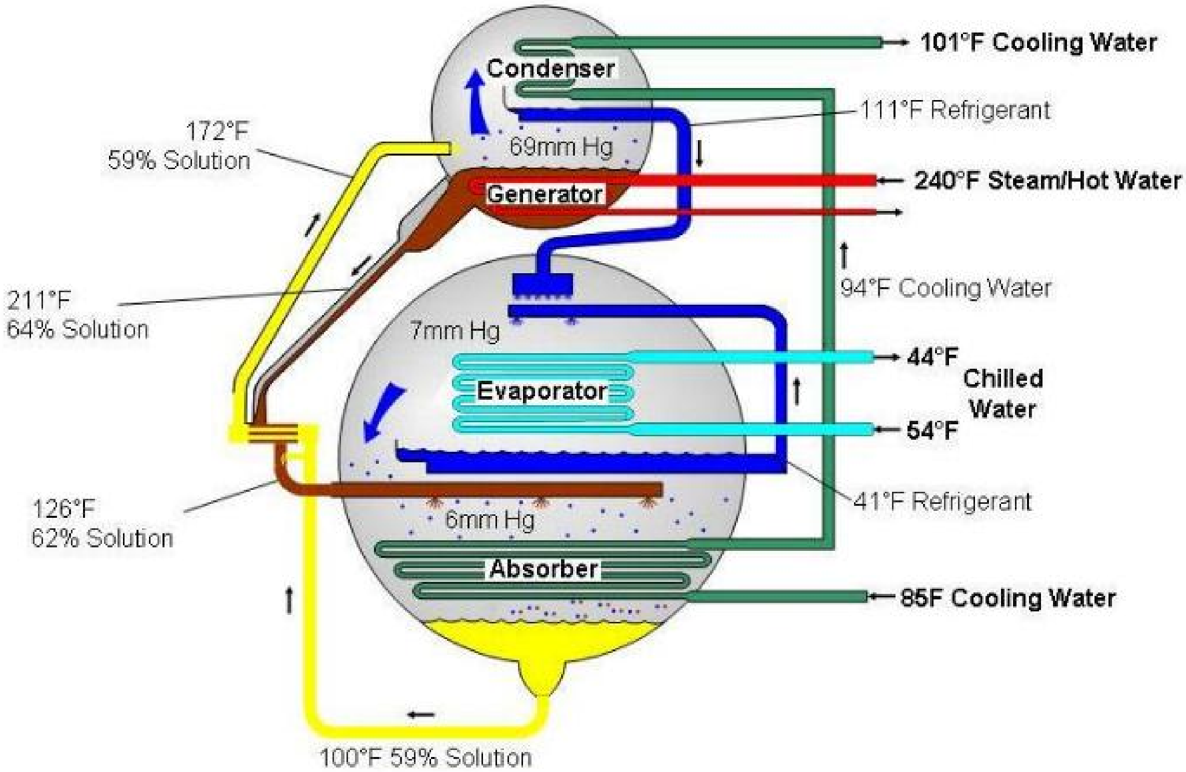

FIGURE 7: Diagram of a typical lithium bromide/water absorption refrigeration system, Li Br/H2O. (Picture from http://www.gasairconditioning.org).

Heat supplied (steam or hot water) in the generator section is added to a solution of Li Br/H2O. This heat causes the refrigerant, in this case is water, to be boiled out of the solution in a distillation process. The water vapor then passes into the condenser section where a cooling medium is used to condense the vapor back to a liquid state. The water then flows down to the evaporator section where it passes over tubes containing the fluid to be cooled, which is passed to the refrigeration application.

6. WORLDWIDE DIRECT USE OF GEOTHERMAL ENERGY IN 2010

In the worldwide direct applications review of geothermal energy in 2010, it shows that 71% was used for heating processes (49% for heat pumps, 14% for space heating, 8% for agriculture process), 25% for balneology, 2.7% for industrial uses and less than 1% for other processes, as presented in Figure 8.

Table 1 shows the major countries with the largest direct applications of the geothermal resources in 2010, having a total capacity of 40,000 MWt and Annual Use of 317,000 TJ/yr.

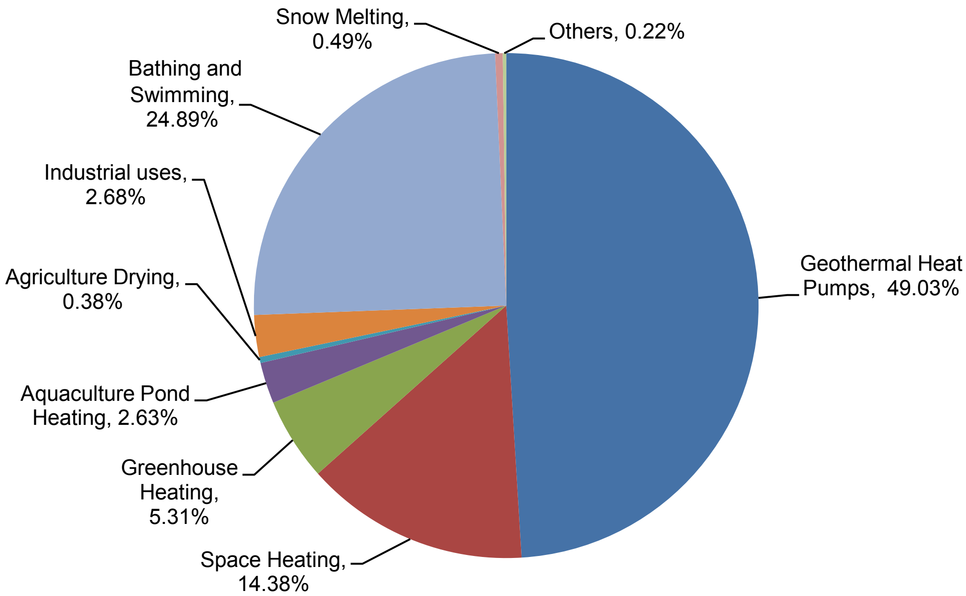

FIGURE 8: Worldwide direct use of Geothermal Energy in 2010
(Modified from Lund et al, 2010)

TABLE 1: Countries with largest direct applications in 2010
(Modified from Lund et al, 2010)

No.	Country	Capacity (MWt)	Annual use (TJ/yr)
1	United States	12,611	56,552
2	China	8,898	75,348
3	Sweden	4,460	45,301
4	Germany	2,485	12,765
5	Japan	2,100	15,698
6	Turkey	2,084	36,886
7	Iceland	1,826	24,361
8	Netherlands	1,410	10,699
9	France	1,345	12,929
10	Canada	1,126	8,873
11	Switzerland	1,061	7,715
12	New Zealand	393	9,552
Total		**39,799**	**316,679**

Table 2 shows several categories of direct application from geothermal energy in 2010 (TJ/yr) for some reference countries: United States and China due to their greater capacity, Iceland and New Zealand for the abundance of geothermal resource.

China and the United States have a wide application of geothermal heat pumps for space conditioning (heating and cooling); Iceland has the biggest district heating in the world, supplying hot water to more than 90% of its population, and New Zealand has the biggest industrial uses, applying geothermal steam for pulp and paper processing, as well as the drying of wood.

TABLE 2: Summary of the various categories of direct applications in 2010
(Modified from Lund et al, 2010)

Annual use (TJ/yr)	2010	China	United States	Iceland	New Zealand
Geothermal heat pumps	214,782	29,035	47,400	20	39
Space heating	62,984	14,799	2,134	17,483	181
Greenhouse heating	23,264	1,688	800	677	379
Aquaculture pond heating	11,521	2,171	3,074	1,835	273
Agriculture drying	1,662	1,038	292		
Industrial uses	11,746	2,733	227	1,642	6,104
Bathing and swimming	109,032	23,886	2,558	1,256	1,733
Snow melting	2,126		20	1,448	
Others	956		48		843
Total	**438,073**	**75,348**	**56,552**	**2,4361**	**9,552**

7. CENTRAL AMERICA AND MEXICO'S DIRECT USE OF GEOTHERMAL ENERGY

Central America, as considered in this paper, consists of six countries: Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama, all of which have its electricity grid interconnected (SIEPAC).

Central American countries, including México, have abundant geothermal resources, both high and low temperature, due to its geographic location along the Pacific Ring of Fire. The institutional strategies of each country have focused more in the exploration and exploitation of high enthalpy geothermal resource for electricity production.

Very few have been done to the direct application of geothermal resources, limited to technical feasibility studies (for drying fruits, vegetables, etc.). However, there are some individual investments planning to develop small project for tourism attraction, mainly in thermal swimming pool, for uses of the natural discharge of hot water.

Central America has a warm and tropical climate, limiting the implementation of heating systems (for houses or buildings) or greenhouses, and focusing more in agro-industrial processes and other applications.

The installed thermal capacity (MWt) and annual use (TJ/yr) of geothermal energy in the Central American countries and México in 2010 is shown in Table 3, where 98% has been used in balneology and swimming pool. Mexico has exploited this resource by the abundance of hot springs along its territory.

Guatemala, through BLOTECA company, had industries application of geothermal resource by using geothermal steam for curing concrete blocks for more than ten years. At present, the facility is abandoned and production wells are drilled for installation of a new geothermal power plant ("El Ceibillo", Batres, 2012).

8. COUNTRY REVIEWS

8.1 Mexico

The "Comisión Federal de Electricidad" (CFE) has developed some studies for direct uses of geothermal resources in Los Azufres geothermal field, including a wood-dryer, a fruit and vegetables dehydrator, greenhouse and a system for heating its offices and facilities in this field.

TABLE 3: Summary of the thermal capacity (MWt) and annual use (TJ/yr) in Central American and México, 2010. (Modified from Lund et al, 2010)

			Annual use (TJ/yr)						
No.	**Country**	**Capacity (MWt)**	**Bathing & swimming**	**Agri-culture drying**	**Green-house heating**	**Fish farming**	**Space heating**	**Industrial uses**	**Total**
1	México	155.82	4,018.23	0.10	0.06		4.40		4,022.79
2	Guatemala	2.31	3.96	12.10				40.40	56.46
3	El Salvador	2.00		20.00	10.00	10.00			40.00
4	Costa Rica	1.00	21.00						21.00
5	Honduras	1.93	45.00						45.00
6	Nicaragua	??							??
7	Panamá	??							??
Total		**163.06**	**4,088.19**	**32.20**	**10.06**	**10.00**	**4.40**	**40.40**	**4,185.25**

Along the country, several thermal areas have been identified for direct uses, mainly for thermal swimming pool. There are 20 facilities with recreational purposes and some locations with therapeutic uses, like Manantiales de Taxidho, Arenal, Balneario Gandho, Grutas de Tolantongo, and others. Almost all of the resorts have been developed and operated by private investors, yet there are isolated facilities operated by federal, state or municipal government.

In the last two years, 96 geysers were found in the Maguarichi thermal area, in Chihuahua. The average temperature of the water is between 95 to 98°C (114 °C hottest, up to 4 m height). Since 2001 to 2007, a 200 kW Ormat Binary Power Plant was installed providing electricity to Maguarichi Village. The field has two shallow wells and more than 12 thermal waters. Maguarichi has a great potential to develop many geothermal direct use projects due to the availability of this resource, which gave way for a project for the economic development of the village and its inhabitants, consisting of the use of the two existing shallows wells, the hot water will be used for Chiltepin drying, aquaculture (Tilapia farming), greenhouse, and bathing as shown in the Figure 9 (Arrubarrena and Pelayo, 2012).

8.2 Guatemala

A food dehydration pilot plant was constructed in the Zunil Geothermal Field to demonstrate the use of geothermal energy for industrial applications (Maldonado et al, 1991). The facility was connected though a slim-hole exploratory well. The Los Alamos National Laboratory was responsible for the design of the facility, while the construction was done by INDE (InstitutoNacional de Electrificación),

Industrial uses has been done only in Amatitlán Geothermal Field by two private companies: the first one was BLOTECA, a construction block factory established about 20 years ago, which uses geothermal steam for more than 10 years in the curing process of concrete products. At present the

facilities are abandoned. The other one is Agroindustrias La Laguna, a fruit dehydration plant, built to use the heat from a geothermal well in the drying process by means of a down hole heat exchanger. The company produces dehydrated fruit by the trade name Eco-Fruit. The drying fruit produced are pineapple, mango, banana, apple and pears (Merida, 1995).
There are many thermal swimming pools and spas in Quetzaltenango (example "Las Georginas") and Amatitlán using natural discharge of hot water, mainly for tourism attraction.

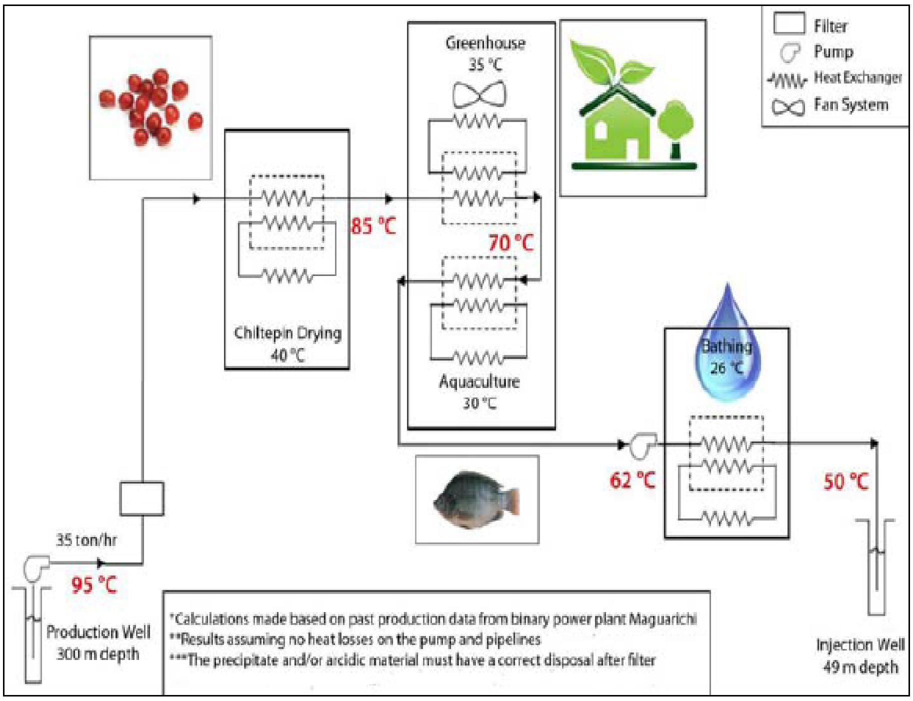

FIGURE 9: Diagram for direct uses in Maguarichi Area, México (Arrubarrena and Pelayo, 2012).

8.3 El Salvador

Studies of direct uses for drying fruit started in Ahuachapán Geothermal Field in 2003. A pilot plant was built in Berlin Geothermal Field because the temperature in the pipe system is higher than Ahuachapán. Recently, all direct applications are operated by FundaGeo, and the total production is for local consumption.

The Ahuachapán Geothermal Field has some applications of geothermal resources like a "steam room" or "sauna" for relaxation, using fresh water which passes into horizontal heat exchanger (installed over the wellhead AH-8) for steam production. Condensate water from the cooling tower is used for irrigation at the yards of the power plant and the geothermal field during summer. It is also used for Horticulture (growing tomatoes, radish and lettuce), the total production is for local consumption.

The Berlín Geothermal Field has some direct applications of geothermal resources like a drying fruit Pilot Plant, a Geo Tourist Park, where it has a restaurant, several "bungalows", cold swimming pool and a "steam room" (**Note:** the hot water and the steam coming from fresh water is heated in horizontal heat exchanger (4 m long) located along of the separated water pipe). Condensate water from the cooling tower is used for irrigation at the yards of the power plant and the geothermal field during summer. It is also used for Aquaculture (Tilapia Farming), the total production is for local consumption.

There is a few public and private investment for the use of natural discharge of hot water for thermal swimming pools, mainly for local tourism, like Aguas termales de Santa Teresa, Aguas termales Alicante, Termos del Río and others.

“Los Infiernillos” was a tourist park located in the flanks of Chinchontepec Volcano. It had a restaurant, some thermal swimming pools, paths for visiting the fumaroles, etc., however it was destroyed in November 2010 by Tropical Storm Ida (Duran, 2009).

8.4 Costa Rica

Various studies have been completed in Miravalles Geothermal Field for drying fruit and vegetables by means of the discharge of water from the power plant, where a pilot plant is planned to be constructed (Mainieri, 2010). Direct use of geothermal resource is limited to mountain hotel pools for ecological tourism like Tabacón, which is a luxury resort/spa built on the flanks of Arenal Volcano, and where warm and cold water springs merge.

8.5 Honduras

Honduras will develop its first geothermal power plant in Platanares Geothermal Field. In direct applications, a number of thermal pools is reported (for example Tamara, Gracias 1 y Gracias 2) for tourism attraction, which will be heated by natural discharge of geothermal water.

8.6 Nicaragua

The geothermal resources in the country have been developed for electric power generation (Momotombo, San Jacinto Tizate). In direct applications, a few thermal swimming pools are reported (for example: aguas termales de Tipitapa, aguas Claras) for tourism attraction, which are heated by natural discharge of geothermal water.

8.7 Panama

Studies have been conducted to identify high temperature reservoir for electric generation; there are four areas with high potential (SENACYT, 2002). A few thermal pools are reported for tourism attraction (for example: Aguas Termales in Valle de Anton), which are heated by natural discharge of geothermal water.

9. REMARKS

There is a wide range of direct applications of geothermal resource around the world. It has the technology and knowledge to use the heat from the fluid; the limiting factor is the *availability* of the resource and not the *applicability*.

Central American and Mexico are rich in geothermal resources, however only a small portion has been developed for electricity generation and few for direct applications, mainly on thermal swimming pools for local tourism.

The region has a warm and tropical climate, limiting the implementation of heating systems (for houses or buildings) or greenhouses, focusing more in agro-industrial processes and other applications.

The use of heat from geothermal fluid for direct applications could help the industrial process in the reduction of burning fuel for steam production.

The main strength of the geothermal resources is that the heat is 24 hours accessible for 7 days a week and is cheaper in relation to other energies.

Non-production wells and hot reinjection systems in the geothermal field could be used for direct applications.

The advantages of geothermal energy and its direct applications to develop new projects that will contribute to economic development of the country should be presented to the industrial market.

Any direct applications business using geothermal energy could provide job creation and economic benefits to local communities.

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REFERENCES

Armstead, H.C., 1983: *Geothermal energy: Its past, present, and future contributions to the energy needs of man* (second edition). E. & F.N. Spon, New York, NY, United States, 404 pp.

Arrubarrena, M., and Pelayo, L., 2012: Potential development zones for geothermal direct uses in Mexico with a specific site recommendation. *GHC Bulletin, 31-2*, 5-8. Web: http://geoheat.oit.edu/bulletin/bull31-2/art2.pdf

Batres, A., 2012: *Generar luz desde el subsuelo*. El Periodico, 3 December 2012. Website: http://www.elperiodico.com.gt/es/20121203/economia/221448

Culver, G. and Lung, J. W., 1999: Downhole Heat Exchangers. *GHC Bulletin September 1999*. Web: http://geoheat.oit.edu/bulletin/bull20-3/art1.pdf

DiPippo, R., 2005: *Geothermal power plants: Principles, applications and case studies*. Elsevier Science, New York, NY, United States, 512 pp.

Duran, J., 2009: *Apertura turicentro el infiernillo*. Chaletvicentino.com. Website: http://chaletvicentino.com/viewtopic.php?f=9&t=2157

Lund, J. W., 2003: Direct heat utilization of geothermal energy. Web: http://oregon.gov/energy/RENEW/Geothermal/docs/directheat03-USA.pdf

Lund, J.W., and Freeston, D.H., and Boyd, T.L., 2010: Direct utilization of geothermal energy 2010 worldwide review. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 23 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0007.pdf

Mainieri, A., 2010: Costa Rica update report. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 6 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0115.pdf

Maldonado, O., Altseimer, J., Cooper, L., Caicedo, A., and Thayer, G.R., 1991: *Geothermal demonstration: Zunil food dehydration facility*. Los Alamos National Laboratory, Los Alamos, NM, United States, report LA-12180-MS / DE 91017467, 52 pp. Web: http://www.osti.gov/scitech/servlets/purl/5493998

Merida, L., 1995: Curing blocks and drying fruit in Guatemala. *GHC Bulletin, 20-4*, 19-22. Web: http:/geoheat.oit.edu/bulletin/bull20-4/art4.pdf

Norden, B. (editor), 2011: *Geothermal energy utilization in low enthalpy sedimentary environments*. Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum, Potsdam, Germany, 116 pp. Web: http://gfzpublic.gfz-potsdam.de/pubman/item/escidoc:23142:5/component/escidoc:23166/1106.pdf%3Bjsessionid=A8C4E770E894C19C1895CF3F673A2BAF

Rafferty, K. D., 1998: Absorption Refrigeration. *GHC Bulletin March 1998*. Web: http://geoheat.oit.edu/bulletin/bull19-1/art6.pdf

SENACYT, 2002: *Geotermia en Panamá*. Proyecto de energía geotérmica GEOFISQUI, 16 pp. Web: http://www.energia.gob.pa/pdf_doc/Geotermia.pdf

USDOE-OGT, 1998: Direct use of geothermal energy, 2 pp. Web: https://www1.eere.energy.gov/geothermal/pdfs/directuse.pdf

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

PHASES OF GEOTHERMAL DEVELOPMENT IN ICELAND: FROM A HOT SPRING TO UTILIZATION

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ABSTRACT

The use of geothermal energy in Iceland was very limited through the centuries and it was not until the beginning of the twentieth century that geothermal started to really contribute to the energy budget in Iceland. The usage has, however, increased dramatically during the last 100 years and today geothermal energy supplies over 85% of the primary energy used in Iceland. The most important use has been for space heating but geothermal power production has increased rapidly during the last fifteen years. Exploration and the development of the geothermal fields are divided into several stages or phases starting with preliminary studies, and continuing with appraisal studies, project design, construction and operation of the geothermal plant, and the final phase of the life cycle of the development is the shutdown and the abandonment of the plant after operation for decades.

1. INTRODUCTION

Iceland is an island in the North Atlantic just south of the Arctic Circle. The island lies across the Mid Atlantic Ridge, the rift zone along the constructive boundary between the American and the Eurasian tectonic plates which move apart at an average rate of 2 cm per year. Iceland resides on a mantle plume and a hot spot in the rift zone and has been formed in frequent volcanic eruptions continually from Miocene time to present. This explains why this part of the ridge rises above sea level and forms an island with an area greater than 100.000 km^2. The presently active zone of rifting and volcanism crosses Iceland from southwest to northeast. Volcanic eruptions are very frequent in this zone and take place typically every few years. The Icelandic crust is therefore very young on the geological time scale and rocks on surface range in age from zero near recently active volcanoes to 15-16 million years in the coastal areas furthest away from the volcanic zone in the east and the west.

Iceland is rich in geothermal resources due to the volcanic activity, and heat flow through the crust is several times higher than the world average. Traditionally the geothermal fields are divided into high-temperature fields, where temperature above 200°C is found at 1 km depth, and low-temperature fields, in which temperature is lower than 150°C in the uppermost kilometre. Some 30 high temperature fields have been identified in Iceland, all within the active volcanic zone as shown in Figure 1. The low temperature activity is highest on the flanks of the volcanic zones but some low temperature resources are found in most parts of the country (Figure 1).

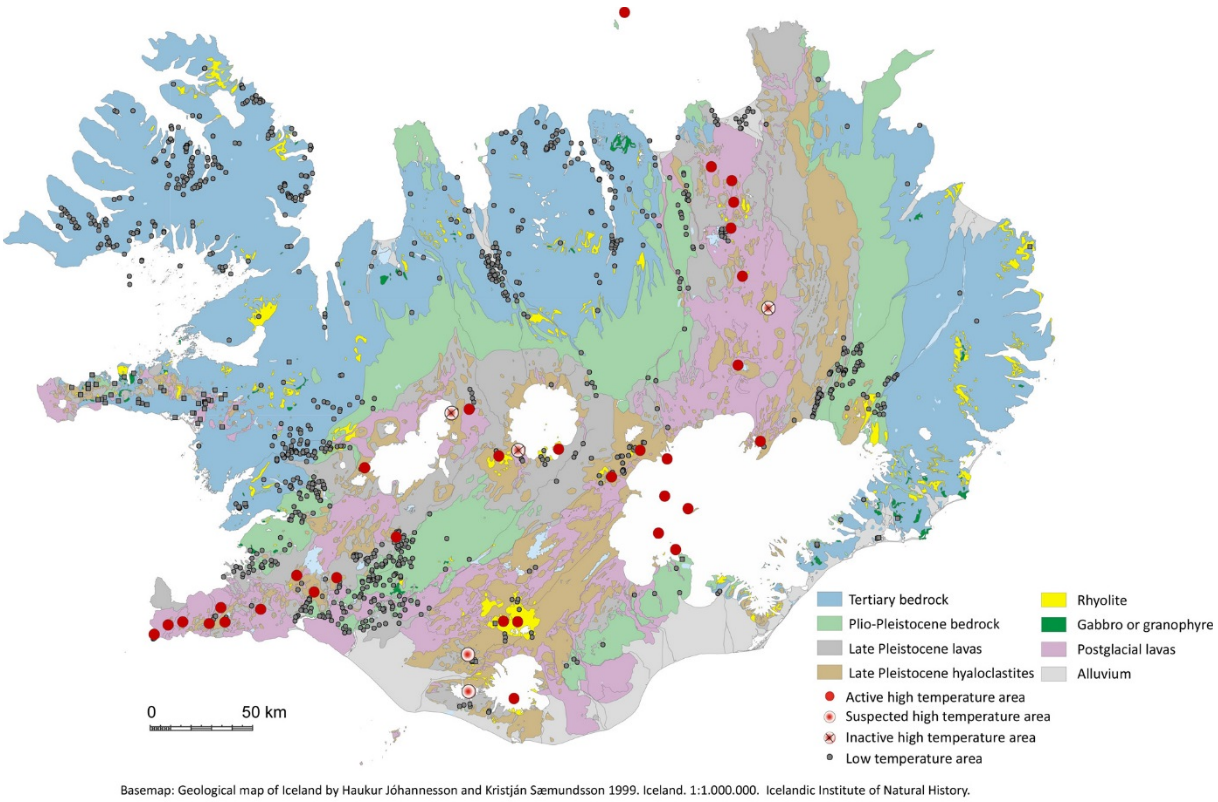

FIGURE 1: Geothermal map of Iceland. High-temperature fields inside the active volcanic zone are shown as red circles, and hot and warm springs as yellow circles

The utilization of the geothermal resources of Iceland was very limited through the centuries. Hot water from warm springs was, however, used locally in some areas for bathing, cooking and washing, and sulphur was mined from a few of the high temperature areas and exported to Denmark. It was, however, not until at the beginning of the last century that utilization of the geothermal resources really started. Initially the geothermal development focused on the utilization of low temperature resources for space heating. Later utilization of the high temperature resources for electrical generation, space heating and some industrial uses followed.

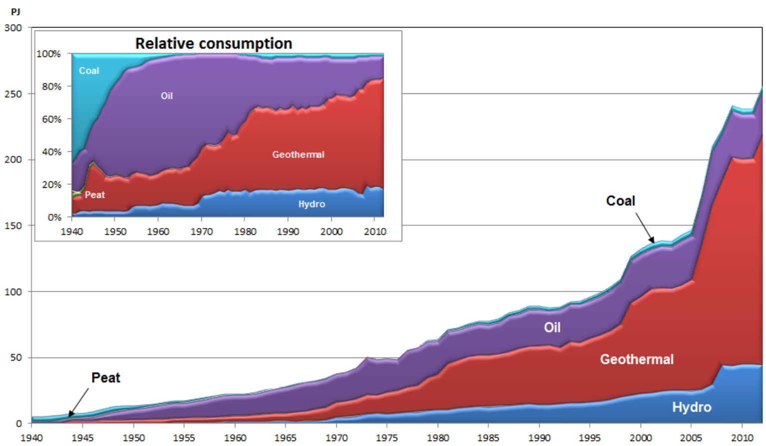

FIGURE 2: Primary energy consumption in Iceland 1940-2007. Source: National Energy Authority

Large scale utilization of geothermal resources in Iceland began in 1930 when a district heating system started operation in Reykjavik (capital of Iceland) supplying hot water to a hospital, a school, a swimming pool, and some 70 homes. The utilization grew gradually over the next decades (Figure 2). During the energy crises in the 1970s an effort was made to exclude use of oil for house heating and replace it with geothermal energy. This was a very successful development and today almost 90% of houses in Iceland are heated by geothermal energy and electricity (generated by hydro and geothermal) serves about 10% the heating market. During the last few decades the geothermal utilization has continued to grow as geothermal power production has increased. The installed geothermal power capacity is at the end of year 2013 was 659 MWe. Geothermal energy has become the main source of energy in Iceland supplying over 85% of the primary energy used in the country (Source: National Energy Authority).

The objective of this paper is to give a general overview of the methodology used in geothermal exploration and development in Iceland. We will do this with a step by step discussion leading through the exploration and the development and grouping the steps into project phases similar to what is done internationally, e.g. in the Philippines (Dolor, 2005), and in Kenya (Mwangi, 2005).

Before we start to describe the phases of geothermal exploration and development we should keep in mind that all human efforts are limited by factors which will determine the success of our endeavour. Some of these factors we can control, others not. For the successful development of geothermal fields the factors that first come into mind are the following: (1) *Market opportunity*: Initial geothermal field studies have the aim of understanding the basic properties of the geothermal fields and have therefore a general knowledge seeking purpose. Utilisation of the field will on the other hand depend on whether there are possible geothermal users for fluid or energy from the fields, i.e. is there a market for the geothermal fluid and the geothermal energy? Several geothermal fields are located close to populated areas and can easily be developed economically. Others are in remote areas, high up in mountains, and in Iceland some of the fields are underneath the ice cap of glaciers (Figure 1). Utilization of such fields is not possible for obvious technical and economical reasons. (2) *Knowledge and technical skills.* The exploration and development of a geothermal resource demands an experienced and skilled team of geothermal specialists, both various kinds of geoscientists and engineers. (3) *Time*: The development of a geothermal field takes several years. The construction of a geothermal power plant takes at least a couple of years and if we add the exploration and drilling period and the time needed for flow tests of wells, environmental impact studies and licensing, a time frame of 6 to 10 years is common. (4) *Financing:* Large geothermal projects are high cost projects. To develop a field for power generation the cost is of the order of 3-6 million US dollars per MW installed, depending on the properties (mainly temperature) of the field being developed. The geothermal developer must therefore have access to a mechanism to finance their projects. (5*) Luck*: Not all the parameters are known when you are evaluating the potential of a geothermal field and the feasibility of a geothermal project. One has therefore to take important decisions from limited information, especially early in the project. Unforeseen events will in addition of course happen during the life time of the project, and some of them can have serious influence on the project. In Iceland we ran into an eruptive period of the Krafla volcano only six months after the construction of the Krafla Geothermal Power Plant started. The eruptions had a serious effect on the geothermal system and changed at least temporally the production characteristics of the field. The eruptions delayed the development of the Krafla field but did not stop the project and the power plant is in full operation today. The Krafla volcano had been dormant for 250 years.

2. STUDIES OF GEOTHERMAL SURFACE MANIFESTATIONS

The exploration and development of a geothermal field leads us through several steps. In the geothermal literature you will find various approaches in defining the steps. The first step in geothermal investigations is usually the studies of the geothermal activity found on the surface in the area under investigation. These manifestations are the first indication or evidence for the existence of a potentially exploitable geothermal resource. The manifestations can be of various types, ranging from active hot springs and fumaroles to hot and steaming grounds and cold but altered grounds indicating extinct geothermal activity on the surface.

The studies of surface manifestations include visual inspection of activity. Photographs are taken with conventional cameras or cameras that sense the infra red radiation of the hot manifestations. Maps are drawn to show the distribution of the manifestations and the soil temperature is measured and mapped. The fluid temperature and flow rate of the hot springs is measured as well as the temperature of the steaming fumaroles. Measurement of the steam flow rate from fumaroles is not easy but indirect (or relative) estimation of the steam flow has been developed and applied in few high temperature areas in Iceland. Historical records of the geothermal activity in the area are collected to evaluate the stability of activity. Fluctuations in the activity are often related to earthquakes and volcanic activity.

The surface activity offers a window to the underlying geothermal system. Sampling of the geothermal fluids from the manifestations and analyses of the samples give indications on the fluid chemistry of the geothermal reservoir and through the application of geothermometers the reservoir temperatures can be estimated from the fluid chemistry. The distribution of the manifestations and the soil heat maps often indicate that the flow path for the upflow of the geothermal fluid to the surface is fracture controlled.

The studies of the surface manifestations and their results are gathered and described in a summary or reconnaissance report. The possibilities of utilizing the field are also described in the report and environmental aspects of utilization schemes are evaluated. The report concludes the first step of the geothermal exploration. Many geothermal fields in the world have only undergone exploration of the surface manifestation. Others have been explored further and several developed for utilization.

3. PHASES OF GEOTHERMALEXPLORATION AND DEVELOPMENT

The methodology and the strategy of the exploration and development of the Icelandic geothermal fields have been under critical discussion and review ever since their utilization started. The strategy adopted for early development was to estimate the power capacity of each field through exploration and drilling, and subsequently to design and construct a power plant with a view to fully utilize the estimated field capacity in a single power development. Later this strategy has been changed to stepwise development where the capacity of the field is tested with a relatively small power unit and later expanded in steps until the full potential of the field is developed.

A generic phase plan was proposed in 1982 for the systematic exploration and development of the Icelandic high-temperature fields (Stefánsson et al., 1982). The plan, which is shown in Figure 3, divides the developments into the following five phases:

3.1 Preliminary study

The preliminary study starts with collection and critical review of existing geological, geophysical and geochemical data available for the area. On the basis of these a detailed multidisciplinary exploration program is defined and executed. The program usually includes various surface exploration methods, i.e. mapping of the geothermal manifestations and measurements of temperature and flow rate to compare with previous information, if available. The geothermal fluids are sampled for chemical analyses and chemical geothermometers are used to estimate reservoir temperatures. The geological studies would include lithological mapping, structural geology, volcanism, hydrogeology, geo-hazards and environmental geology. Geophysical surveys include gravity measurements to determine the density variations of the lithological units, and magnetic measurements to trace faults and dykes. Natural seismicity activity is monitored to reveal active fractures which may act as flow channels within the geothermal reservoir. The most important geophysical method in geothermal exploration is, however, the resistivity surveys. Various resistivity methods are applied including Sclumberger, TEM, CSAMT and MT. The resistivity anomalies are used to outline the probable extent of the geothermal field and define upflow and outflow zones.

The surface exploration concludes with a definition of potential drilling targets. Then a few (often 3–5) exploration wells, 1 to 3 km deep, are drilled at these strategic sites. The main objective with the exploratory drilling is to confirm the existence of a hot resource and prove the productivity of the drilling targets defined from the surface exploration. After successful completion of the exploration drilling, all the information obtained during the preliminary studies are incorporated into a conceptual model of the field and a comprehensive resource assessment carried out. The feasibility of further development of the resource is analysed and presented in a pre-feasibility report.

3.2 Appraisal study

The appraisal study is the next geothermal development phase after a positive conclusion of the preliminary study. It includes drilling of appraisal wells in order to determine production capacity and characteristics of wells and to obtain data to evaluate the reservoir characteristics and to confirm the existence of a productive resource for long-term operation of the planned power development. The reservoir evaluation includes detailed geological reservoir model showing the geological structures, the main lithology units and their hydrothermal alteration within the reservoir. The model should delineate the production zone and the potential injection areas, distribution of productive aquifers, reservoir temperature and pressure distribution, reservoir fluid chemistry as well as reservoir permeability and porosity. The wells are flow tested and measurements carried out to determine the mass (liquid or liquid and/or steam) flow capacity of wells and the average fluid enthalpy. The production decline and pressure drawdown with time are evaluated at least on a short term basis and future changes predicted. Scaling and corrosion potential of the geothermal fluid is also evaluated during the appraisal studies.

The conceptual model of the geothermal field is revised and updated according to the new reservoir data. Based on the conceptual model, a numerical natural state simulation model is developed and calibrated against available field data and production data from the wells. The final part of the appraisal phase is an economic feasibility study of the planned project to estimate the capital and operating cost of power plant.

3.3 Project design and construction

Project design and construction are the next two phases following the appraisal study completion. These phases include, as their names indicate, a detailed design of the project and thereupon the construction of the development and the installation of the plant equipment. Production and injection wells are drilled with the purpose of providing sufficient production and injection capacity for the project. The time is also used for testing of the wells, often several wells at the same time to observe and get quantitative measurements of the short term response of the reservoir to considerable production or production similar to what it will be when the power plant starts operation. The reservoir data obtained during these phases are used to revise existing conceptual and numerical models of the reservoir and make a prognosis for the future response of the reservoir to production. These models are imperial in deciding the production management of the reservoir during the operation of the plant.

3.4 Commissioning and operation

Commissioning and operation are the project's final phases of the generic plan depicted in Figure 3. Successful operation of geothermal projects calls for a comprehensive monitoring and management plan for the utilized geothermal field in order to predict changes that may happen in the reservoir characteristics, well productivity/injectivity and fluid chemistry during long term operation. The management of geothermal resources is discussed in some detail in the next subchapter.

3.5 Shutdown and abandonment

The sixth development phase, *"shutdown and abandonment"*, is often added to the generic plan to complete the life cycle of the development, though not shown in Figure 3. This is the final phase of any geothermal development (Dolor, 2005; Mwangi, 2005).

During exploitation of the geothermal reservoir, the reservoir pressure and the well output normally declines in the long term. The rate of decline depend on the rate of natural recharge of heat and fluid into the reservoir. They can also be controlled to some degree by the production and re-injection strategy and proper reservoir management. In addition to this "depletion" tendency of the reservoir the power plant components and other surface equipment get old and may start failing to an extent that makes it uneconomical in operation. There are a few examples of geothermal power plants that have been abandoned. A few geothermal power plants in the Geyser field in California have been shut down, however, because of the lack of steam due to over-exploitation of the field. This could have been avoided, if the generating capacity of the field had been adequately known prior to the construction of these plants, or realized in time. Other geothermal plants have been partially rebuilt to meet changes in steam characteristics (i.e. steam pressure and gas content), e.g. the Wairakei plant in New Zealand which celebrated its 55th anniversary of operation in November 2013. It is generally accepted that geothermal power plants can be operated for several decades if both the plant and the geothermal field are properly managed and operated.

The generic plan in Figure 3 illustrates the relevance of the main tasks required for each development phase discussed above. Also shown in the figure is a rough relative estimate of the associated exploration and development cost. It clearly indicates that the relative cost of the preliminary studies is small, but escalates when production drilling and construction of the project starts. Figure 3 also gives an estimate of the timeframe for the development. According to the figure, it takes ten years of exploration and drilling before a decision to construct the plant is taken and a total of 13 years from the start of the project until the plant is finally commissioned and starts operation.

4. STEPWISE DEVELOPMENT STRATEGY

The development strategy described above assumes that the production potential of the geothermal field is known prior to the decision on utilization. A generating capacity of the power plant is subsequently decided to fully match the field potential. The above described strategy is probably borrowed from hydropower development in Iceland, for which the determination of production capacity is rather easy and is known at a relatively early stage in the exploration phase. This does, however, not apply to geothermal areas where reliable knowledge on the maximum generating capacity can only be obtained through an extensive exploration, research and well testing as detailed above.

Stefánsson (1992) discussed several examples of geothermal projects worldwide and pointed out that a stepwise development strategy for geothermal resources has considerable economical benefits compared to full utilization of the geothermal filed in one big step. By following the generic plan in Figure 3 but selecting a relatively small (20–50 MW) power unit as a first step, the time scale can be reduced and the first unit commissioned and put into operation much earlier than is possible for a "full" size plant. Monitoring of the field's response to the first development step is then used to determine if and when the next step can be undertaken, a new power unit (20-50 MW) installed and so on until the full potential of the reservoir is utilized. One can say that in the stepwise strategy the resource's sustainable generating capacity is first known when the field is fully utilized, whereas in the one step strategy the production capacity is determined (and not necessarily on basis of sustainability) before the power plant is built. A comparison of these two strategies is shown in Figures 3 and 4.

The Icelandic energy companies have been applying the stepwise development approach in their latest developments, but their approach has been more aggressive than initially assumed, i.e. when the stepwise plan was suggested twenty years ago. An example of this is the power plant at Hellisheidi, which is in the south-western part of the Hengill geothermal area only 20 km from Reykjavík (Gunnlaugsson, 2012). Hellisheidi has been a candidate for utilization for decades. The first idea dates back to the 1940s when it was suggested that the field could be developed for space heating in Reykjavík. The preliminary studies customary at that time were carried out and one shallow exploration well drilled to about 100 m depth. The project was never realized, however, but geothermal studies were continued in the area as a part of the geothermal exploration undertaken for the Hengill area. The geology was mapped during 1965 to 1985 and the geophysical surveying was carried out between 1975 and 1985. Finally an 1800 m deep exploration well drilled in 1985 confirmed the existence of a 280°C resource.

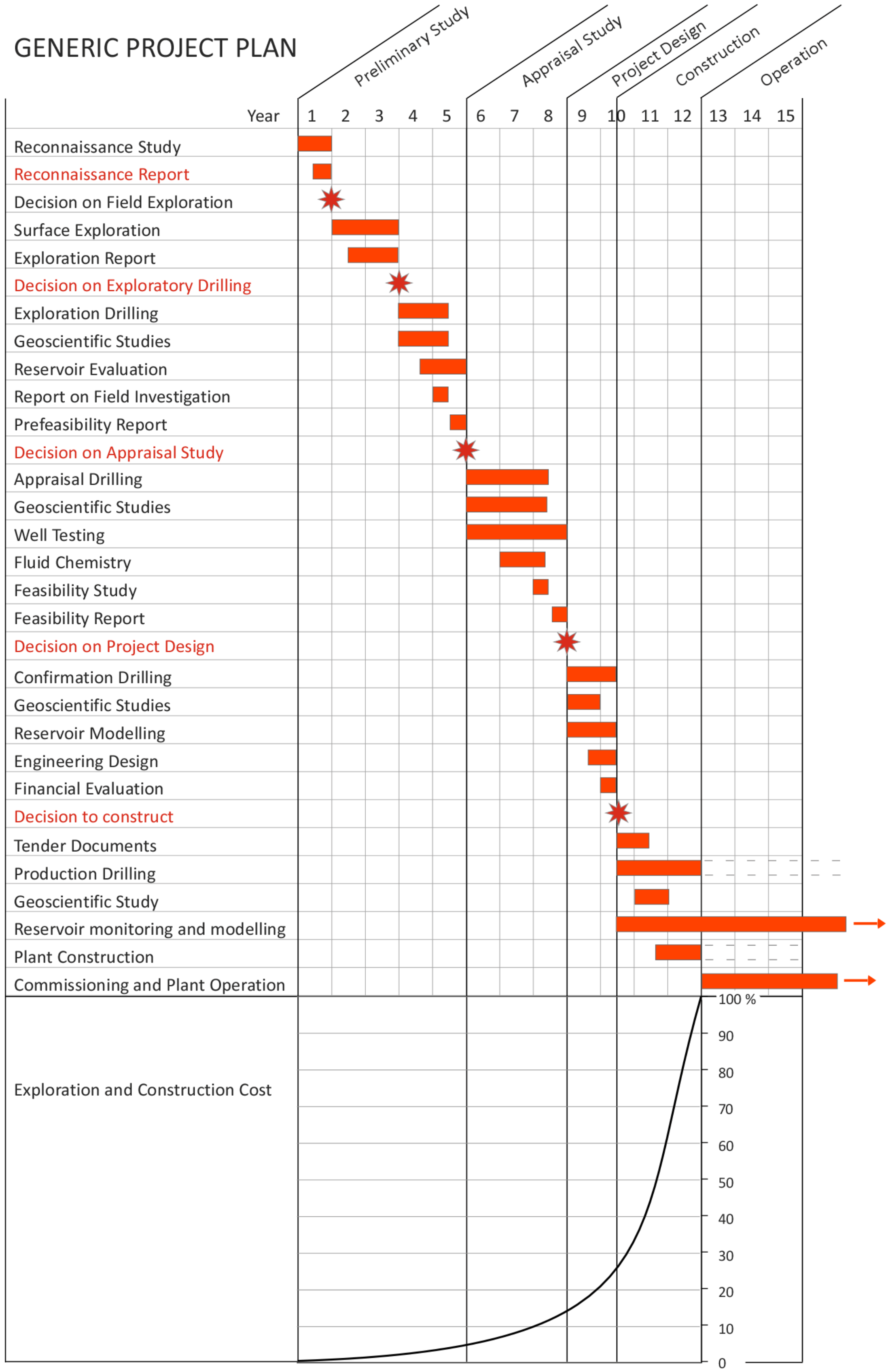

FIGURE 3: The Icelandic generic plan of 1982 for geothermal power development

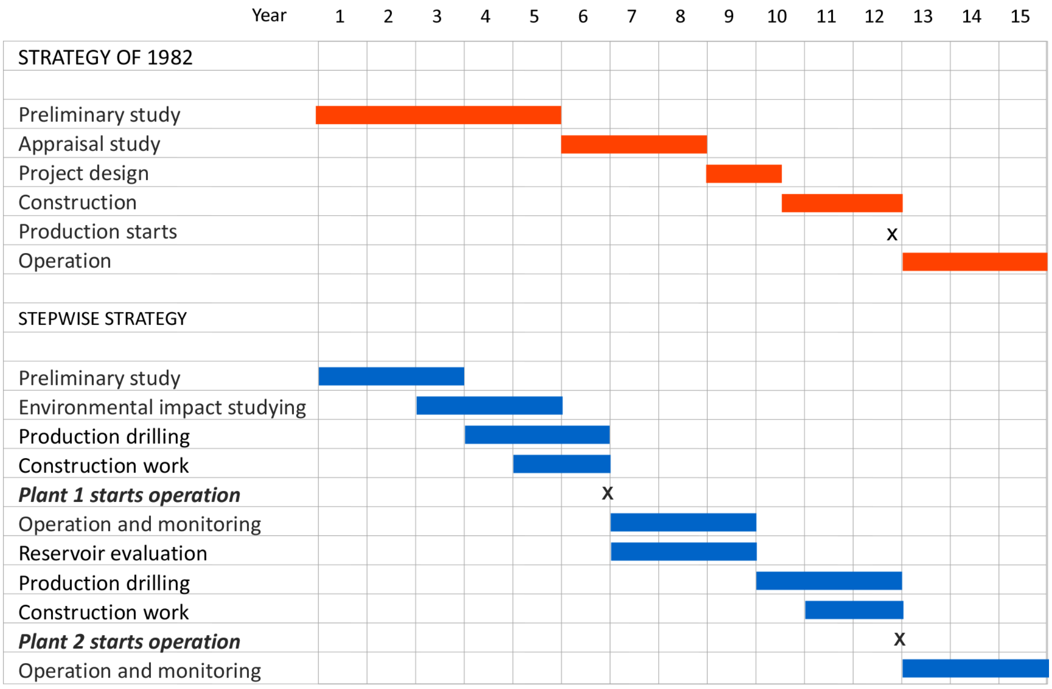

FIGURE 4: The stepwise development strategy (lower part of the figure) compared to the strategy of 1982 (upper part of the figure) where the full potential of the field is matched in one power plant

The drilling of the deep exploration well in 1985 completed the preliminary studies of the Hellisheidi field at that time. Further development of the field was, however, delayed until 2001 when Reykjavík Energy decided to develop the field for power generation and hot water production for space heating in Reykjavík at a later stage. The appraisal phase was carried out during the following three years with the drilling of 8 deep wells and additional preliminary studies. An environmental impact assessment was carried out and in 2004 Reykjavík Energy decided to start production/injection drilling and construction of the power plant and build it in stages according to the stepwise development strategy.

The first two 45 MW_e turbines were commissioned in 2006. A low pressure bottoming unit was added in 2007 and two additional 45 MW_e turbines in 2008. The construction of the heating plant started in 2008 and the first stage, 133 MW_{th}, started operation in 2010. Finally additional two 45 MW_e turbines were commissioned in 2011 bringing the installed power to 303 MW_e and 133 MW_{th}. Further power generation is not planned but the heating plant will be expanded to 400 MW_{th} as the demand for hot water for space heating in the Reykjavik area increases.

5. CONCLUDING REMARKS

The discussion in this paper has been focused on the geothermal developments in Iceland. A similar approach has been applied in other geothermal countries (Dolors 2005; Mwangi, 2005) and several publication describing the phases of geothermal development are available in the geothermal literature. One of the latest publications on is the "Geothermal Handbook: Plnning and Financing Power Generation" Published in 2012 by ESMAP (Energy Sector Management Assistance Program) technical report 002/12 and can be downloaded from ESMAP webpage: http://www.esmap.org/Geothermal_Handbook.

REFERENCES

Dolors, F., 2005: Phases of geothermal development in the Philippines. *Presented at "Workshop for Decisions Makers on Geothermal Projects and Management", organized by UNU-GTP and KenGen in Naivasha, Kenya*, Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-01-05.pdf

Gunnlaugsson, E., 2012: The Hellisheidi geothermal project – financial aspects of geothermal development. Presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo in Santa Tecla , El Salvador, 9 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-14-12.pdf

Mwangi, M.N., 2005: *Phases of geothermal development in Kenya*. *Presented at "Workshop for Decisions Makers on Geothermal Projects and Management", organized by UNU-GTP and KenGen in Naivasha, Kenya*, 11 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-01-06.pdf

Stefánsson, V., Gíslason, G., Torfason, H., Georgsson, L.S., Sigurmundsson, S.G., and Thorhallsson, S., 1982: *A systematic exploration of high temperature areas in Iceland*. Orkustofnun – National Energy Authority of Iceland, report OS82093/JHD13 (in Icelandic), 177 pp. Web: http://www.os.is/gogn/Skyrslur/OS-1982/OS-82093.pdf

Stefánsson, V., 1992: Success in geothermal development. *Geothermics, 21-5/6*, 823-834.

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UNITED NATIONS UNIVERSITY
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GEOTHERMAL EXPLORATION AND ASSOCIATED COST IN ICELAND

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ABSTRACT

This paper describes in a general way what kind of surface studies are carried out in Iceland in exploration of our geothermal fields. It is outlined what one can expect to have to do to engage in a complete exploration work in a new greenfield geothermal resource area. This is presently usually what is needed to fulfil the requirements to apply for, or receive exploitation rights in a geothermal area. The aim of the work is based on three main components.

- The recognition of possible geothermal resources to develop;
- The geo-scientific work needed to estimate its size and potential; and
- The project development work to be able to carry out the exploration and plan for the exploitation and estimate its feasibility.

The recognition of a geothermal resource starts with a reconnaissance study. This is a project area assessment and the purpose is to collect as much as possible of the information and scientific data that are already available, regarding the geothermal resource. Usually this will result in the ranking of the area compared to other areas and a first estimation of which areas are more promising than others.

The objectives of the geo-scientific work mainly consists of identifying the main geothermal reservoir and roughly estimate the size, reservoir temperature, energy potential and accessibility and put forward a preliminary conceptual model. The area(s), which are deemed interesting, will get to the next stage where the "run of the mill" geo-scientific research will be carried out. This stage is done through a series of different research methods.

The project development work will address technical, physical, environmental and economic factors connected to the expected utilization of the resource. One of the main outcomes of this work is a road map for the development of geothermal power, which can be a platform to put forward a strategy in the development of geothermal energy.

1. INTRODUCTION

Iceland is rich in geothermal resources due to the volcanic activity (Figure 1), and the heat flow through the crust is several times higher than world average. Traditionally the geothermal fields are divided into *high-temperature fields,* where temperature above 200°C is found at 1 km depth and *low-temperature fields,* in which the temperature is lower than 150°C in the uppermost kilometre. Resources with temperatures between 150 and 200°C have sometimes been referred to as *intermediate*. Some 30 high temperature fields have been identified in Iceland, all within the active volcanic zones that cross the country from southwest/south to northeast/north, as shown in Figure 1. The low temperature activity is highest on the flanks of the volcanic zones but some low temperature resources are found in most parts of the country.

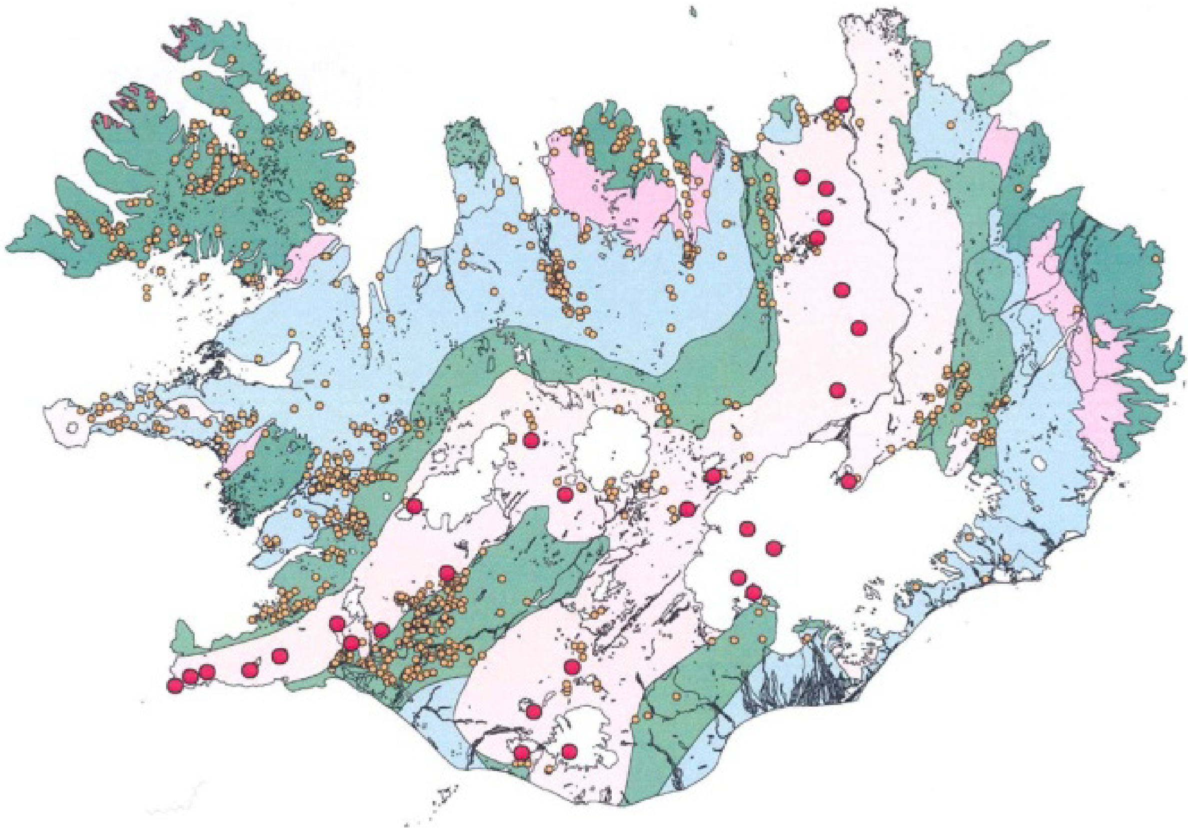

FIGURE 1: Geothermal map of Iceland. High-temperature fields inside the active volcanic zones are shown as red circles, and hot and warm springs as yellow circles.

Exploration, drilling and utilization of the low temperature fields for space heating started during the first half of the last century but during the last decades the development of the high temperature fields for power generation has been the main issue in geothermal developments in Iceland.

The methodology and the strategy of the exploration and development of the Icelandic high temperature geothermal fields have been under critical discussion and review ever since their utilization started a few decades ago (Björnsson 1970, Stefánsson et.al. 1982).

The strategy adopted for early development was to estimate the power capacity of each field through exploration and drilling, and subsequently to design and construct a power plant with a view to fully utilizing the estimated field capacity in a single power development. Later this strategy has been changed to stepwise development where the capacity of the field is tested with a relatively small power unit and later expanded in steps until the full potential of the field is developed (Stefánsson, 2002).

The objective of this paper is to give a general overview of surface exploration methods applied in Iceland with the main focus on the volcanic high temperature fields.

2. GEOCHEMICAL EXPLORATION

The exploration and development of a geothermal field takes several steps. In the geothermal literature various approaches in defining the steps can be found. The first step in geothermal investigations is usually studies of the geothermal activity found on the surface in the area under investigations. These manifestations are the first indication or evidence for the existence of a potentially exploitable geothermal resource. The manifestations can be of various types, ranging from active hot springs and fumaroles to hot and steaming grounds and cold but altered grounds indicating diminishing or extinct geothermal activity on the surface.

The surface activity offers us a window to the underlying geothermal system. The main objective of a geochemical exploration as a part of a geothermal exploration programme is to obtain information on the subsurface chemical composition of the fluid in the geothermal system and to use this information to estimate the temperature of the reservoir as well as the source of the fluid and to locate active upflow zones. Speciation programs are used to obtain equilibrium speciation of the fluid and to simulate processes of e.g. boiling and cooling and to predict potential corrosion and scaling. Potential environmental effects can be predicted and the geochemical information is used together with other data to model the geothermal system.

The geochemical studies of thermal fluids are performed in three steps: Sampling of water and gas; analysis of the fluid, and interpretation of the data. For the most part sampling and analysis are routine work whereas the interpretation is not and a number of methods have been proposed. Subsurface reservoir temperatures are estimated with the help of geothermometers based on the composition or isotopic ratios of thermal waters and gasses. Geothermometers are often divided into three groups: Water geothermometers, gas geothermometers, and isotope geothermometers. The water and gas geothermometers are often referred to as chemical geothermometers (Figures 2 and 3); they can be described as either univariant, e.g. SiO_2, CO_2, H_2S and H_2 or based on ratios of elements such as Na/K, CO_2/H_2, CO_2/N_2 and CO_2/Ar. The univariant geothermometers are simple to use but have the disadvantage that they are sensitive to secondary changes such as dilution, condensation and steam loss (Figure 3). On the other hand, geothermometers based on elemental ratios are not as susceptible to the

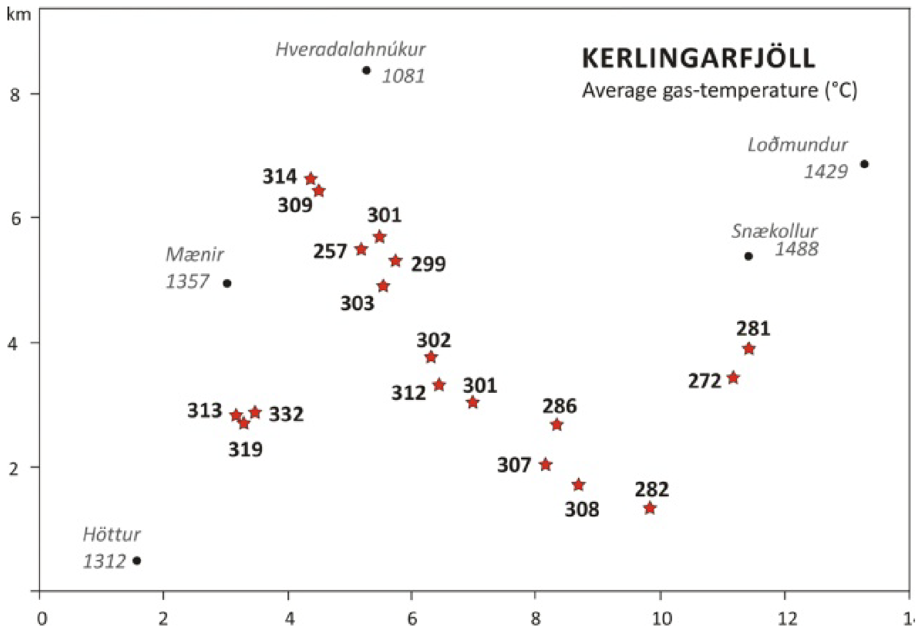

FIGURE 2: The calculated average reservoir temperatures (°C), based on several gas geothermometers, from fumaroles in the Kerlingarfjöll high temperature area, central Iceland. Black dots and names represent mountain peaks with elevation in meters. The scale on both axes is in kilometres (Hjartarson and Ólafsson, 2005a).

secondary changes, but rate and equilibrium conditions may limit their usability. It has proven useful to use as many geothermometers as possible as the discrepancies between different geothermometers may provide important information about the nature of the geothermal system.

To trace the origin of fluids in geothermal systems the most powerful tracers are stable isotopes and conservative elements and their ratios to chloride. Ternary diagrams such as Cl-Li-B and Cl-SO_4-HCO_3 have also proven useful as well to distinguish waters of different origins.

Soil temperature and diffuse degassing measurements are used to locate up flow zones and active faults and are helpful methods to assess the size of a geothermal system and to better site exploration wells (Figures 4 and 5). The soil degassing measurements also allow the evaluation of natural heat loss from the geothermal system.

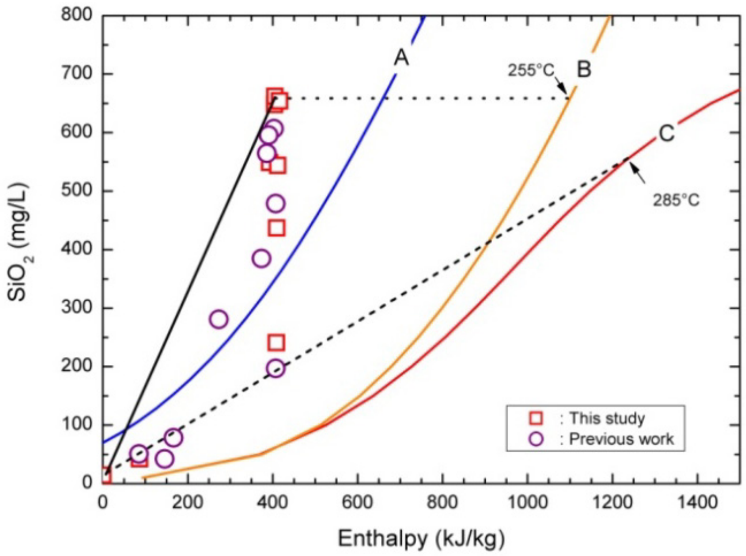

FIGURE 3: Silica-enthalpy mixing model for waters from the Hveravellir high temperature area, central Iceland. Curve A=solubility of amorphous silica; curve B=quartz solubility corrected for steam loss by adiabatic boiling to 100°C; curve C=solubility of quartz (Hjartarson and Ólafsson, 2005b)

3. GEOLOGICAL EXPLORATION

After the reconnaissance study and in parallel with the detailed studies of the geothermal surface manifestations, geological mapping is carried out in the geothermal area under exploration. These tasks usually involve geological and structural mapping as well as the mapping of the thermal manifestations (Figure 6). Samples are collected of the thermal alteration minerals and sampling of rocks for dating and chemical analyses is a key factor. Mineralogical studies of volcanic rocks and the thermal alteration, including chemical analysis, x-ray diffraction etc. which are used for creating a detailed map of the area which will be necessary for the conceptual model for the area. Relative ages of structures and volcanic activity in the area may enhance the understanding of the geothermal activity and help in predicting what the controlling structures of the geothermal resource are. It is our experience that the

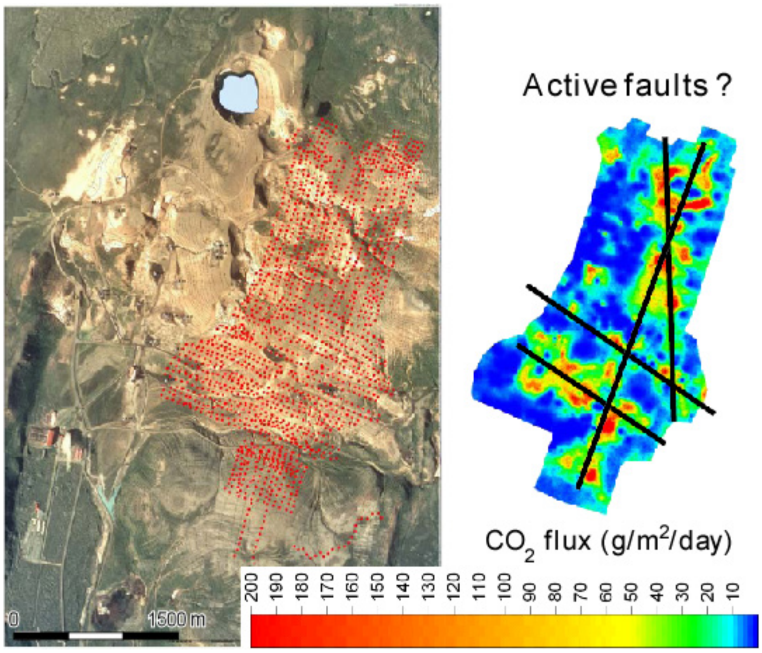

FIGURE 4: Soil diffuse degassing at the Krafla, high temperature area, north Iceland. To the left, red dots show the locations of soil flux measurements, and the map to the right shows the magnitude of the diffuse CO_2 flux through soil (Ármannsson et al., 2007)

volcanic fissures are often highly permeable and a good target for drilling wells (Franzson et.al. 2010). The chronological order of the various volcanic events is dated based on historical accounts and on C^{14} and tephra chronological data. For this work, the interpretation of aerial photographs, satellite images and other remote sensing techniques to delineate faults, lineaments, terrain etc. may prove vital. This may also include infrared photography to outline possible surface heat flow anomalies.

FIGURE 5: Mapping soil diffusion in the field in Iceland

A digital elevation model is constructed based on existing data, e.g. topographic maps, aerial photographs, satellite data, and control data points obtained during other fieldwork. This will be a basemap for the collection of maps produced during the exploration phase and later development of the field and stored and maintained in a GIS system.

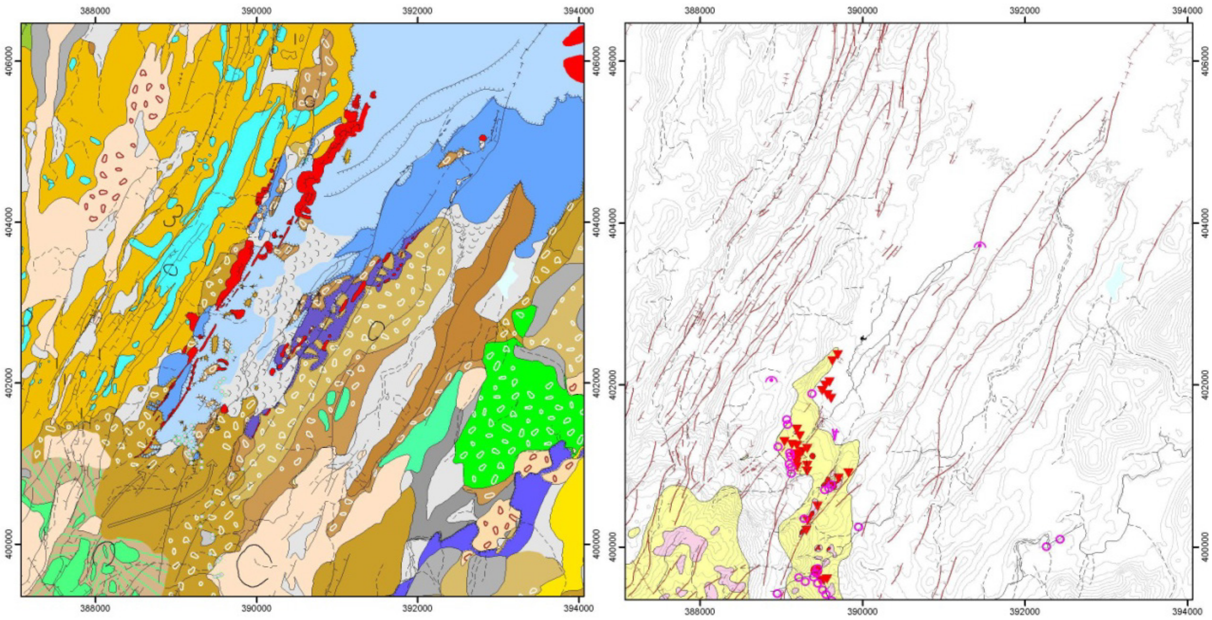

FIGURE 6: A typical geological map (left) from the Nesjavellir geothermal field, Iceland. Red colour are volcanic fissures. Structural- and geothermal information from the same field are shown on the right map. Yellow and pink areas are geothermal alteration and triangles and circles are fumaroles and springs (Sæmundsson 1995a and 1995b)

Historical evidence for the volcanic history of the field is studied. This is used for the evaluation of geological hazards in the area of geothermal exploitation and to plan for mitigating measures. This is partially included in the geological mapping. Information on the seismic activity in the area is also collected. The volcanic and seismic history data forms the basis for the risk assessment in developing the field.

4. GEOPHYSICAL EXPLORATION

The first step in the geophysical exploration of a geothermal field is a resistivity survey of the area. Resistivity methods have been used extensively in geothermal exploration in Iceland for decades. At first DC methods were used in the eighties but were succeeded by the TEM (transient electro-magnetic) method.

The Transient Electro Magnetic (TEM) and Magneto Telluric (MT) measurements involve measurements of stations strategically located, covering the geothermal area. The parameters controlling the resistivity of rocks are temperature, fluid content of the rock, salinity of the fluid and the type and concentration of the geothermal alteration minerals.

In high temperature fields the rock minerals undergo alteration dependent on the in situ temperature. From temperatures of 100°C up to 220°C, zeolites and smectite are dominant minerals. Smectite is a highly conductive clay mineral. At temperatures of 220-240ºC zeolites disappear and the smectite is gradually replaced by more resistive chlorite. At temperatures exceeding 250ºC the resistive chlorite and epidote are the dominant minerals. This results in a characteristic resistivity structure of a high temperature field with an up-doming low resistivity cap underlain by a high resistivity core. The interface of the two marks the 240°C isotherm in the geothermal field provided there is an equilibrium between the temperature and the alteration at present (Arnason et.al., 2000).

The TEM resistivity method is used to delineate the geothermal system within the uppermost 1000 meters below surface. To explore further depths the MT (magneto-telluric) method is applied. MT measurements can detect resistivity structures some tens of kilometres below ground surface (Figure 7) and may detect the heat source and up flow zones of the geothermal field. They have been used for the last few years in geothermal exploration in Iceland and are considered to be a standard exploration tool in the future along with the TEM method. Interpretation is usually 1D but when it comes to more complicated areas, 2D or even 3D interpretation is necessary to explain the resistivity structures.

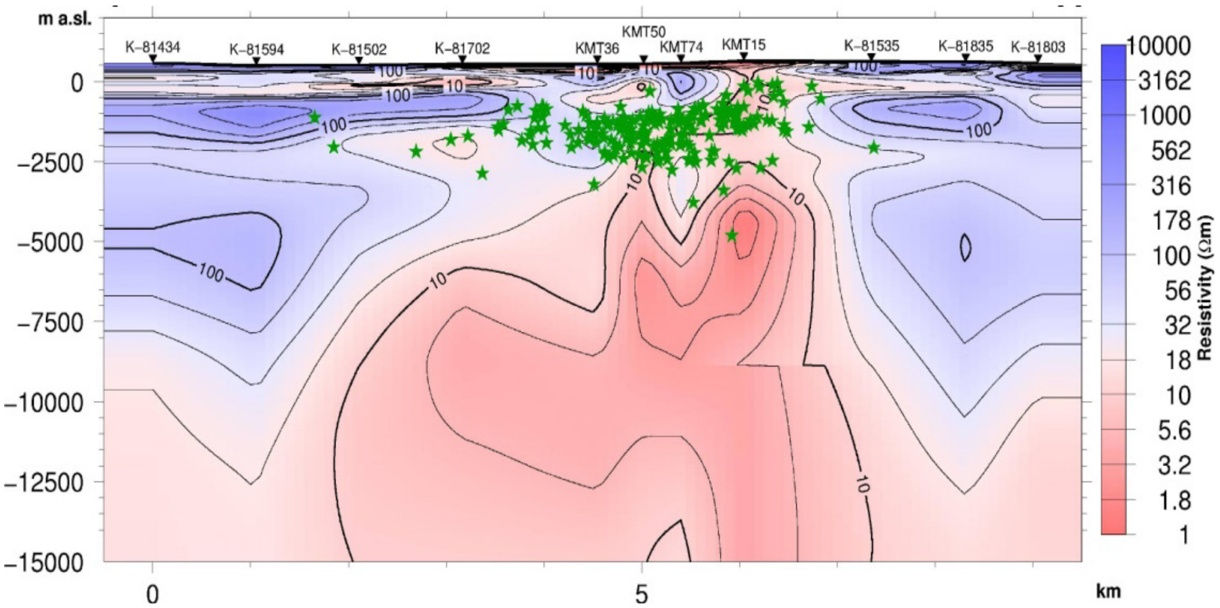

FIGURE 7: Resistivity section in the Krafla high temperature area combined from TEM and MT measurements. The low resistivity at the surface dipping down to 1-2 km depth is the so called low resistivity cap. The low resistivity layer at 10-12 km depth doming up under the geothermal field to about 2 km depth shows the heat source, possibly the magma chamber under the volcano. Green stars are the epicentres of earthquakes. (Arnason et.al., paper in progress)

During the exploration phase and prior to the utilization of the field it may be feasible to carry out a gravity survey with GPS elevation and location coordinates. This is done to map out gravity anomalies that might be linked to the geothermal resource. The gravimetric surveys together with the GPS data are also used as a base of information for later to monitor land elevation and gravity changes caused by seismicity, volcanism and, last but not least, by the proposed utilization of the geothermal field (Figure 8). A micro-gravity study may also be used to get indications on larger faults in the area which may not be clearly visible or hidden at the surface.

Aeromagnetic measurements are sometimes used at the start of an exploration phase in a high temperature area for the purpose roughly outlining the areas which have been demagnetized due to temperatures. Magnetic measurements are also sometimes used in the exploration of low temperature fields, since the water bearing fractures are often connected with dykes and faults that may be easily detected with magnetic measurements.

Available data on seismic activity in the area is usually studied and active zones of seismicity are mapped out and correlated with known fractures in the area as the earthquake activity will reveal active fractures that may act as flow channels for the geothermal fluid within the reservoir. It will show areas of heat extraction (cooling cracks) where fluid might be cooling hot intrusives. In some cases in Iceland, several seismometers have been installed to monitor the area in question for a few months or even years to collect micro-seismic data. This has proved to produce valuable data for the purpose of recognizing the controlling structures of the reservoir and to map out the most likely structures to be permeable (Julian and Foulger 2009).

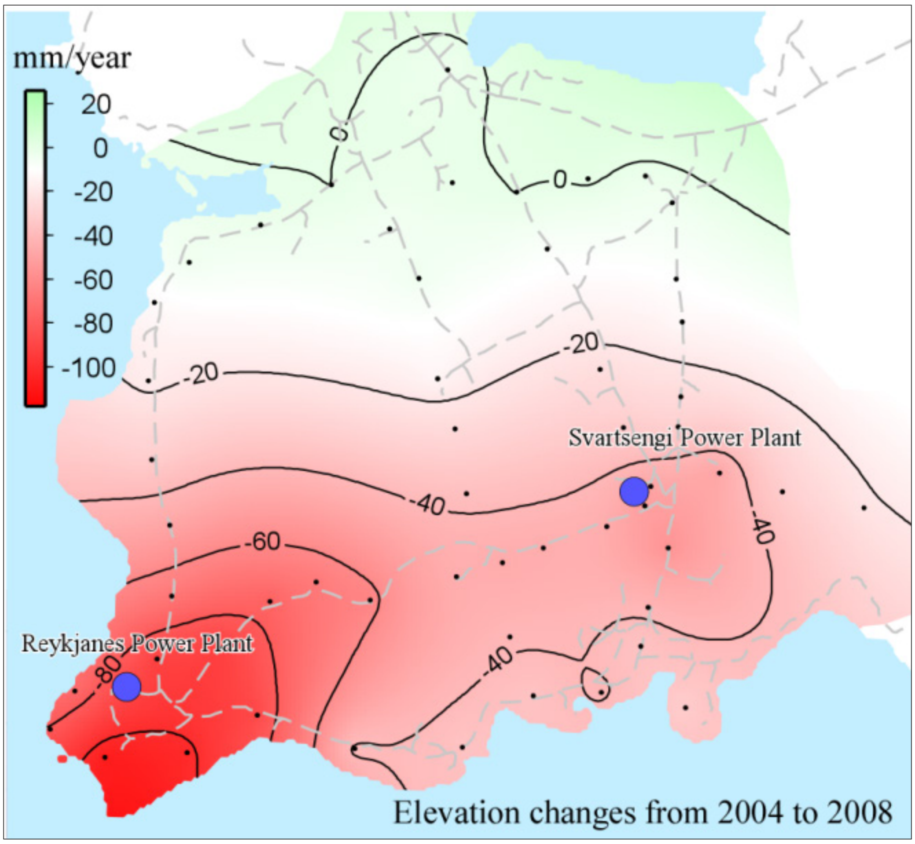

FIGURE 8: Elevation changes during exploitation during the years 2004-2008 in Svartsengi and Reykjanes geothermal areas, Reykjanes peninsula, Iceland (Magnússon 2009)

5. THE EXPLORATION RESULTS

The general surface exploration phase for Icelandic geothermal fields concludes with exploration reports where the results of the various disciplines are described and discussed. A conceptual model derived from all the data collected is presented for the field, drilling target defined and 1-3 sites for exploration drilling suggested. At this stage a rough volumetric resource assessment is carried out, often using the Monte Carlo approach.

The geothermal surface exploration in Iceland has mainly been financed by the government and Icelandic energy companies. The conclusion of the exploration phase defines a milestone in the development. The government itself will not continue to develop the fields but the question is if the exploration results will encourage a developer (in our case the Icelandic energy companies) to take the exploration to the next level or not, which is proving the resource at depth with exploration drilling.

Under normal circumstances, the exploration phase of developing a high temperature geothermal resource includes the drilling of two to five exploration wells. In Iceland the normal procedure for these exploration wells is to drill a full size well in a commercial diameter. This way shallow geothermal gradient wells and the deeper slim wells are bypassed. In high temperature areas the gradient wells have to be several hundreds of meters deep to give the appropriate gradient information. Drilling the full sized wells is more expensive than the slim wells and geothermal gradient wells, but for the purpose of flow testing and sampling the resource at depth, the larger wells are more efficient and it is our experience that such wells give much more valuable and reliable information than gradient wells or slim wells can offer us. If the full sized wells are successful, they may later be used as producers or injectors when utilization commences.

A preliminary reservoir model is based on available information on parameters such as reservoir thickness and areal extent, reservoir temperature and pressure, formation porosity and permeability, flow characteristics of wells and the fluid chemistry and others, results from the surface exploration and from the exploration wells.

The first approach to evaluate the resource upon completing the exploration is to carry out a volumetric assessment of the resource. This assessment is later revised when information is obtained from the exploration drilling, often by applying Monte Carlo statistics to the volumetric assessment. Long term testing of productive exploration wells will define the expected productivity of future wells as well as yield information on the pressure response (drawdown) of the reservoir to fluid production. This is necessary to be able to plan for the next steps of developing the geothermal resource, getting the first estimate on the potential and where to start focusing the work within the exploitation license area.

6. EXPLORATION AND ASSOCIATED COST

The cost estimation of surface exploration can vary considerably from one geothermal field to the next. This varies mainly due to the different sizes of area to be explored and different geological settings, previous studies already carried out, if any, and the accessibility of the area. When estimating exploration cost, we will make the assumption here that the geothermal field in question is a greenfield development. We look at two types of fields (1) a high temperature field covering 100 km^2 exploration area in a volcanic region and (2) a low to intermediate temperature field in a tectonically active region covering some 50 km^2 of land, as these systems are usually not as extensive as the volcanic high temperature fields (Tables 1 and 2). Both fields are considered fairly open and accessible.

As mentioned earlier in the paper, the general studies necessary to conduct when it comes to geothermal surface exploration are geological, geochemical and geophysical studies.

Reconnaissance study: The first phase in a greenfield geothermal surface exploration is the Reconnaissance study (the project area pre-assessment). This entails a thorough desktop study of previous exploration work in the geothermal area i.e. receiving and reviewing all data provided and otherwise relatively easily available, and the evaluation of the quality of the earlier work and recognizing where data are lacking.

The desktop study should be followed by a visit of two to three geothermal experts to the geothermal sites. The purpose of a site visit is to collect additional existing data and maps, meet with local authorities and local geo-scientists and engineers who may have studied the field and gather whatever additional information there may be available regarding the geology, geochemistry, geophysics, engineering, reservoir, drilling, and accessibility of the site. This may also include some sampling and analyses of geothermal water and/or steam, preliminary mapping, temperature and flow measurements and so on. The site visit will primarily give the specialists a chance to evaluate at first hand, and estimate the pros and cons of the exploration development and the potential market for the geothermal energy. It will also provide the necessary basic information to be able to work out a more detailed budget for the exploration phase.

The reconnaissance study is concluded by a review of the geothermal field by a group of geothermal experts. A reconnaissance report on the findings should be submitted as well as recommendations on the exploration strategy if the project is deemed feasible. The environmental aspect of the development should be evaluated. A budget for the exploration work should be estimated at this stage.

Geological studies:

1. Geothermal mapping/structural mapping, including remote sensing techniques. Geothermal specialists (geologists/structural geologists/hydrogeologists and geochemists), map out the main structures and geological units, map out and connect the geothermal surface manifestations to underlying structures/stratigraphy. Preliminary hydrogeological mapping.
2. Collect samples for analysis (geothermometers, age determination, petrophysics etc.) and temperature measurements of surface manifestations.
3. Soil temperature mapping may be carried out. Soil temperature is used to locate up flow zones and active faults. A relative cheap and quick method by mapping the temperature (down to 40-50 cm). Tens of stations can be measured daily.

Geochemical studies:

1. Chemical sampling, analyses and interpretation of fluids from the geothermal springs and estimate subsurface temperatures using conventional geothermometers as well as estimating potential chemical and gas problems during drilling, flow testing and power production. Development of a preliminary hydro-geochemical model of the resource. High synergy with geological studies.
2. CO_2/Radon mapping. Diffuse degassing measurements are used to locate active faults. A relative inexpensive and quick method by mapping the gas flow at the surface. Tens of stations measured daily.

Geophysical studies:

1. Surface geophysical methods for subsurface resistivity measurements (TEM and MT) for outlining the geothermal anomaly at depth and defines up-flow and out flow zones and potential heat sources. The density of the measurements is typically one MT/TEM measurement per km^2 for the survey area.
2. Gravity surveying: This is to map out any gravity anomalies that might be linked to the geothermal resource. This may include a micro-gravity study.
3. Magnetic mapping is used in the low temperature exploration to map dykes and faults in the bedrock.
4. Micro-seismic monitoring (passive seismic) is used to recognizing magmatic bodies at depths and controlling structures of the reservoir and to map out active fractures and fracture zones (epicentres of very small earthquakes) likely to be permeable. Several (7-10) seismometers may be installed to monitor the area in question for a few months to collect seismic data.

Additionally shallow (50-150 m) thermal gradient wells may be of value. Usually this method is used in low to intermediate temperature areas, where the geothermal anomaly is found at a shallow depth in the crust. If they are considered to be needed they have to be drilled, measured and analysed to try to locate even further the main heat anomaly indicating fractures that bring convection geothermal water close to the surface, as well as to estimate the outer borders of the geothermal area. 5-15 wells might be needed, depending on the results from other surface exploration methods. The drilling of each temperature gradient well (50-150 m), may take only a few days or up to one week.

Finally the exploration data are evaluated and a Conceptual Model of the geothermal field presented before a preliminary Volumetric Assessment is carried out. The conceptual model as well as the volumetric assessment are included in a detailed geo-scientific report for the site explored. This report should present recommendations, preliminary well design and positioning of 2-3 deep (500-2000 m) exploration wells as well as preliminary development strategies for the area.

Geothermal gradient wells (~50-150 m deep) could be roughly 200 USD/m (Icelandic prices) or 10,000 to 30,000 USD each, depending on the mobilization cost, number of wells, depth of wells and size of the drill rig.

TABLE 1: Cost estimation for typical surface exploration of a volcanic 100 km^2 high temperature field

Study type	**Cost estimation**
Reconnaissance Study	50,000-75,000 USD
Geological Studies	200,000-250,000 USD
Geochemical Studies	100,000-150,000 USD
Geophysical Studies	700,000-900,000 USD
Geo-scientific Report	150,000 USD
Total	**1,100,000–1,425,000 USD**

TABLE 2: Cost estimation for typical surface exploration of a low-intermediate geothermal field (~50 km^2)

Study type	**Cost estimation**
Reconnaissance Study	40,000-50,000 USD
Geological Studies (mainly structural elements)	100,000-120,000 USD
Geochemical Studies	40,000-60,000 USD
Geophysical Studies	200,000-300,000 USD
Geo-scientific Report	70,000 USD
Total	**450,000–600,000 USD**

6. CONCLUSIONS

The Icelandic experience through decades of exploration of high and low temperature areas is that the investment in a proper and thorough exploration program before the drilling of exploration wells is money well spent. This is the basis for the decision of developing the geothermal area further or not, and if the results are encouraging, the multidisciplinary approach of collecting data will in most cases be a sound foundation when placing and designing exploration wells.

One failed well, which can be linked to lapses in the exploration work weather it is omission of doing the exploration, collection of poor data or misinterpretation, can cost up to five times more than the full spectrum of a solid multidisciplinary surface exploration program.

It is therefore, in our view, extremely important to put great emphasis on the exploration phase before deciding to drill an exploration well, so that that the siting of the well can be made with good confidence. It will not, however, remove the risk from the drilling but will certainly lower it. Saving a few tens of thousands of dollars on exploration might cost a few million dollars in the end.

REFERENCES

Ármannsson, H., Fridriksson, F., Wiese, F, Hernández, P., and Péres, N., : CO2 budget of the Krafla geothermal system, NE-Iceland. *Proceedings of the 12th International Symposium on Water-Rock Interaction 2007,* Taylor & Francis Group, London, 189-192.

Arnason, K., Karlsdottir, R., Eysteinsson, H., Flovenz, O.G., and Gudlaugsson, S.T., 2000: The resistivity structure of high-temperature geothermal systems in Iceland. *Proceedings World Geothermal Congress 2000, Kyushu - Tohoku,* 6 pp.

Arnason, K., Vilhjalmsson, A. M., Bjornsdottir, Th.: A study of the Krafla volcano using gravity, micro earthquake and MT data. *ISOR report in progress.*

Bjornsson, S., 1970: *A program for the exploration of high temperature areas in Iceland*. Orkustofnun, Reykjavik, Iceland, 15 pp.

Franzson, H., Árnason, K., Sæmundsson, K., Steingrímsson, B., and Gunnlaugsson, E., 2010: The Hengill geothermal system, conceptual geological model. *Proceedings World Geothermal Congress 2010, Bali, Indonesia,* 9 pp.

Hjartarson, Á., and Ólafsson, M., 2005a: *Kerlingarfjöll. Könnun og kortlagning háhitasvæðis (Kerlingarfjöll. Exploration and mapping of a high temperature area). Iceland GeoSurvey, report ISOR-2005/012 (in Icelandic),* 60 pp.

Hjartarson, Á., and Ólafsson, M., 2005b: *Hveravellir. Könnun og kortlagning háhitasvæðis (Hveravellir. Exploration and mapping of a high temperature area).* Iceland GeoSurvey, report ISOR-2005/014 (in Icelandic), 44 pp.

Julian, B.R., and Foulger, G.R., 2009: Monitoring geothermal processes with microeartquake mechanism. *Proceedings Thirty-fourth workshop on Geothermal Engineering, Stanford University, Stanford, California, United States,* 3 pp.

Magnússon, I.Th., 2009*: GNSS- og þyngdarmælingar á utanverðum Reykjanesskaga 2008 (GNSS- and gravity measurement on the western part of Reykjanes peninsula)*. Iceland GeoSurvey, report-2009/029, 60 pp.

Stefánsson, V., Gíslason, G., Torfason, H., Georgsson, L.S., Sigurmundsson, S.G., and Þórhallsson, S., 1982: *Áætlanir um skipulegar rannsóknir á háhitasvæðum landsins (A systematic exploration of high temperature areas in Iceland)*. Orkustofnun, report OS82093/JHD13 (in Icelandic), 176 pp.

Stefánsson, V., 2002: Investment cost for geothermal power plants. *Geothermics, 31,* 263-272.

Saemundsson, K., 1995a: *Hengill, jarðfræðikort (berggrunnur), 1:50.000 (Hengill, geologic map (bedrock), 1:50,000)*. Orkustofnun, Reykjavik Energy and National Land Survey of Iceland.

Saemundsson, K., 1995b: *Hengill, jarðhiti, ummyndun og grunnvatn, 1:25.000 (Hengill, geologic map (geothermal manifestations, alteration and groundwater)*. Orkustofnun, Reykjavik Energy and National Land Survey of Iceland.

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LaGeo S.A. de C.V.

EIA AND PERMITTING: TIME AND COST CONSIDERATIONS

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ABSTRACT

Environment law and regulations in El Salvador provide compliance requirements of environmental protection through the environmental assessment process for industrial projects, infrastructure, among others, power generation, but in the last case, undefined size of the power plant from renewable energy sources such as geothermal and/or fossil fuels.

Time and costs for project developers, particularly for obtaining Environmental Permits or Environmental Resolutions have become legal and institutional barriers which have required more attention by clients of the Environmental Ministry (MARN).

There are specific initiatives managed by partnerships between the National Energy Council (NEC) and the German Agency for International Cooperation (GIZ) in Renewable Energy and Energy Efficiency Program in Central America (2011) and proposal to the Establishment of the System of Environmental Auto-Regulation, submitted by LaGeo-CCAD MARN in 2005, all of which to facilitate the environmental assessment process to reduce time and costs for renewable energy projects, including geothermal medium and small scale. MARN has taken concrete actions to expedite response to the developers applying Categorization Project recently extended and contemplated in the Law.

1. INTRODUCTION

The environmental regulatory framework for low enthalpy geothermal projects in El Salvador is still in its incipient stage, due to the fact that the country energy plans for more than four decades were aimed at generating electricity on a large scale and at accelerated pace, therefore, geothermal development has been based mainly on the use of high enthalpy (above 180°C) resources that can compete at the same rate of electricity generation sources by either bunker or hydroelectric base.

Low enthalpy geothermal resources have not yet been explored and developed in the country, with the exception of geo-scientific studies of thermal springs and shallow wells in some areas with hydrothermal manifestations developed only for tourism.

For concessions that tap resources in the country, the developer must submit to the recent changes of the legal and regulatory framework (SIGET Agreement No. 283-E-2003) for the development of geothermal and hydro power projects of low scale, or with the new law recently approved, Article 18 of the Law on Concessions for small developers, Agreement 460.

According to the Environment Law, electrical power plant projects, including geothermal, require full compliance with the Environmental Assessment process according to Articles 21 to 29, which are presented in the General Regulations of the Law.

Since the creation of the Environment Law in 1998, there has been improvement and re-interpretation of some loopholes in reducing the processing for all types of projects. But still, efforts to continue to remove legal barriers, cultural, social and other types on the issue of development of renewable energy, including geothermal, is being carried out for the purpose of improving the response time of the Ministry, and thus contribute to short and long term sustainable development of the country, improving the energy matrix in accordance with the energy and environmental policies widely diffused to all sectors.

This paper presents the environmental regulatory framework for electricity power projects with emphasis on "Categorization: providing environmental assessment legal framework". Some legal recommendations are presented for industrial project applications to promote the use of renewable energies, especially the use of low enthalpy geothermal resource.

2. EXISTING LEGAL FRAMEWORK

2.1 Concessions

The government of El Salvador has made major revisions in the regulatory framework for geothermal development projects and concession adjustments in the past two years. Previously, the Electricity and Telecommunications Superintendence (SIGET in Spanish) based on the General Law and Regulations of Electricity provides the granting of concessions for exploration and exploitation of geothermal and hydro resources. Currently, the granting of concessions is now the responsibility of the Legislative body based on the Articles 83, 84,103,110,120 and 131 of the Constitution of the Republic.

Despite the changes of the General Electricity Regulation, SIGET will still continue to make an important role in the establishment of generation contracts, development of technical standards for verification and compliance audits required by law to developers and administration of fiscal incentives for renewable energy projects, etc.

2.2 Environmental Assessment (EA) process in El Salvador

The Environmental Assessment (EA) under the Environment Law is known as the process or set of procedures that allows the state, based on an environmental impact study, the assessment of the environmental impacts that could cause on the environment during the execution of a particular work, activity or project, and also, to ensure the implementation and monitoring of environmental measures to prevent, eliminate, correct, address, offset or enhance, if necessary, these environmental impacts.

Article 21, f) of the Environmental Law requires the submission of an Environmental Impact Study on electricity generating power plants based on nuclear, thermal, geothermal, hydro, wind and tidal energy regardless of their size. However, progress in the categorization of projects as a tool for environmental analysis allows the evaluator to determine how significant the project is. This topic will be discussed in detail in section 2.2.2.

Figure 1 presents graphically the major entities involved in the environmental assessment process which includes the project developer, MARN and the civil society, Furthermore, three global stages are part of the process.

Stage a) *Initial Environmental Assessment*, where the Ministry is lead agency and analyzes the magnitude of the project presented in the Environmental form. Likewise, field inspection is undertaken where the project is located.

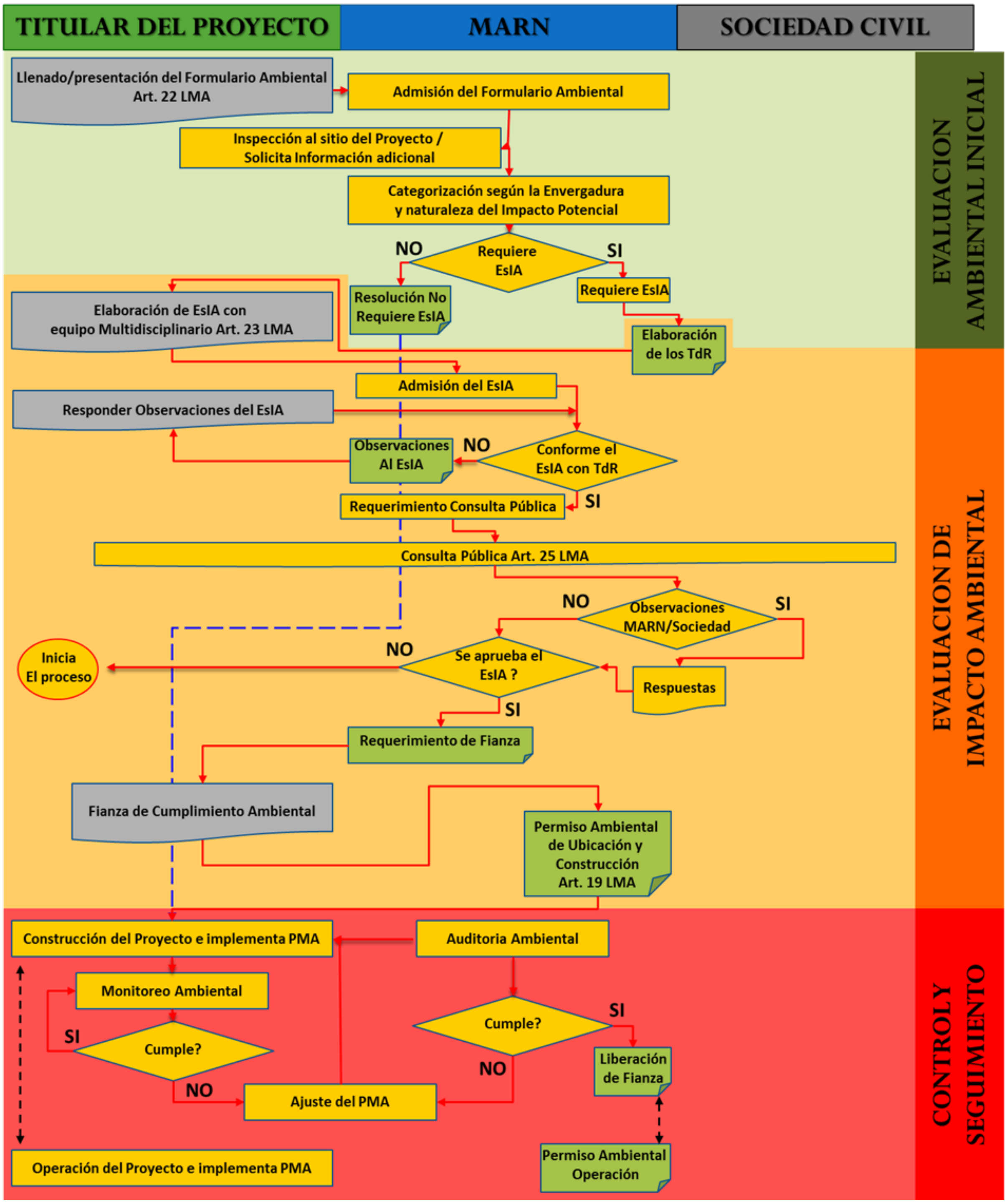

FIGURE 1: Environmental Assessment process for geothermal projects

At this stage, the MARN Categorization criteria applied determines whether or not the project requires an Environmental Impact Study (EIS). If so, then MARN sends to the developer terms of reference (TOR) for them to prepare. The TOR are instruments designed to define the content and approach to adopt the EIS and ensure that resources (time and money) are allocated to the acquisition of the information needed for decision-making and not just an excessive research.

Stage b) *Environmental Impact Assessment* is for project developers advised to prepare the EIS, a document that allows objectively the analysis of the environmental impacts of their activities, supported by scientific information; predicts and evaluates these impacts ($^{+}$/-) that can be generated during the project construction/operation. Also included in this study are measures for mitigation (Environmental Management Program and corresponding monitoring, which includes the implementation, effectiveness and validation of environmental measures). The Environmental Management Program requires payment of an Environmental Guarantee equivalent to the amount of all environmental measures to be carried out in the project environmental feasibility.

Subsequently, the EIS is submitted to public consultation process where the project is summarized and publicize for three days in a local newspaper of the country. Simultaneously, the document should be available on the website of MARN and physically shown in the Municipality where the project is located. If there are no complaints from the public that the project may cause a negative effect on their health, then MARN can grant the Environmental Permit (PA) to the developer, but the PA does not exempt them from other related authorizations or permissions to ensure the implementation of the project.

The process ends with stage c) *Control and Monitoring*, where the developer is audited by MARN to determine the compliance stipulated in the conditions of the Environmental Permit, and the release of the Environmental bond. At this stage also, the Municipal Environmental Units and social organizations play a key role in the Environmental Audit and Inspections.

2.2.1 Categorization of geothermal resource project utilization

Categorization is based on Article 22 of the Environmental Law where the final part states that the Ministry categorizes the activity, work or project, according to size and nature of the potential impact", which in turn is based on the list of activities, work or projects requiring a study on Environmental Impact, according to Article 21.

It should be noted that the scope of an activity, work or project refers to the size, volume or extension, and the nature of the potential impact is related to the sensitivity of the site or condition of the environment where it is required to construct and the type or nature of activity, work or project to be undertaken.

More important are the specific objectives of Categorization, namely:

- Strengthen the technical criteria used in the process of environmental assessment activities, works or projects;
- Introduce to the developer of activities, works or projects these technical criteria under which the Ministry will evaluate the environmental documents, whether Environmental form, Environmental Impact Assessment, Environmental Management Program, etc.; and
- Reduce the discretion of the official of the Ministry of Environment, responding to the needs with the efficiency and effectiveness in the analysis of environmental impact assessment in order to promote sustainable development.

According to the categorization, the document presented by the Ministry of Environment and Natural Resources is divided into two groups:

Group A, called "activities, works or projects with low potential environmental impact" where the developer of the activity, work or project should not submit environmental documentation.

Group B, known as "activities, works or projects with minor and moderate or high environmental impact potential" where the developer of the activity, work or project must submit environmental documentation.

This group is divided into two categories; the first one is addressed to minor projects with low potential environmental impact (B1) and the second one, those with moderate or high potential (B2) environmental impact. As a result of the environmental assessment by the Ministry, category B1, as part of the resolution, the project will not require preparation of an Environmental Impact Study.

According to technical criteria for categorization, if the project is B2 category, then it must prepare an Environmental Impact Study, which should be given approval. As an example, Figure 2 presents the criteria for determining the category B1 and B2 for an activity or geothermal project.

Criterios	Grupo B	
	Categoría 1	Categoría 2
Localización	▪ Dentro del sistema campo-planta dentro del área concesionada. ▪ Fuera de áreas naturales protegidas y sus zonas de amortiguamiento, sitios de valor cultural.	▪ Fuera del sistema campo-planta dentro del área concesionada. ▪ Dentro de áreas naturales protegidas, sus zonas de amortiguamiento y/o sitios de patrimonio cultural.
Emisiones atmosféricas	▪ Hasta 100 Ton CO_2/día. ▪ Hasta 10 Ton H_2S/día.	▪ Más de 100 Ton CO^2/día. ▪ Más de 10 Ton H_2S/día.
Área	▪ Hasta 3 Ha. Si se encuentra fuera del sistema campo-planta dentro del área concesionada. ▪ Hasta 5 Ha. Si se encuentra dentro del sistema campo-planta dentro del área concesionada.	▪ Más de 3 Ha. Si se encuentra fuera del sistema campo-planta dentro del área concesionada. ▪ Más de 5 Ha. Si se encuentra dentro del sistema campo-planta, dentro del área concesionada.
Cobertura vegetal	Menor de 30 árboles/Ha., con DAP igual o mayor de 20 cm.	Mayor de 30 árboles/Ha., con DAP igual o mayor de 20 cm.
Vías de acceso	No requiere apertura de caminos (utiliza accesos existentes, los mejora o amplia) o requiere la apertura de vías de hasta 500 m. de longitud si se encuentra dentro del sistema campo planta con Permiso Ambiental.	Requiere apertura de vías en áreas fuera del sistema campo-planta o requiere apertura de vías de más de 500 m. de longitud dentro del sistema campo-planta.
Volumen de material de desalojo	Hasta de 10,000 m^3 por plataforma.	Más de 10,000 m^3por plataforma
Pendiente	Hasta 30%.	Más de 30%

FIGURE 2: Technical Criteria for the categorization of a geothermal project

2.2.2 Cost and length of time in the EA process

Time and costs associated with the EA process vary and are controlled by external variables that do not depend directly from the projects if the study is structured with good quality with reference to TOR. It can affect the evaluation process due to political situation, the technical evaluation of the project, the technical knowledge in geothermal and different stages of implementation. Table 1 presents considerations of cost and time for geothermal power projects based on LAGEO's experience.

TABLE 1: Time and Costs estimated for geothermal project implementation managed by LaGeo, SA de CV

ACTIVITY/PROJECT	PHASE OF GEOTHERMAL PROJECT CYCLE	PERIOD IN PROCESS	LAGEO STAFF COSTS*	EXTERNAL STAFF COSTS **
C.W & Drilling of 2 wells in CHI-4 Pad	Chinameca Prefeasibility (Deep exploration)	6	$16,600	-
C.W & Drilling Wells on 4 Pads in Chinameca Geothermal Field	Chinameca Feasibility	40	$108,000	$18,000
C.W & Mechanical Works for Binary Cycle 2 Berlin Geothermal Field	Development of Berlín Geothermal Field	27	$72,900	$18,000
C.W & Drilling of 4 wells in SV-5 (SV-5 A,B,C,D)	San Vicente Prefeasibility (Deep Exploración)	8	$21,600	-
C.W & Drilling of one aditional well on AH-35 (D) Pad	Operation & Maintenance of Ahuachapán Power Plant	8	$21,600	-
O.C y mecánicas de la interconexión AH-34/AH-16, C.G.AH	Operation & Maintenance of Ahuachapán Power Plant	9	$24,300	$20,500

* Cover direct and indirect costs of one person/ month
** Cover payment for professional services in preparation of the study during 3 months

As mentioned above, Table 1 shows that the time of response does not depend on status or significance of project impacts, but to the discretion of the technical reviewers of the Ministry.

3. STRATEGIES AND PROPOSALS FOR IMPROVING EA PROCESS

Developers of power projects still experience legal barriers that do not allow them to act towards a clear process for exploration and exploitation of renewable natural resources. The origin of the conflict of interest is heightened from the policy of decentralization of electricity market created in 1998, which was established apart from the other institutions involved in the sector; hence some gaps arise, confusing the developer of power projects.

For more than ten years of an institutional framework for renewable energy development, several initiatives have emerged to contribute to the efficiency and effectiveness of government services in terms of administrative processes.

Some institutional policy to improve the EA process and the electricity sector initiatives are shown in the following.

3.1 Environmental Auto Regulation System

Proposal prepared by LaGeo and CCAD and submitted to MARN in 2005, among other objectives presented are:

- Standardize criteria regarding quality requirements with environmental and social impact, under conditions of transparency, sustainability, monitoring and control in the context of geothermal projects and the operation of geothermal power plants;
- Streamline business processes and procedures and overcome legal gaps between requirements and MARN- SIGET;
- Promote better compliance with predetermined standards for achieving environmental policy goals in El Salvador; and
- Promote the development of culture on the importance and promotion of the exploitation of this kind of energy source.

3.2 Proposal Incentive Renewable Electric Generation Resources

The Summary Progress Report (2007) UNDP / GEF project which concluded that the main barriers to investment are more of administrative nature. Among them are:

- It is proposed to establish specific and brief MARN rules for granting environmental permits for power plants below 5 MWe to reduce the participation of many technical specialists, focusing only to those areas with greatest environmental impact;
- It is proposed that public consultation be carried out together with the opposing groups on the projects; and
- Remove the bail application for projects where mitigation of environmental impacts is integrated into design system for generation and should be budgeted for implementation.

3.3 Proposal prepared by GIZ-CNE

The consultancy with partnership of GIZ-CNE June/13 is known as "Entry Barriers to Low Enthalpy Geothermal Projects in El Salvador and Proposed Solutions". The main purpose of the study is to establish strategies to facilitate the implementation of low-enthalpy geothermal projects within the appropriate socio-economic and climatic conditions in El Salvador, such as industrial, commercial or residential applications. As entry barriers to the use of this resource, the following were identified:

- Lack of a legal framework to regulate the quick granting of concessions at low enthalpy geothermal projects for generation of electricity; and
- Lack of environmental legal framework to regulate and facilitate the exploitation of low enthalpy geothermal resources.

3.4 Energy Policy in El Salvador

The National Energy Council (NEC) issued the El Salvador Energy Policy for 2010-2014, which established as one of its principles, diversification of the energy matrix towards sustainable development and proper integration with other sectors. One of its objectives is to strengthen the institutional and legal framework to promote, guide and regulate the development in the energy sector. Diversification of the energy matrix and the promotion of renewable energy sources comprise the following key concepts:

- Design appropriate policy framework for the development that encourages private investment and to ensure energy supply to end users;
- Identify the national potential of renewable energy through different studies to determine the potential and allow proper planning of new projects; and
- Ensure benefits for communities involved and affected by projects of renewable generation, contributing to energy sustainability of the country.

The last proposal issued by the NEC is to have greater aperture to help improve the administrative processes and procedures for the investment of energy projects. The organizational structure of the Council, represented by the Ministers of Environment and Economy, is facilitating the institutional decision to give quality service to public and private user.

4. RECOMMENDATIONS

Considering the application of environmental legal framework of the electricity sector, it should be made possible the implementation of renewable energy projects and especially the strengthening of management processes for the use of low enthalpy geothermal energy. The following recommendations are given:

Make proposals where the developers agree with the renewable energy projects, including geothermal high, medium and low enthalpies.

- The coordination should be handled by the National Council of Energy through civil participation (private schools, public schools, academes, non-governmental organizations, municipalities, etc.). All involved and interested parties should contribute on the efficient management processes without personal interests and compliance with the existing legal framework.

- That rightful institutions ensure legal compliance of the regulatory framework for the power sector, and must establish administrative processes and procedures considering the time and costs for developers and policy-state projects as well as strategies to rescue legal framework credibility.

- For the proposal in 3.3, a summary is prepared by GIZ and CNE, where in the introductory part of the original document presents a list of geothermal applications of low enthalpy in El Salvador by type of industry, however, there are barriers evaluated as lack of a legal framework to regulate the quick granting of concessions at low enthalpy geothermal projects, other than power generation activities. Secondly, the response time for obtaining permits is longer, thus delaying the start of the project and the return on investment; and the risk in obtaining financing. In this regard, it is worth reviewing the implementation of the Categorization of Environmental Law to Environmental Resolution included in the EA process, where no processing will be required by the Ministry for the Group A, which could also be applied to agro-industrial projects and residential-commercial sectors.

REFERENCES

Asamblea Legislativa de la Republica de El Salvador, 2007: Ley de incentivos fiscales para el foment de las energías renovables en la generación de electricidad. Republic of El Salvador, decree 462, 8 pp.

Ayala de Arévalo, A.S., 2005: *Propuesta de autorregulación ambiental para proyectos geotérmicos*. LaGEO-CCAD, Santa Tecla, El Salvador.

Ayala de Arévalo, A.S., 2011: Evaluación de impactos ambientales de proyectos geotérmicos en El Salvador. *Presented at "Short Course on Geothermal Exploration and Development", San Salvador, El Salvador*.

García, J.J., 2013: Barreras de entrada a los proyectos geotérmicos de baja entalpía en El Salvador y propuestas de solución. Consejo Nacional de Energía, San Salvador, El Salvador.

SIGET, 2011: *Anexo A. Documento de consulta. "Normativa técnica para caracterizar los proyectos que aprovechan las fuentes Renovables en la generación de energía eléctrica"*. Superintendencia General de Electricidad y Telecomunicaciones, Acuerdo N-584-E-2011, 41 pp. Web: http://www. siget.gob.sv/attachments/1558_AnexoNormativaTecnica.pdf

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GEOTHERMAL DRILLING: THE PRICE OF REACHING THE RESOURCE

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ABSTRACT

Geothermal projects typically have high initial investment costs due to drilling needs, power plants built and the relatively low operating costs. The replacement cost of steam for a 75 MW project represents 25% of the cost in a period of 30 years. Operating costs vary depending on the plant capacity, thermodynamic and reservoir transmissibility chich directly affects the numbers of the replacement wells (new wells to recover lost production or injection capacity).

The costs of the steam supply not only include drilling or workovering wells, also have to consider the exploration and resource confirmation, surface facilities and infrastructure costs. The costs of the components and factors influencing them are usually independent of each other, and each component is described in the following text, including its impact on total investment costs.

The first components includes acquisition or lease land in order to do a geological and geophysics prospection, wells location, roads as well as building the drilling pad.

The second component is the drilling of production or injection wells which have a success rate range from 60 to 90% percents, the cost of this factor include the depth of the wells, rig availability, well design (vertical or directional), special fluid circulation, drilling times, wells number and financial considerations in drilling contracts. (Hance de 2005;. Tester et al, 2006).

The third component is well equipment to obtain steam and to handle brien, such as separators, valves, pumps, pipes and roads access. If the brine handling is not necessary the installations to obtain steam has the lower costs. Factors than incises in this cost are related to the chemical composition of the fluids, prices of raw materials (steel, cement), topography, accessibility, slope stability, the well average productivity and its location regarding to the power plant (pipes, diameters and length), and fluid parameters as pressure, temperature or chemicals characteristics (Hance, 2005).

1. INTRODUCTION

Geothermal field location depends among others factors on the natural process that lead to the geothermal reservoirs formation, for which several studies are performed, with different objectives, some conducted to evaluate the geothermal reservoir potential, others to describe physical and environmental conditions, and others more in order to define the commercial exploitation feasibility of the geothermal resource.

Once defined the geothermal reservoir, begins the development of geological, geochemical and geophysical studies, involving the collection of ground surface level data, without the intervention of the environmental setting. These studies allow creating a Conceptual Model, which give future scenarios for development, (Hiriart-LeBert, 2011).

The next stages mainly consist of drilling wells at variable depth, depending on reservoir local conditions. The main objective is to prove the existence of the adequate conditions of a geothermal fluid for exploitation and subsequent electricity generation. Deeper exploration consists of several types of drilling with different targets, from gradient shallow thermal wells (300-100m small diameter) to exploration wells typically completed with large diameters and deeper (1000-3000 meters).

The wells depth in Mexico varies between 600 and 3500m, depending of the region and the zone of the permeable geological structure. The appropriated drilling equipment is selected according to the depth of the projected well, the formations to be drilled and the specific reservoir conditions. The drilling time depend of the programmed depth and the geological subsoil conditions. According to Mexico´s experiences, the perforation time of a typical well varies from 45 days to 180 days, noteworthy that for the latter case, external factors influenced in the prolongation of drilling times.

Within of the costs structure is necessary differentiating the two main items: the operation and maintenance costs (labor and equipment) and the steam supply and replacement costs. In order to exploit a steam ton, addition to the investments involved in the productive well, have to incur in operation costs and contribute to the maintenance of the structure costs (indirect costs).The operations costs varies depending of the power plant capacity, the reposition wells (new wells to recover lost production or injection capacity).The construction of wells to steam replacement as well as to repair production or injection wells during the lifetime of a project (30 years) in a 75MWpower plant represents 25% of the total costs, (CFE 2011).

The costs of the steam replacement not only include drilling or repairing wells, also have to consider the exploration and resource confirmation, surface facilities and infrastructure costs. The costs of the components and factors influencing them are usually independent of each other, and each component is described in the following text, including its impact on total investment costs.

2. PREPARATION OF THE DRILLING PAD

The first component of the cost includes acquisition or lease land roads as well as building the drilling pad, once selected the new well location (Figure 1). In existing drilling pads as well in new ones is necessary weed, clean, race, even the well and conditioning the drilling pad. In this step the costs will depend of the road length. In Mexico the usually the dimensions of the drilling pad are 40 x 80m. The length of the access roads is 6 m wide. The cost of building a standard drilling pad of 40 x 80 m is USD 75,000.

FIGURE 1: Drilling pad and roads access

3. DRILLING PRODUCTION AND INJECTION WELLS

The second component is the drilling of production or injection wells which could have from 60 to 90% percentage of success (Hance, 2005; GTP, 2008) The cost of drilling a well depends on different factors such as the wells depth, rigs availability, well design (vertical or directional), special fluid for circulation, number of wells to be drill and the financial considerations in drilling contracts (Hance de 2005;. Tester et al, 2006).

Once building the roads access, drilling pads and mud dam, but before installing drilling equipment proceeds to waterproof the new drilling pad, to avoid spillage of fuels and lubricants on the ground, also mud dams are waterproofed to place and crop waste material generated during drilling (Figure 2). At the end of this activity, these residues are stored, removed and sent to authorize landfills. Subsequently, begins with the assembly of the drilling equipment and its installation on the drilling pad.

FIGURE 2: Site selected for the mud dam and waterproofed

The drilling time depends, firstly, of the well length, due to the deeper formations are harder to drill and for the other hand and secondly, due to the "reposition time" which increases with depth whenever of the string drilling has to be replenished. As well as the drilling time depends also of the each lithological formations that are drilling, for example if we found limestone or sandstone or shale the advance of drilling time decrease or even can be adjourned. In other case if there high probabilities of unexpected pressures, it is needed to prepare a program of special coating, which will take more time to install, (Jennejohn, 2009).

However, this time can vary from 45 days to a well 1,800 m deep to 150 days for one whose depth reaches 3500 m.

In Mexico the geothermal drilling steps have been standardized and only, depends on the depth of the well varies the area where the different pipes are cemented. The drill hole is started with a depth of 5 m and 1 m (40 inch) diameter, in which the annular conductive tube is installed. This tube has an inner diameter of 0.762 m (30 inch).

The following activity is drilling up to 50 m deep to install the TR of 508 mm (20 inch) Diameter pipe called surface pipe. This hole drilling is carried out first, using auger 311 mm (12 ¼ inch) diameter, extending later, at 508 mm, and finally to 660 mm (26 inch).

The next step is to drill the hole to 500 m depth using auger 311 mm in diameter and its extension to 444 mm (17 ½ inch) . The procedure to install the anchor pipe 340 mm (13 ⅜ inch). In the next stage the well is drilled up to 1200 m deep well with 311mm diameter auger. In this section will be installed and cemented the production tubing of 244 mm (9 ⅝ -in), from the surface to a few meters (5 m) above the bottom of the hole. In the last phase, was directionally drilled with auger 216 mm (8 ½ inch) in order to locate producing area to find attractive or sooner if conditions of pressure and temperature are localized before. At this stage pipe (liner) of 178 mm (7 inch) diameter is installed. This is characterized by vertical slots along its length to allow access of the geothermal fluid. Table 1 shows in summary the types of pipes and setting depth of these and in Figure 3 a typical layout of the pipe configuration of a well in Mexico.

TABLE 1: Pipe diagram configuration and settlement depth

Diameter of bit	Diameter of pipe	Tube type	Setting depth
40”	30”	Conductor	5 m
26”	20”	Superficial	50 m
17 ½”	13 3/8”	Anclaje	500 m
12 ¼”	9 5/8”	Conductora	1200 m
8 ½”	7”	Producción	2000 m

The total wells cost tends to increase exponentially with depth (Shevenell, 2012), (Table 2). In special areas, the mobilization costs and demobilization of drilling equipment must be taken into account, as they can reach several hundred thousand dollars. This will significantly increase the drilling cost. For example, in Mexico typical well of 2200 meters depth cost about $ 5.5 million. Figure 4 shows a graph of the cost of drilling well with depth and time.

TABLE 2: Approximate costs according to well depth

Depth	Costs
1500 m	USD 4,500,000
2200 m	USD 5,500,000
2500 m	USD 6,300,000

In Figure 5, the graph shows the percentage that each item in the total cost of the well. Well casing costs represent 18% of the well drilling cost, while cementing represents 14% of total cost. 38% of the total cost represents the actual operation of drilling the well.

The fixes costs can vary greatly from one well to another, even within the same general area. These costs relate to the administration, data interpretation, decision making, etc. and, usually expressed as a percentage of the costs of geophysical studies and drilling exploration. In areas well known and developed the fixed costs can be low and represent 15% of the geophysical costs and 10% of drilling costs, while new areas, fixed costs are generally high: about 25% of the first and 20% of the latter.

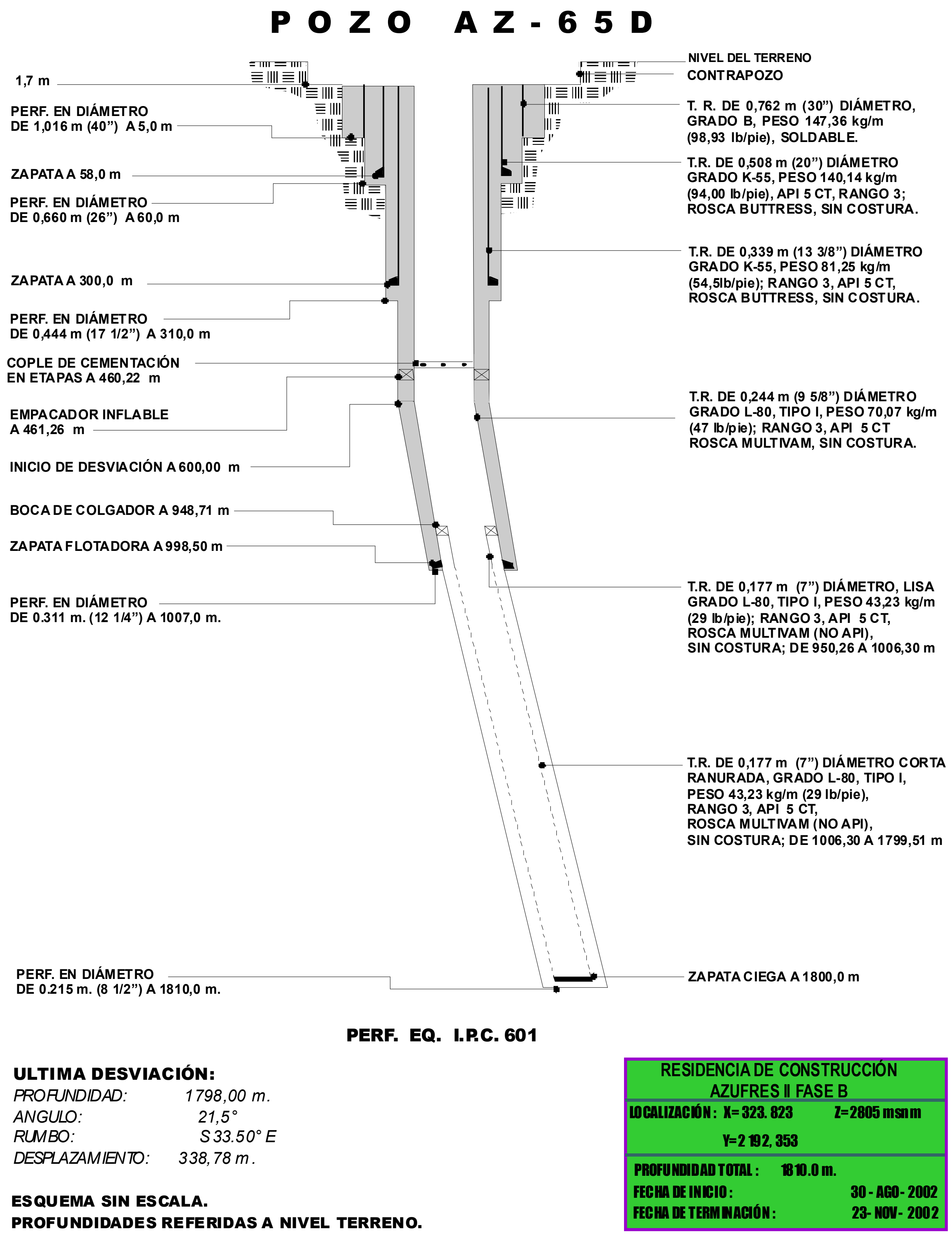

FIGURE 3: Pipe diagram configuration of a typical well in Mexico

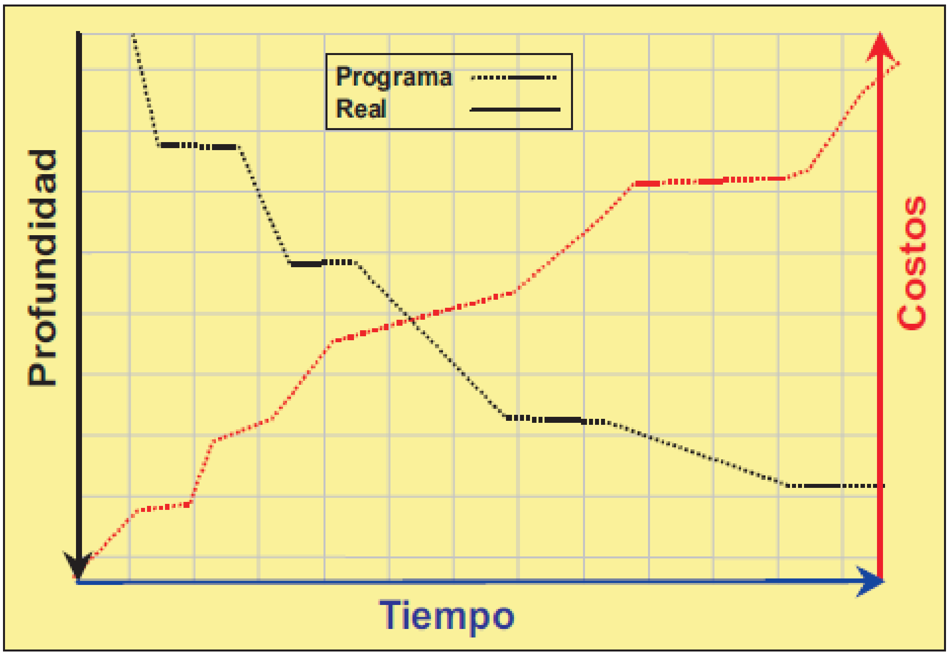

FIGURE 4: Drilling cost with respect to well depth and time

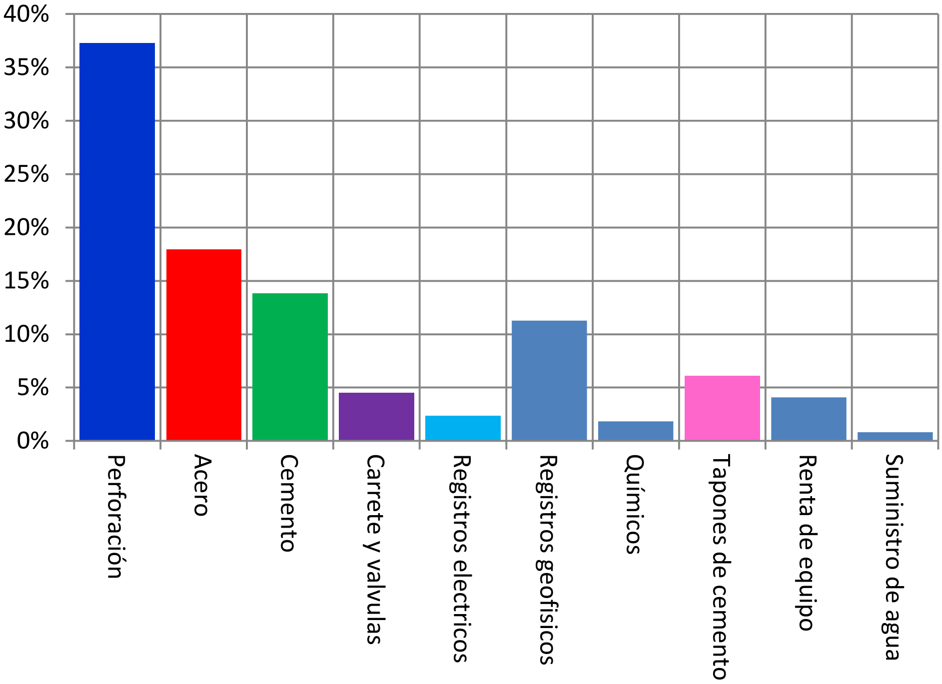

FIGURE 5: Distribution of well costs

4. INFRASTRUCTURE FOR THE EXTRACTION OF STEAM

A third component is the neede installation to obtain steam and to handle the separated brine; separators, pumps, pipes and roads access. If the brine handling is not necessary the installations to obtain steam has the lower costs. Some of the factors are; chemical fluids compositions, prices of raw materials (steel, cement), topography, accessibility, slope stability, the well average productivity and its distribution (pipes, diameters and length), and fluid parameters as pressure, temperature or chemicals characteristics (Hance, 2005).

Once drilled the well to produce steam, it is required to perform the necessary infrastructure for evaluation, development and integration of the well to the steam supply system. The mixture of water and steam flowing in each well is sent to a separator where the water is separated from the steam, each separator is installed in the well drilling pad, but in some cases several wells production is sent to a separation island, the mixture enters the separator tangentially with respect to the equipment body, inducing a centrifugal force separating the phases, because of the higher density of water related to steam, it acquires greater inertia than steam, will stick to the wall of the separator and by gravity falls to the bottom of the device. The separated steam flows the top through the central pipe, to be sent to the turbines by means of a steam pipe designed and built with carbon steel materials and thermally isolated to ensure efficiency.

The cost of the equipment of each well to supply the steam to the power plants varies depending on the distance between the well and the interconnection point with existing steam pipe. In addition to the steel pipe, valves are required as well as centrifugal separators, silencers and pipelines to transport the flash brine to the injector wells. A standard cost for this concept oscillates around USD 640,000 thousand

5. CONCLUSIONS

Within of the costs structure it is necessary to differentiate the two main items: the operation and maintenance costs (labor and equipment) and the steam production and replacement costs.

The construction of wells to produce steam as well as work overs in production or injection wells during the lifetime of a project (30 years) in a 75MWpower plant represents 25% of the total costs.

The costs of the steam not only include the drilling or workovering g wells, also have to consider the exploration and resource confirmation, surface facilities and infrastructure costs. The costs of the components and factors influencing them are usually independent of each other.

The total well cost tends to crease exponentially with the well depth. This will increase significantly the cost of drilling. In special areas the mobilization and demobilization of drilling equipment must be taken into account, as they can reach several hundred thousand dollars. For example, in Mexico 2200 meters typical well costs about USD 5.5 million. Well casing costs represent 18% of the well drilling cost, while cementing represents 14% of total cost. 38% of the total cost represents the actual operation of drilling the well.

The cost of equipping wells for steam supply system varies depending on the distance between the well and the interconnection point with existing steam pipe. In addition to the steel pipe required the installation of valves, centrifugal separator, silencer and works to transport the flash brine to the injector well.

REFERENCES

CFE, 2011: *Programa de obras e inversiones del sector eléctrico 2009-2018*. CFE, Subdirección de Programación, Coordinación de Planeación, 262 pp.

Hance, C.N., 2005: *Factors affecting costs of geothermal power development*. Geothermal Energy Association, 64 p.

Hiriart-LeBert, G., 2011: *Evaluación de la energía geotérmica en México*. Informe para el Banco Interamericano de desarrollo y la comisión reguladora de energía, 164 p.

Jennejohn, D., 2009: *Research and development in geothermal exploration and drilling*. Geothermal Energy Association, Washington D.C., United States, 25 pp. Web: https://www.novoco.com/energy/resource_files/reports/geo_rd_1209.pdf

Shevenell, L., 2012: The estimated costs as a function of depth of geothermal development wells drilled in Nevada. *Geothermal Resources Council Transaction, 36*, 121-128. Web: http://pubs.geothermal-library.org/lib/grc/1030220.pdf

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

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OPERATION, MAINTENANCE AND MONITORING: MANPOWER AND MATERIAL NEEDS OF AHUACHAPAN POWER PLANT, EL SALVADOR

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ABSTRACT

In El Salvador, like many countries in the world, the production of electricity from geothermal resources is considered as base load and is very important from environmental and economical points of view as the gas emissions are cleaner and the production costs are lower compared with others resources.

The geothermal energy production in El Salvador dates back to 1975, with the first 30 MW unit in Ahuachapán. Today, there are two geothermal fields in operation: Ahuachapán and Berlín with an installed capacity of 95 MW and 109 MW, respectively.

In El Salvador, the production of electricity with geothermal resources contributes 24% (average January, March 2013, according to UT) to the energy consumption of the country.

This paper describes the operation, maintenance and monitoring: manpower and material needs of Ahuachapan geothermal power plant.

1. INTRODUCTION

With regards to the supply of electrical generation, the market in El Salvador shows the leading position of thermal generation, with almost half of the total energy generated. Hydro generation takes the second place, and finally an important portion of geothermal generation.

Maximum capacity installed in June 2009 showed an increase with respect to June 2008 to 7.2% (50 MW).

According to Figure 1, it can be observed that thermal generation would tend to increase and geothermal production would decrease during its maintenance activities, therefore the production of hydroelectric plants must be in its normal capacity to maintain the distribution of energy production (SIGET, 2009).

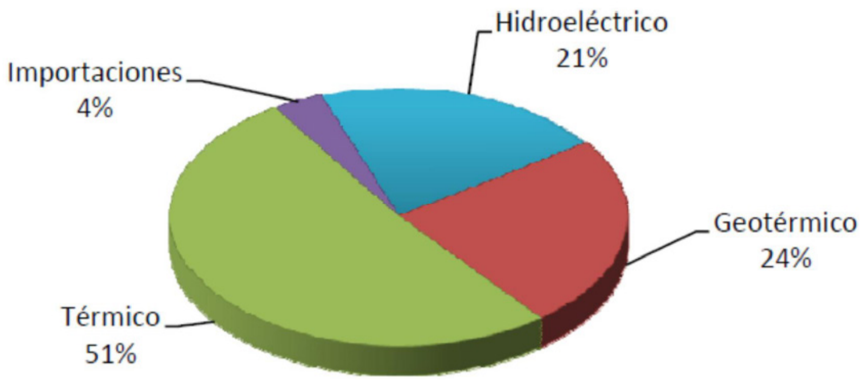


FIGURE 1: Generation in 2013 by type of resource (%)

Figure 2 shows the prices according to the statistical report of UT 2009. Prices vary according to the source of energy production. The low costs are obtained first from hydroelectric and then geothermal, while the high ones correspond to the thermal production due to its dependence on the price of fuel.

It is the objective of this paper to provide the best way to undertake maintenance activities in geothermal power plants by reducing the working time, and preventing excess participation of the thermal production.

2. DESCRIPTION OF THE AHUACHAPAN POWER PLANT

2.1 General information

The Ahuachapán geothermal power plant is located 103 km west of San Salvador, the capital city and 3 km east of Ahuachapan city (Figure 3).

The operation of the power plant started with the installation of a Mitsubishi unit (30 MWe single flash condensing type) in 1975 and a few months later in 1976 an additional, identical Mitsubishi 30 MWe unit was added. In 1980, a new Fuji 35 MWe, unit 3 (double flash) went on line using the separated brine to produce low pressure steam, bringing the total installed capacity to 95 MWe. The reservoir pressure from 1975 to 1983 was maintained, however it experienced a pressure drop which was considered to be overproduction of the reservoir.

In 1983, the power plant operated with three units but not to their full capacity. In 1984, the operation programme was changed, with only two units working, while the other one was in standby as there was not enough steam to run the three units at the same time. New sites in the southern part of the actual production zone are being evaluated to find more steam to put the other unit in operation.

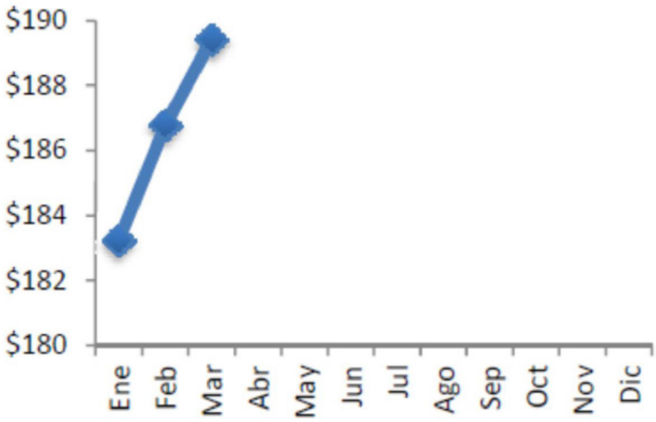


FIGURE 2: Average price of electricity in El Salvador (January to March, 2013)

The three units were put into operation again, increasing the total output from 65 to 80 MW as shown in Figure 4. Rodriguez (2007) estimated the reservoir pressure drop to be almost 1 bar. Figure 5 shows the evolution of the reservoir pressure in Ahuachapan geothermal field.

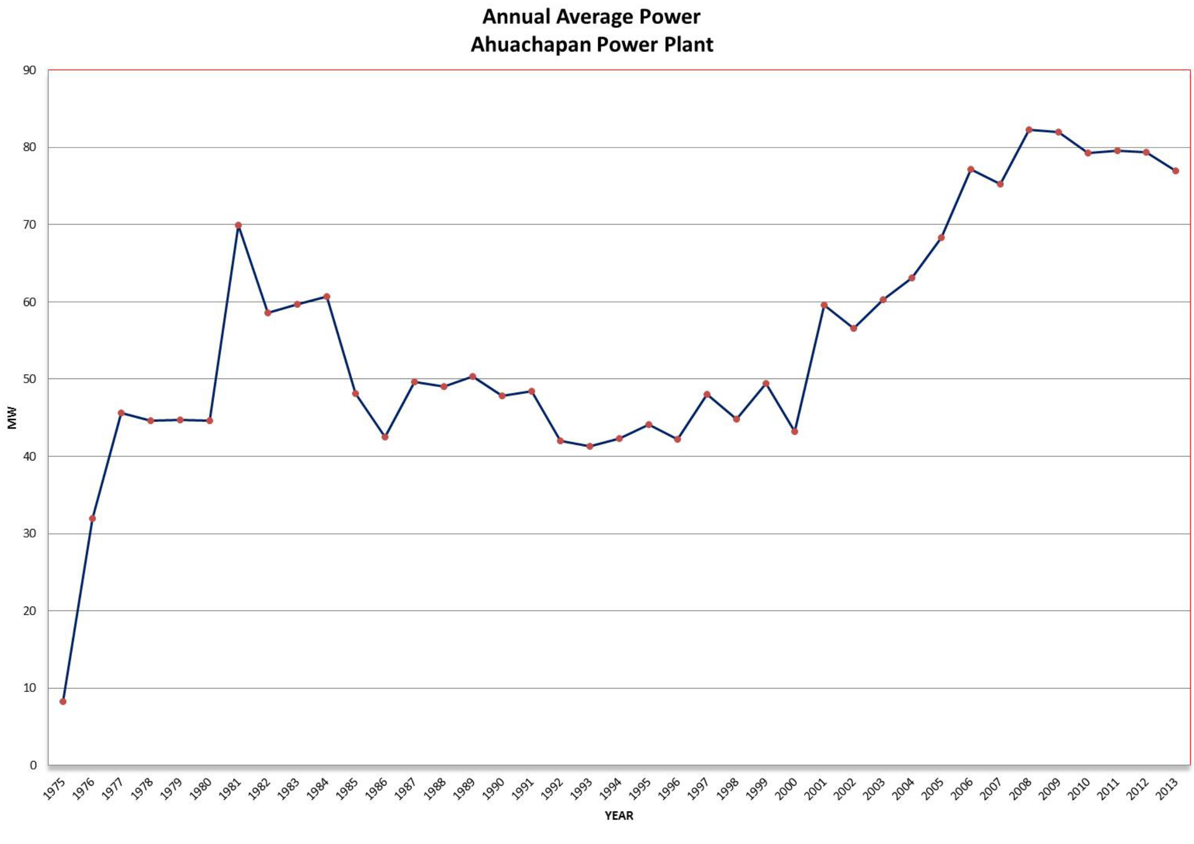


FIGURE 4: Annual average production of Ahuachapan power plant

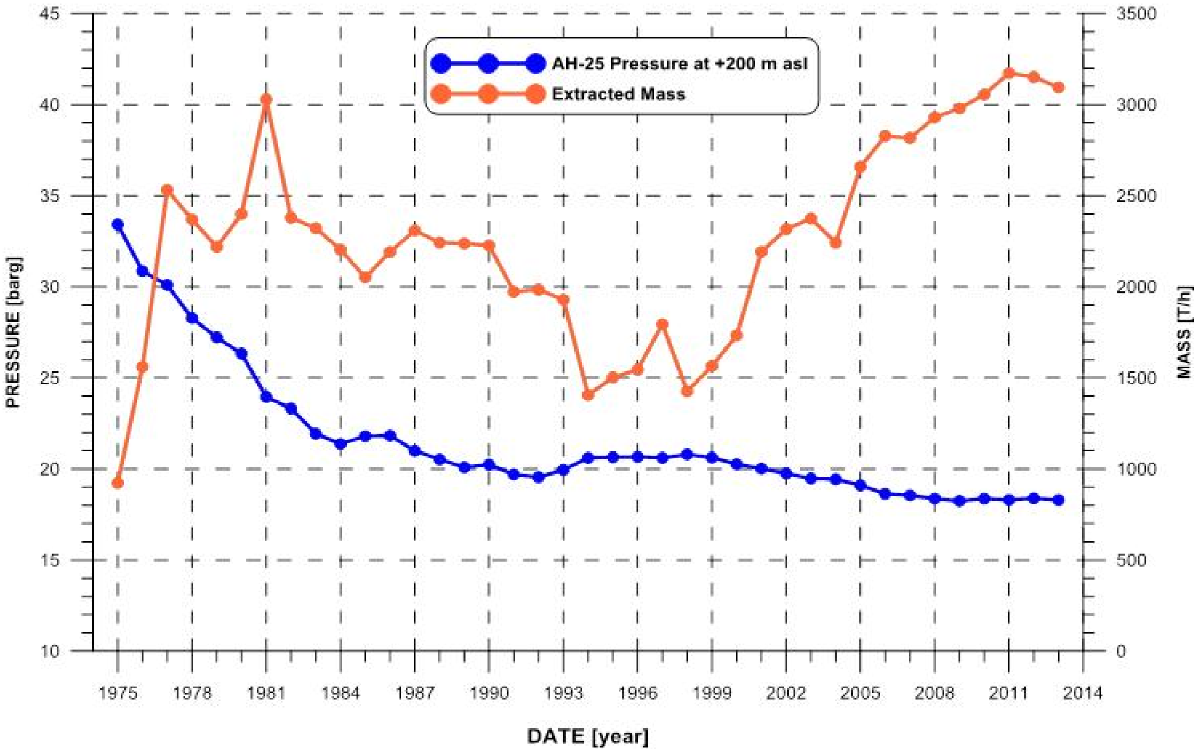


FIGURE 5: Reservoir pressure in Ahuachapan field

2.2 Operation characteristic in Ahuachapan Power Plant

The energy production of the power plant is provided by the three units: two single flashes condensing units with an output of 30 MW each, both supplied by Mitsubishi; and one double flash of 35 MW by Fuji. The full load steam consumption of these turbines is 460 t/h (127 kg/s) of saturated steam at a pressure of 4.6 barg that comes from two pressurized tanks called steam headers, which collect the steam produced by a number of producing wells (Figure 6).

At the exit of the turbine, a direct contact barometric condenser is located, where cooled water is sprayed to condense the exhaust steam. This water comes from a cross flow, forced draft cooling tower with five cells. The total flow of cooling water is approximately 8650 m^3/h and the ambient temperature is 27 degrees C; the average pressure in the condenser is 0.085-bar. The condenser is connected to a gas extraction system such as steam-jet ejectors, which has a cooling system that cools 0.2% by weight of non-condensable gases that go along with geothermal steam (Figure 6).

The gas extraction system has two stages with inter condenser and after condenser. These ejectors are required to operate a steam flow of 4100 kg / h of steam to compress gas from the vacuum in the condenser to external weather conditions in the discharge zone.

The turbines are attached directly to a synchronous generator with a brushless exciter and a closed air cooling system to prevent contamination by hydrogen sulphide (H2S) of the copper conductors. The nominal capacity of the generators is 35,000 KVA with a power factor of 0.85. The voltage output of the generator is 13.8 kV, which is connected to the national grid of 115 kV through a step-up transformer located at the substation (Figure 6).

The third unit of the plant is a 35 MWe double flash unit supplied by Fuji and went into commercial operation in 1980. Unlike the other two units, this one uses a lower steam pressure (1.5 bar-a) in addition to the medium pressure steam. The low pressure steam is obtained from a double process of separation of geothermal fluid. To carry out this process, water is headed to a two - low pressure separators (flashers) where low pressure steam is obtained and sent to the collector, then to the last stages of the turbine. With this arrangement, the output of the plant was increased by 15%.

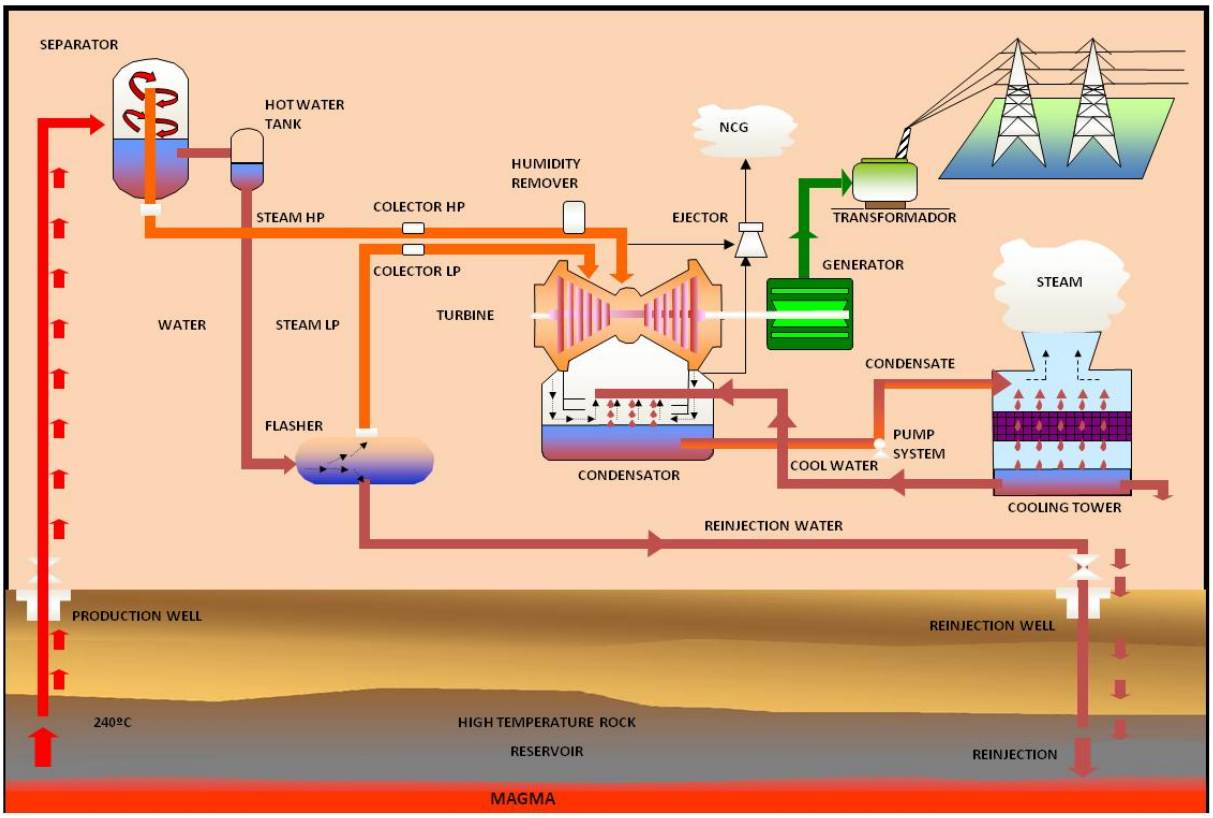


FIGURE 6: Simplified process flow diagram for a geothermal power plant

2.3 Mechanical equipment installed in Ahuachapan Power Plant

2.3.1 Turbine and auxiliaries

The turbine is one of the most important parts of the equipment of a geothermal plant and also one of the most expensive (Figure 7). According to records, the turbine is the equipment where it needs more time to do the job of overhaul. Some of the main parts of the turbine are: rotor, stationary blades, main oil pump, auxiliary oil pump, outer casing, inner casing, coupling bolts, turning gear, overpressure rupture disks, condenser, bearings, gaskets, oil sealing, storage tank, steam strainer, barometric pipe and over speed safety device.

FIGURE 7: Machinery room in Ahuachapan power plant

2.3.2 Cooling system

The cooling water system is composed of the cooling tower, the main circulation water pumps, the cooling pumps and the system of auxiliary pumps.

Mechanical work in the cooling tower during the overhaul includes the inspection of the system of fan gear box, which are dismantled to verify internal conditions.

2.3.3 Gas extraction system

It is designed to operate with two steam-jet ejectors, the steam for this system is taken directly from the main steam line. There are another two steam-jet ejectors mainly used as a back-up system.

At present, the normal operation of the non-condensable gas extraction system is done with a vacuum pump and the ejector system described above as standby.

Some of the main parts of the old gas extraction system are four steam-jet ejectors and two auxiliary water pumps, valves. The new system is composed by one ejector, valves, vacuum pump, reducer gear box and lubrication water pump.

2.3.4 Generator

Normally, the disassembly and internal inspection of this equipment is necessary after every four years of continuous operation. It is the responsibility of mechanical area the disassembling and inspection of all mechanical components, while the electrical aspects like insulation condition assessment, cleaning and testing are the responsibilities of the electrical area. When the electrical inspection is finished the mechanical area starts the re-assembling.

A summary of the main components in the process is shown in Table 1. Only the major components under each system are presented.

TABLE 1: Information about the systems, equipments and components

Main systems	Main equipments	Main components
Steam conduction and transmission (gathering system)	Wellhead, Separator station, Steam transmission and Water transmission	Master valves, flow control valve, two-phase pipeline Separator vessel, pressure relief device, level control Steam pipe, condensate drains, steam pressure, controllers, steam driers, steam flow meters Hot water pipeline, hot water pressure relieves. Humidity separators
Turbine and auxiliaries	Inlet devices Steam Turbine Oil system	Steam strainer, emergency and governor valves Rotor, nozzles, diaphragms, bearings, casing, packing gland seals Oil pumps, servomotors, oil pipes.
Cooling system	Cooling towers and water pumps condenser	Fans, motors, gear reducers, structure, fills, cold water ponds, strainers Large hot well pumps and motors, auxiliary pumps Condenser heat exchangers, nozzles, gas cooling
Gas extraction system	Steam jet ejector and Vacuum pump	Control valves, isolating valves, nozzles, intercoolers Vacuum pump and motor, water seal pump and motor gear reducer box.
Generator and electrical	Generator, Transformers and Protection	Rotor, stator, exciter, bearings, coolers Step up transformers, station transformers Relays, switchgears,

3. TYPES OF MAINTENANCE IN AHUACHAPAN POWER PLANT

The types of maintenance in the power plant are preventive, predictive and corrective maintenance.

3.1 Preventive maintenance

For the preventive maintenance, this type of management system is based on computerized /manual, written/updated procedures, and audited (Figure 8). Written programs of routine activities are developed, and a computerized maintenance management software (MAXIMO) is usually applied. It has the objective of providing information necessary at a suitable moment to realize the activities for maintenance. The program can be done following the recommendations given by the machinery manufacturer and furthermore, the experience gained by the maintenance and operation personnel. This also facilitates the gathering of information to determine which parts of the equipment demand more man-hours and money.

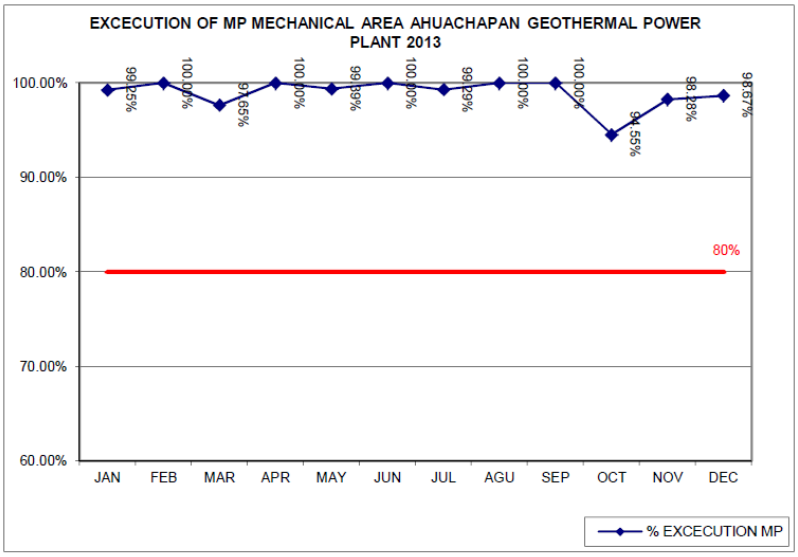


FIGURE 8: Control about MP in Ahuachapan power plant

It is also possible to obtain information on the amount of work orders for preventive, corrective and predictive maintenance.

3.2 Predictive maintenance

The common maintenance procedures carried out under the predictive maintenance include vibration analysis, thermography, ultrasonic and oil analysis. Table 2 gives a summary of the predictive maintenance and their applications. The first four are the common procedures and are described in detail.

TABLE 2: Advantages and disadvantages of predictive maintenance

No	Predictive Maintenance	Applications
1	Vibration analysis	Misalignment, out of balance weights, wear of bearings etc
2	Thermography analysis	Overloading, excessive friction or wear, abnormal electric resistance
3	Oil analysis	Contamination, breakdown of lubrication properties, signs of wear
4	Current measurement	Electric overloads, faulty bearings, current leakage
5	Visual inspection	General defects that can be detected by human senses of sight, hearing and feeling
6	Insulation tests	Check status of electric insulation
7	Power rate	Bearing failures, damaged turbine blades, vacuum loss
8	Voltage measurement	Brush failure, excitation faulty, insulation failure

Vibration analysis: Software for vibrations analysis is used in predictive routines. In the main water circulation pumps, equipment is inserted to obtain vibrations without having to execute routines of measurement with portable equipment. This facilitates the information on the conditions of operation of the pumps. This equipment is considered important for the good operation of the generating units. With this, it is possible to observe in the control room the magnitudes of vibrations of the pumps as well as the graphs for further analysis (Figure 9).

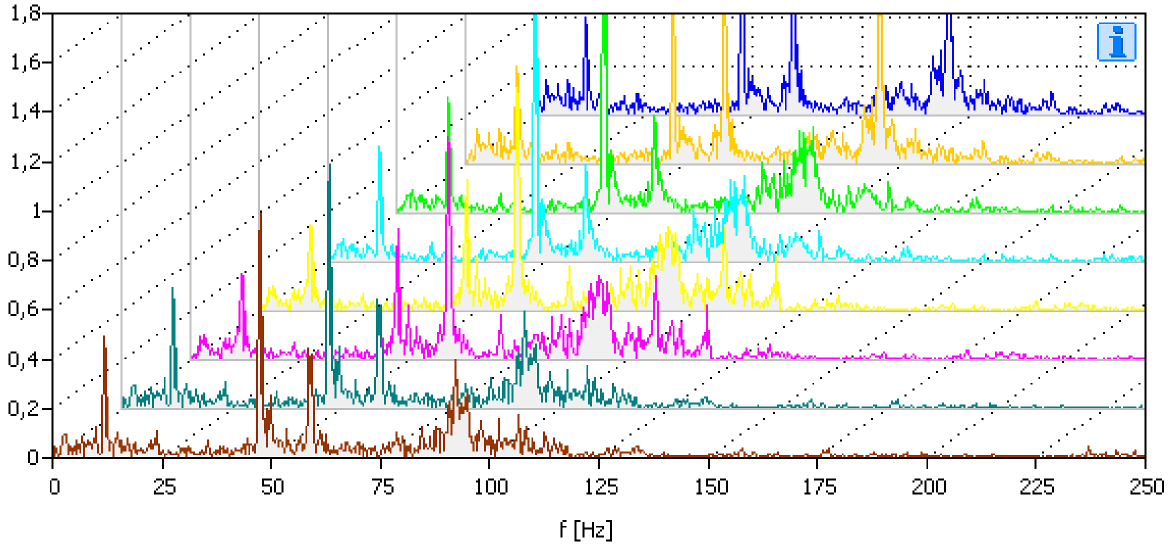


FIGURE 9: Operation condition register

3.3 Corrective maintenance

Through the MAXIMO software, it is possible to get statistics of corrective maintenance, for example in October and November 2010, there were less than 2% monthly of corrective maintenance (Figure 10).

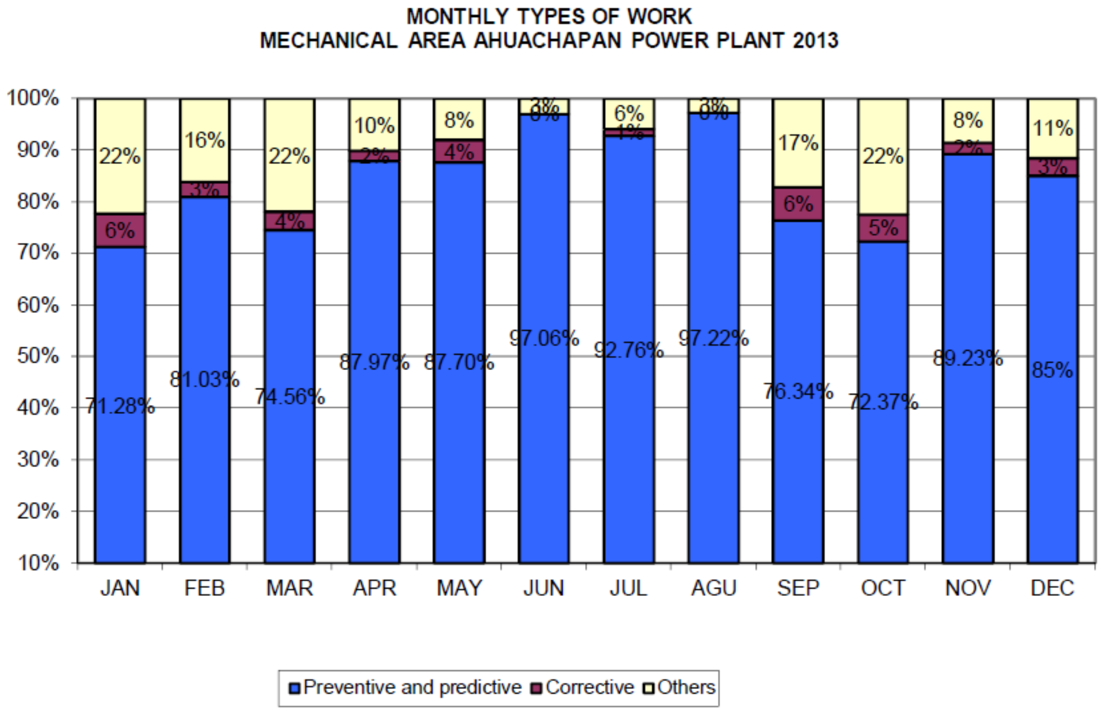


FIGURE 10: Control about types order work

4. OVERHAUL IN AHUACHAPAN GEOTHERMAL POWER PLANT

4.1 General information

The overhaul of a unit is carried out every two years of continuous operation. This maintenance usually takes four to six weeks to complete, depending on which unit is to be maintained. For this type of maintenance, it is necessary to optimize the time and cost, the time because when one geothermal unit is shut down, the electrical system in El Salvador requires putting online thermal plants, thus the electricity produced by these plants is considerably more expensive (López, 2006).

When the Ahuachapan power plant undergoes overhaul in any unit, it is necessary to prepare the working tools , possible spare parts and the temporary personnel to be hired during the programmed time to carry out the work.

Due to the provisions of the energy system of the country, it is necessary to schedule overhauls so that the power system operator (UT) can guarantee the supply of energy by scheduling the maintenance of the electrical power plants. UT evaluates if it is possible to authorize it or not; which depends on the generating conditions of the hydroelectric plants, otherwise high contribution of thermal production would be required, which could cause the high price of electricity.

4.2 Manpower for overhaul in mechanical area

The organization chart of mechanical area is shown in Figure 11 for permanent workers only. In the power plant, for overhaul, it is necessary to hire personnel with the required skills to carry out the work. The number of people to be hired depends of the scope that is defined for the maintenance and of the determined time to develop it. Programming is undertaken with the participation of the involved personnel. With the different areas, generally operational ranges are discussed, for example in the cooling tower, the mechanical area is required to disassemble the fan gear boxes for inspection and the group responsible of the electrical part is required to disassemble the motor for inspection. Occasionally, the personnel in charge of the tower, is required to make changes in wood materials and should have a very good coordination to avoid conflict between workers and the subsequent delay.

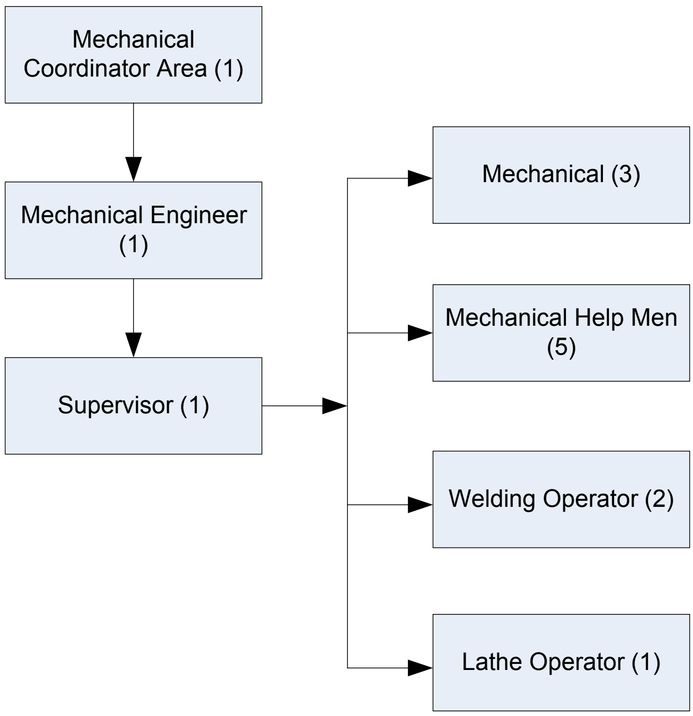


FIGURE 11: Chart of mechanical area Ahuachapan

Thus, it is important to define the program of maintenance to establish a clear view of the objectives and the time to execute it. After designing this guide, it is possible to determine the optimum number of personnel to be contracted for the work.

After considering the first aspect that consists of assuring the availability of important spare parts, personnel has to evaluate the tools to use, since some of them are considered special and the procurement time can be long, so if they are not prepared in advance, delays in the maintenance schedule could occur.

Another important aspect in relation to the tools is to verify their good working condition since when using damaged tools, a high risk of accident for the personnel and the equipment in maintenance is assumed. For this reason, a tool in bad condition is necessary to be replaced to assure its good operation.

The following step is the elaboration of the work program (shown in Appendix 1). Through this, it is possible to determine the number of personnel necessary for the work. It is also important to find ways in which the activities can be carried out in a parallel manner with the aim of reducing the working time. Thus this program should be discussed with the people in charge of the other work areas, since this can produce some delays (López, 2006).

In Figure 12, it can be observed the time required to realize an overhaul operation in each system. As can be seen, more time is spent to overhaul the turbine.

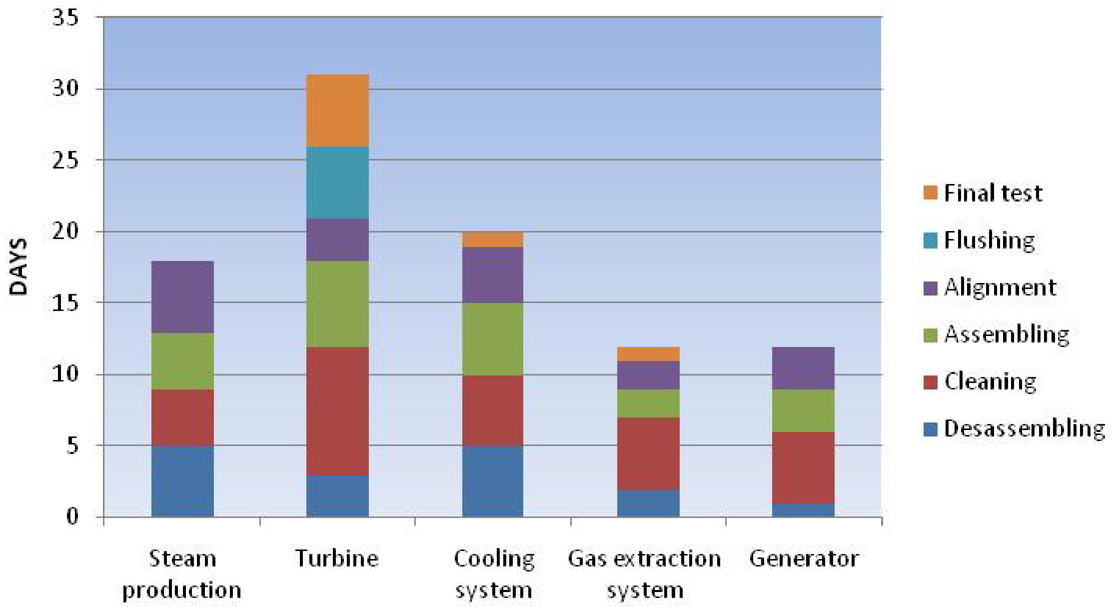


FIGURE 12: Register of time for systems in overhaul

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Procedure for maintenance to reduce the working time and the cost during the overhaul period has been elaborated. It includes good planning and discussion with the involved personnel, the condition of working tools, maintenance management software and work programs.

   In Figure 12, it is possible to see which turbine requires more time during the inspection program.

2. Due to the provisions of the energy system of the country, it is necessary to schedule overhauls so that the power system operator (UT) can guarantee the supply of energy by scheduling the maintenance of the electrical power plants, to avoid the high cost of electricity if more thermal generation is required.

5.2 Recommendations

According to Figure 12, the main problem is the cleaning of turbine parts as it is currently done manually. It is recommended to change this manual method to mechanical method in order to reduce the time to five days.

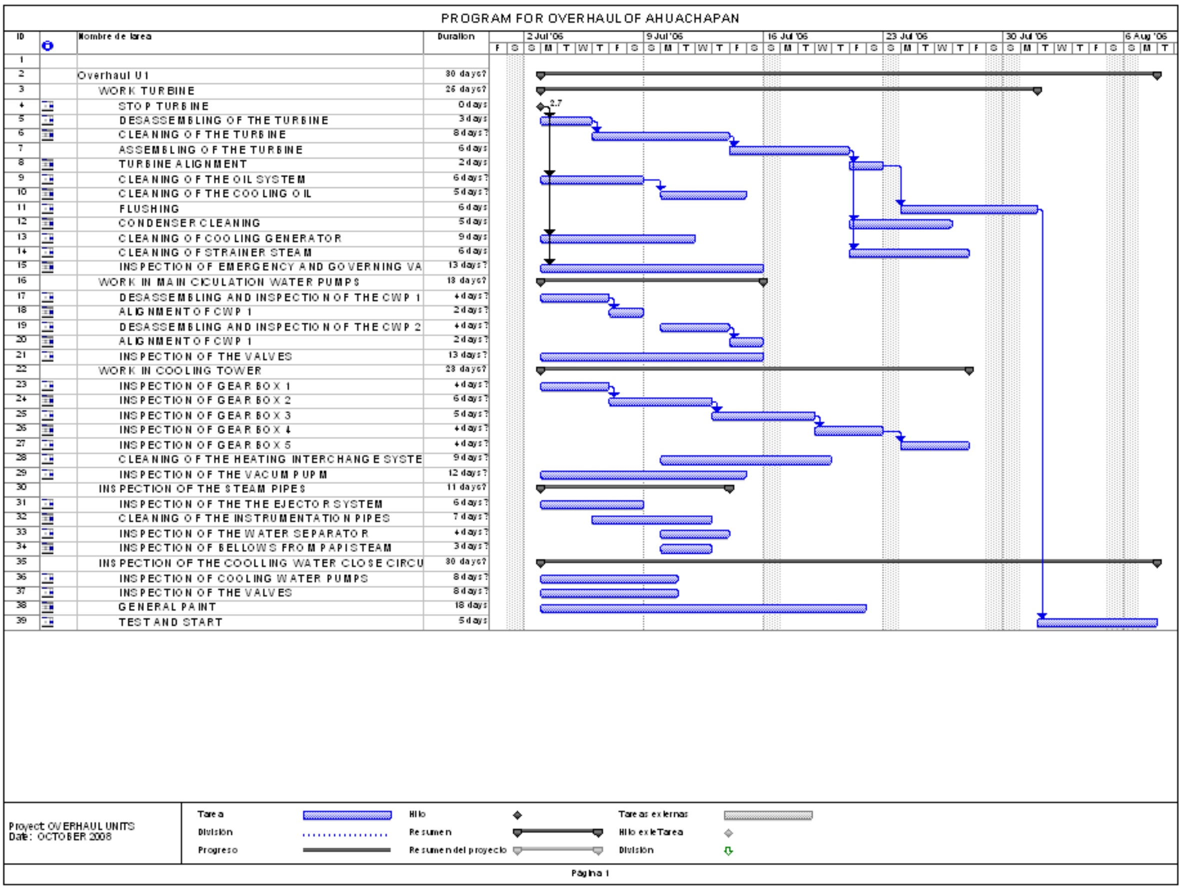
It should also be considered that the use of these techniques can obtain a reduction of five days less during overhaul, which could provide lots of benefit for Ahuachapan geothermal power plant.

REFERENCES

Amaya, J, 2004: *Document preparation for company of insurances mainly risk*. LaGeo, Geothermal Power Plant Ahuachapan, internal report (in English) 2-4.

López, G., 2006: *Informe de revision mayor U1*. LaGeo, Geothermal Power Plant Ahuachapan, internal report (in Spanish).

APPENDIX 1: Program for overhaul in Ahuachapan Power Plant (El Salvador)



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ELECTRICITY MARKETS

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ABSTRACT

This document addresses the evolution of the electrical systems, which have been designed initially from being a vertically integrated monopolized system (usually property of the state) to being a diverse set of public and private systems. In general, generation and commercialization are carried out by competition, while transmission and distribution require the regulation from the state. The evolution of the systems requires special attention due to the challenges currently presented by distributed generation and the interconnection between different systems that need to be harmonized.

1. FROM MONOPOLIES TO COMPETITIVE MARKETS

Due to the importance and strategic role of the electrical sector for the development of the economy, the state has assumed the responsibility in the development of electrical systems since the first half of the 20th century.

In most cases, the local, state, or national governments are responsible for the electrical supply of the countries. One of the most important cases is the Tennessee Valley Authority created in 1933 to develop the hydroelectric resources; however, it is recognized for its role in the generation and distribution of electrical power, making it one of the most famous government initiatives pioneering in large-scale electrical systems.

During most of the 20th century, the governments envisioned the electrical supply as a challenge for development and therefore facilitated the construction of large hydroelectric projects (many of which would be difficult to develop by private companies) requiring agreements between various governments since these were located on the border among different countries.

Large generation projects usually far from the center of consumption made it necessary to develop an increasingly, large transmission network (with higher levels of electrical tension), which made it possible to interconnect different systems that had previously operated individually. At the same time, the growth of cities and the interest in electrification of urban and rural areas opened the doors to the development of distribution systems.

As a result of the 2nd world war, the development of nuclear energy for the generation of electricity in the 60's and 70's, especially after the oil crisis, forced many governments to develop policies aimed at reducing dependence on fossil fuels. The large capacity of nuclear power plants and the technological difficulties inherent to the modulation of the generation led to the construction of pumping stations that took advantage of surplus generation during off-peak hours.

However, much of the growth in demand was supplied by coal and then natural gas, especially when significant pipeline transportation projects were developed.

In the 80's, most state enterprises had few resources to invest in the energy sector. Many of them were indebted due to recent large generation projects, which together with the fiscal deficit of many governments (especially those in Latin America) led to a radical change in the development of the electrical systems, allowing the participation of the private sector.

During the last decade of the 20th century, the liberation of many electricity markets was initiated by Chile and followed by Latin America, Europe, and the USA. The liberation was linked to a full or partial privatization of the assets that were owned by the state and the vertical management of firms.

In this new context, the generation and commercialization of electrical system are carried out under free market conditions, while the operation of energy transmission and distribution are usually monopolized and regulated by the state, creating geographic limit in some cases.

At the same time, consumers in the retail market have the freedom to choose between different suppliers in order to select the one that provides the greatest added value.

The new structure requires a manager of market transactions known as Market Manager, who is responsible for receiving bids from vendors and buyers of energy in order to establish an efficient offer for both energy and established auxiliary services.

Furthermore, the System Operator is responsible for the technical coordination in order to ensure the physical completion of transactions as well as quality control and safety. Both the Market Manager and the System Operator are usually entities independent from the other participants.

Figure 1 shows the breakdown of the various activities of the electricity sector in cases where there is a vertically integrated monopoly versus a competitive market (with several participation of different sectors in order to generate competition).

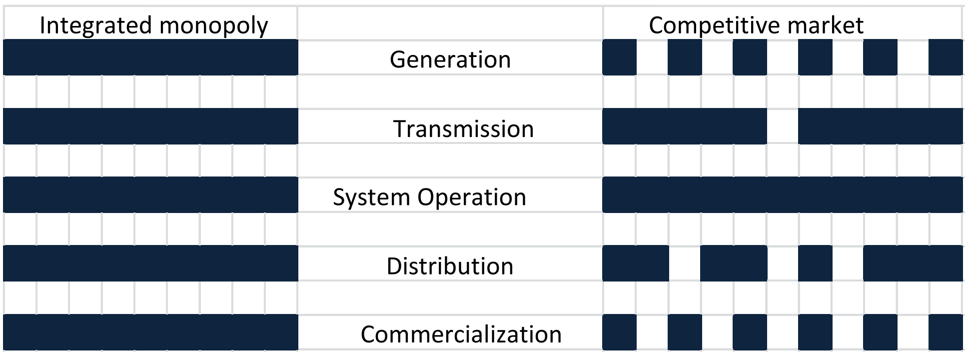

FIGURE 1: Breakdown of activities in the electric sector

The deal among different systems corresponds mostly to economic transactions, rather than a relation to their quality and safety. International trade regulations are established and transmission network management restrictions are established for this purpose.

2. ACTIVITIES DEVELOPED IN COMPETITION

For a liberated market to function properly, the participation of various competitors is necessary which brings about the establishment of prices. Due to the fact that there were few firms involved in the electric industry and in many cases they were vertically integrated, it was necessary to dissolve the existing firms and allow the participation of new sectors.

2.1 Generation

In electricity markets, the various generators must compete with each other through a bidding process scheduled for a short term, in which those offering lower prices or lower production costs will end up selling electricity. The bidding process is usually carried out on an hourly basis. In some cases, economic performance may be affected by technical restrictions of the units, transmission, energy quality conditions, security for the system, etc.

The efficiency and the development of cheaper technologies is promoted with this model, thus favoring the construction of large capacity plants to obtain lower production costs.

In today's electricity markets, there are some systems with pricing models. In this case, the electricity generating companies (or generators) present the required price for each of its generating units to the Market Administrator, with the freedom to define their offering price. This type of model works successfully where there is an abundance of competition and therefore, generators offer a price close to their variable costs of production in order to avoid being displaced by other generators.

On the other hand, there are systems that operate under cost-based production, in which case the generator is subjected to an audit of costs, and the variable cost of production is defined usually associated with energy models as well as operation and maintenance of their equipment. There are usually periodic adjustments based on changes in fuel prices as well as inflation, in which case, there is only a declaration of availability from generators, because its sale offer is conditioned to the value resulting from the audit.

In both cost and price markets, the Market Administrator defines the market "spot" price as the last unit to meet the demand, following the merit order of price/cost. This value is used to compensate to all generators and simultaneously charge buyers in the market.

The establishing of price is based on classical economic theory developed in the 19th century, which in a perfectly competitive economy, the marginal cost of production is equal to the product price, maximizing social well-being for sellers and buyers. This requires establishing a supply and an associated demand curve, as indicated in Figure 2, the point of intersection being the equilibrium point where the price of the good is defined.

This results in maximizing social welfare, which corresponds to the sum of producer surplus plus consumer surplus. Producer surplus is understood as the difference between what the producer actually receives (price P) and what it costs producing goods (supply), while consumer surplus is defined as the difference between what the consumer is willing to pay (demand) and what he pays for the goods (price P).

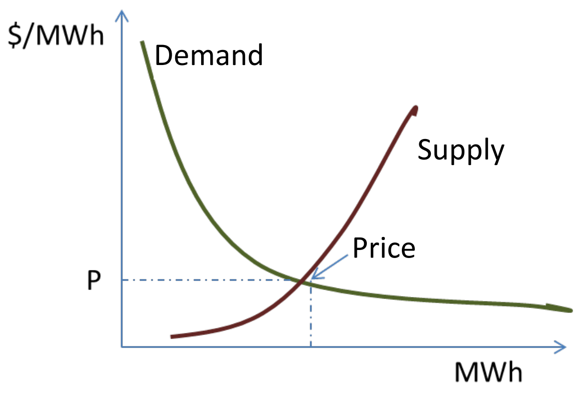

FIGURE 2: Supply and demand curves

Although this economic logic has been applied to electricity markets to define the hourly price of electricity, one important detail is that consumers don't have prior knowledge or the possibility of an option to purchase electricity which has limited behavior, i.e. it does not immediately change its behavior with regards to the response to changes in the price.

Marginal prices from 2003 to 2013, for some Central American countries are shown in Figure 3. All countries have experienced an increase in spot prices due to international oil prices, due to Central America's power system has a large dependence to bunker.

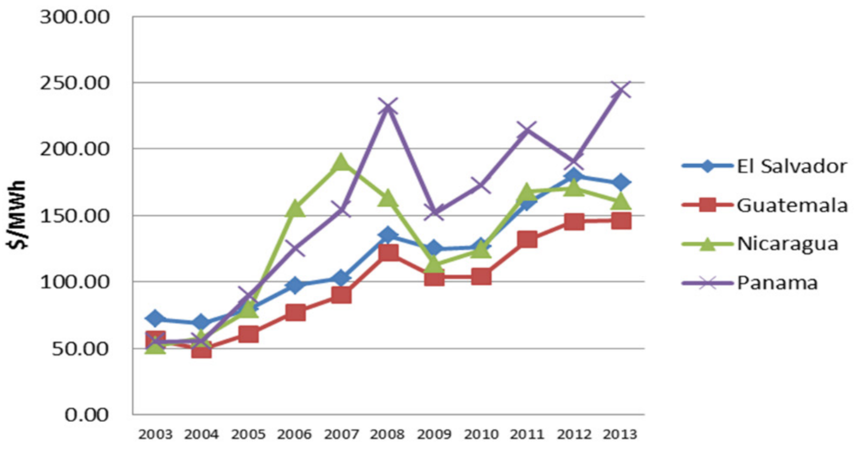

FIGURE 3: Marginal electricity prices in selected Central American countries, 2003-2013

Related to the spot market, various types of bilateral medium and long-term contracts are established in which there is a free deal between the demand and generation. Agents who can trade in these markets are generators, authorized consumers, traders, and distributors.

In many cases, contracts represent financial commitment and do not require the physical delivery of electricity, so that if there is another participant with a lower price than the supplier, the supplier can honor its commitment by buying from this lower-priced participant.

Another unique feature of electricity markets is that there is no storage and it is necessary to maintain a constant equilibrium between demand and generation because the system does not tolerate significant differences for periods of time greater than fractions of a second. The resource needed to achieve this balance, taking into account the inevitable disruptions that occur in real time is called "Auxiliary Services" or "Ancillary Services." Also considered in this category are other resources to ensure the voltage level and other technical restrictions, which in many cases may have market mechanisms similar to those of the energy market.

2.2 Commercialization

Broadly speaking, one can say that the commercialization of electricity is the process by which an intermediary (the supplier) provides energy for a consumer in exchange for certain compensation. Furthermore, this process is often associated with provision of other services, such as advice on the use of energy, metering, etc.

There are several types of commercialization, classifying them according to the type of regulation that is applied, such as:

- Free trade: Where trading agents compete freely with each other and the restrictions imposed by the regulator to the prices they charge customers or the way marketers acquire energy are much reduced and are limited to monitoring the operation of the market.

- Commercialization per rate (or regulated): Corresponds to customers for which commercialization has not been liberated. In this case, the prices to be paid by end customers are administratively set by the market authorities and generally, conditions are established on how regulated suppliers make their purchases (e.g., only buying energy at the wholesale market on a daily basis) and as to which supplier must serve each of these customers. Typically franchises or territorial concessions —as in traditional systems— are set so the distributor in the area should act as the regulated supplier for customers located in that area.

- Default rate: This is a protection model that is applied when the market has been fully liberated and all retail customers are able to choose their supplier, however, the regulator maintains administrative mechanism that works as a safety protection to prevent unreasonable retail competition. In this case, the governing conditions similar to the previous regulated rate are defined, with the difference that the consumers now have the option to give up anytime and choose a free supplier. However, free and regulated suppliers coexist for the same type of customers, which in this case it will be known as default rate providers.

The vast majority of markets have started the process of liberation, keeping all demand under a regulated rate. Further on, as the operation of the wholesale market becomes stable, different consumer segments could be liberated.
There are systems in which all consumers, from high demand (usually industrial) to residential are free to choose their supplier, while in other cases, a minimum level of consumption is required to freely choose a supplier.

3. REGULATED MONOPOLIES

Infrastructure in networks is characterized by heavy investments related to the physical space as their location for long periods of time. It is not advisable to have competition for two companies to construct buildings at the same site providing the same service. The networks would be redundant and the users would have to pay double for the same service.

It is considered that the network services of transmission and distribution are considered as legitimate monopolies and therefore the presence of a regulator defining the rates is justified, preventing the sole supplier of that service from setting higher costs that will result to a loss of economic efficiency to the society as a whole.

The regulator should set rates for distributors and transmitters for the companies to cope up with all the costs of operation, maintenance, expansion or make new investments to increase coverage or improve the quality of supply, and at the same time obtain a reasonable return for the industry, thus facilitating the economic and financial viabilities of the companies for the medium and long term.

The two methods used by regulators to set rates for owners of network companies are:

a) Regulation according to service costs: Also known as rate of return. In this method the user must have the access to the accounting information of the company, thereby determining the appropriate level of expenses to repay the rate of return on invested capital. Under this method, the company is encouraged to be more efficient in spending so as to increase its profitability; rate definition is periodic, usually one or two years.

b) Regulation through incentives: under this method it is possible to define an ideal company whose expenses are associated with the standardized values for the industry and adapted to the reality of the company taking into account the investment needed to expand the network and meet the quality criteria. This process is performed at a frequency of 4-6 years, establishing annual adjustments for inflation so there is an incentive for efficiency and lowering costs, which will be recognized in the next rate review.

In both cases, the pursuit of efficiency and thus increase in profitability of the companies should not lead to a decrease in the quality of service (continuity, voltage levels, frequency, waveform, commercial service, etc.). Because of this, the regulator typically sets parameters for loss levels and quality in order to identify the good service of the company. Otherwise, penalties are given to create incentives to achieve the quality level established in the rate of parameterization.

4. ROLE OF THE STATE

In liberal markets, the state must develop policies, adopt rules and monitor the proper performance of markets. In certain cases, it also acts as another participant subject to the same conditions and rules.

Generally, the state plans the development the electricity sector, defining the required expansion in generation, transmission, and distribution. In the case of the generation (as this is indicative, i.e. there is no obligation for the people involved to comply with the proposed plans of expansion), the state must look for ways to provide guidance and appropriate signals so that private sectors could undertake proposed investments. Such mechanisms may be fiscal, regulatory, contractual, etc.

In the case of transmission and distribution, the state will recognize new investments to be made by companies within the future rate review. In some cases, it may promote competition in the development of new lines, usually transmission, where it is subject to competition from investors.

Regulation is an essential characteristic in new markets when there is an entity in charge of monitoring compliance with regulations and applying appropriate sanctions for noncompliance.

In some cases, the same entity or another in particular is responsible for monitoring market competition and preventing the abuse of market dominance that could distort the market for an advantage. In order to reduce market power, vertical integration of enterprises is limited or at least separate account requirements are established in cases where regulated activities and simultaneous competitions are carried out.

5. NON-TRADITIONAL RENEWABLE RESOURCES

With new markets, generators are exposed to the changes in supply and demand, especially affected by fuel prices for thermal power plants. This creates a significant disincentive to renewable energy sources that mostly possess high investment costs and low operation and maintenance costs. At the same time, investors look to reduce their risk and regain their investment in the shortest possible time, which is why thermal power plants are favored in many cases.

In this context and in especially in systems that improve the economies of scale, it is necessary to create other incentives as well as revenues complementary to those obtained in the market that can make invest in non-traditional renewable energy sources attractive.

As part of state policy, many governments have created incentives to provide additional renewable energy sources into the markets and complement the resources needed to make them competitive. Under this approach, wind and solar energies have had remarkable development both commercially and technologically. In many cases, modifications are necessary to prioritize the release for these sources, due to their randomness, they cannot be programmed similarly like hydroelectric, thermal, or geothermal plants, whose availability is determined in advance and may be scheduled.

6. NEW CHALLENGES

There are developments in electrical systems that require changes in the regulation of markets to adapt to new trends, among these are:

a) Distributed generation: With the development and introduction of renewable energy sources such as solar, wind, small hydroelectric plants and others with lower production, they are distributed within the electrical systems, which contribute to the load on networks and usually require coordination with the distribution company as they are not managed by the system operator due to their large size.

b) Interconnections with other systems: This corresponds to interconnections between countries which facilitates the continuity of supply, making the systems stronger and reliable. By taking advantage of the surplus, markets begin to grow and provide projects for regional generation that can achieve economies of scale, and therefore can be cheaper. However aside from requiring infrastructure, the creation of a market with clear and harmonized rules for the different sectors should be considered.

BIBLIOGRAPHY

Hunt, S., 2002: Making competition work in electricity. John Wiley & Sons, Inc., New York, NY, United States, 450 pp.

Barquín, J., 2004: *La regulación del libre mercado, generación y mercado mayorista (Regulation of the free market, generation and wholesale commercialization)*. Universidad Pontificia de Comillas, Madrid, Spain, Course on the regulation of the electrical sector (in Spanish), Module 4.

Gómez San Román, T., 2004: *Instituciones y economía de la regulación, fundamentos económicos de la regulación (Institution and economy of regulation, economic fundamentals of regulation)*. Universidad Pontificia de Comillas, Madrid, Spain, Course on the regulation of the electrical sector, Module 2.

Friedel, R., Casey, R., Bedi, J., 1984: *A century of electricals - A brief history of electrical engineers 1884-1984*. IEEE Center for the History of Electrical Engineering, New York.

Rivier, J., 2003: *La regulación tradicional de sector eléctrico (Traditional regulation of the electrical sector)*. Curso CEDDET-Comillas, Instituto de Investigación Tecnológica, Madrid, Spain.

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

GOVERNMENT INCENTIVES AND INTERNATIONAL SUPPORT FOR GEOTHERMAL PROJECT DEVELOPMENT

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ABSTRACT

Governments use various tools to support geothermal development in their countries. These include feed-in tariffs, renewable portfolio standards, tax credits, grants, loans, risk insurance, research, technical assistance, and exploration and resource assessment. On the international arena, bi-lateral and multi-lateral development institutions also support geothermal projects, mainly in the developing countries, through direct support, including technical assistance, capacity building, and grants, as well as through financing and risk insurance schemes.

1. INTRODUCTION

The State has an important role in initiating and supporting geothermal development in many countries (Haraldsson, 2012). Bilateral and multilateral development agencies also play a supporting role in some regions. The main channels for such support are discussed in the paper and examples presented.

2. GOVERNMENT SUPPORT TO GEOTHERMAL DEVELOPERS

There are various ways in which governments ensure support to geothermal developers through policies, programs and legislation. Many of these are touched upon in the following subsections.

2.1 Feed-in tariffs (FITs)

Where feed-in tariffs are in place for direct use (space heating) and/or electricity generated from geothermal resources, producers are guaranteed a price for the electricity that they provide into utility grids. Rybach (2010) informs that such tariffs are in place in many countries in Europe, including Austria, Belgium, the Czech Republic, Estonia, France, Greece, Slovakia, Slovenia and Spain, and that the system has led to large scale geothermal development in Germany. Gassner (2010) reports that the German Renewable Energy Sources Act of 2009 obliges operators of electricity supply grids to accept and give priority to electricity provided by renewable energy sources and to pay minimum prices stipulated by law for a 20 year period. The additional costs are passed on to consumers. In this way, Gassner notes, the State itself is not involved in financing, but instead merely controls the framework conditions, which allow project developers, investors and operators to reliably calculate yields for the first 20 years of operation.

The US federal Public Utility Regulatory Policies Act (PURPA) of 1978, which was implemented by individual states, obliged utilities to collect power produced by independent power producers and pay a tariff equaling the avoided costs of the utilities' own generation. According to Reed and Bloomquist (1995), PURPA has proven the single greatest incentive to geothermal development in the United States, by guaranteeing a market for electricity generated from geothermal resources. PURPA led to a dramatic growth in the number of geothermal projects in California and Nevada, where state public utilities aggressively implemented the act in the 1980s. About a third of the 2000 MWe installed during the decade came from plants in the two states taking advantage of PURPA.

Feed-in tariffs for geothermal electricity and heat are currently in place in 19 countries world-wide (REN21, 2014): Austria, Croatia, Czech Republic, Ecuador, France, Germany, Greece, Indonesia, Italy, Japan, Kenya, Serbia, Slovakia, Slovenia, Spain, Switzerland, Turkey, Uganda, and he United Kingdom (Figure 1).

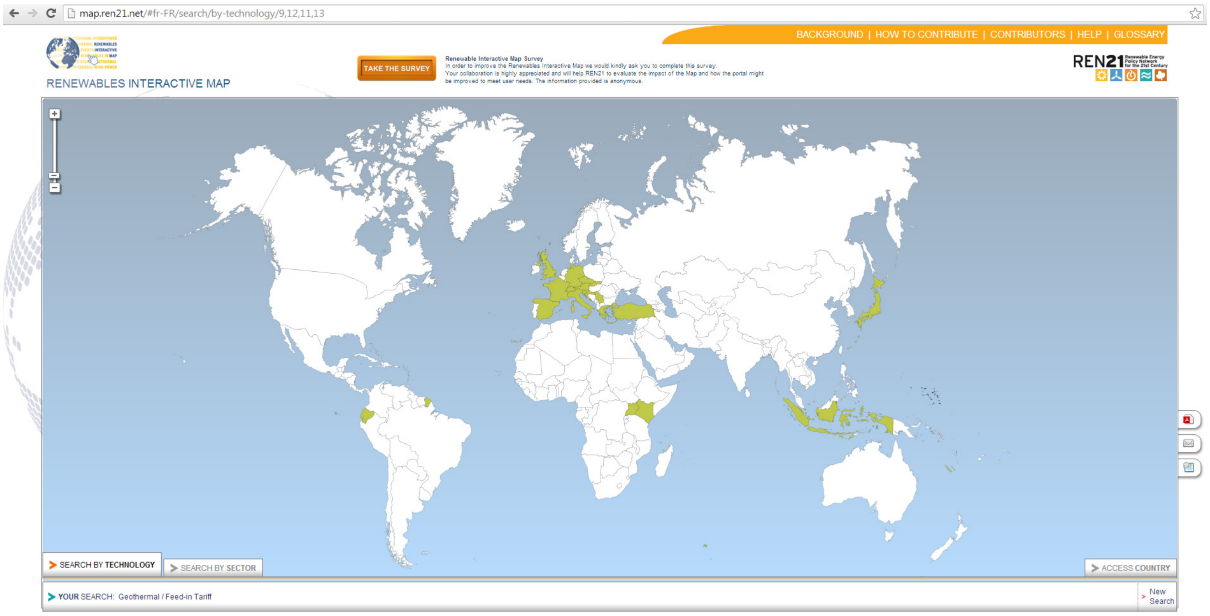

FIGURE 1: Countries with geothermal feed-in tariffs in place as displayed on the REN21 renewables interactive map (REN21, 2014)

Table 1 lists feed-in tariffs for electricity generated from geothermal power in selected countries with contract terms of 15 years or longer. The tariffs range significantly between countries, from 7.7 USD¢ in Uganda to 44.8 USD¢ for small geothermal power plants in Switzerland. Both Japan and Switzerland have more than one tariff category, depending on the size of the power plants. Geothermal feed-in tariffs above market rates were introduced in Japan in July 2012, in the wake of the Fukushima accident, to encourage project development (Watanabe, 2013). This shows how feed-in tariffs can be used as part of government policy to promote geothermal electricity generation.

2.2 Renewable portfolio standards (RPSs)

Renewable portfolio standards require that a certain percentage of utilities' electricity come from specific sources, such as renewables. The International Energy Agency's technology roadmap for geothermal heat and power states that renewable portfolio standards can be effective if they are sufficiently ambitious and binding for utilities – that is, if the financial penalties are set at appropriate levels in case of little or no compliance with the targets (OECD/IEA, 2011).

Miethling (2011) reports that Texas and Arizona employed renewable portfolio standards (RPSs) in 2001 and California followed suit a year later. California's RPS was accelerated in 2006 under a Senate

Bill by requiring that 20% of electricity retail sales be served by renewable energy resources by 2010 (California Energy Commission, 2011). In 2008, the goal was set higher as the state governor signed an executive order requiring that the proportion of electricity sales from renewable resources be increased to 33% by 2020. As of January 2012, 30 US states and the District of Columbia had enforceable RPSs or other mandated renewable capacity policies as shown in Figure 2 (EIA, 2012).

TABLE 1: Feed-in tariffs for geothermal electricity in selected countries with contract terms of 15 years or longer (modified from Gipe, 2014)

Country	**Size of plant**	**Contract term**	**Price / kWh**	**USD¢ / kWh***
Ecuador[1]		15 yrs	0.145 USD	14.5
France[1]	< 12 MW	15 yrs	0.20 EUR	27.3
Germany[1]	All sizes	20 yrs	0.25 EUR	34.2
Greece[1]		20 yrs	0.15 EUR	20.5
Indonesia – Papua[1]		?	0.17 USD	17.0
Indonesia – Sumatra[1]		?	0.10 USD	10.0
Italy[1]	< 1 MW	15 yrs	0.20 EUR	27.3
Japan[1,2]	< 15 MW	15 yrs	42 JPY	40.9
	≥ 15 MW	15 yrs	27.3 JPY	26.6
Kenya[1]		20 yrs	0.20 USD	20.0
Slovakia[1]		15 yrs	0.195 EUR	26.7
Slovenia[1]		15 yrs	0.152 EUR	20.8
Spain[1]		20 yrs	0.074 EUR	10.1
Switzerland[3]	≤ 5 MW	20 yrs	0.40 CHF	44.8
	≤ 10 MW	20 yrs	0.36 CHF	40.4
	≤ 20 MW	20 yrs	0.28 CHF	31.4
	> 20 MW	20 yrs	0.227 CHF	25.4
Uganda[1]		20 yrs	0.077 USD	7.7

1: (Gipe, 2014); 2: (METI, 2012); 3: (Siddiqi and Minder, 2012)
* According to currency exchange rates on 26 February 2014

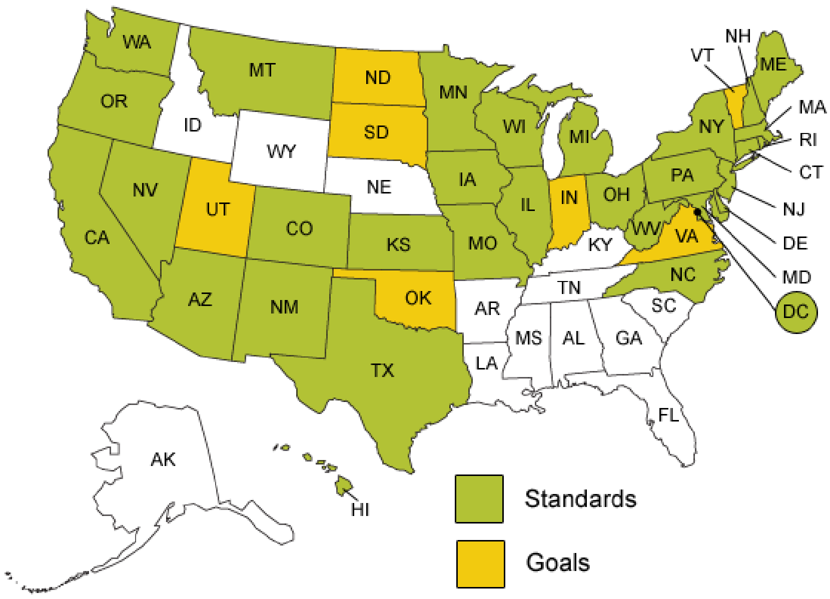

FIGURE 2: US states with renewable portfolio standards (mandatory) or goals (voluntary) in January 2012 (EIA, 2012)

Chile has also enacted an RPS through the Non-Conventional Renewable Energy Law, which requires providers in systems of an installed capacity of 200 MW or greater to demonstrate that at least 10% of the energy provided comes from non-conventional renewable energy resources by 2024 (Haraldsson, 2013). The Renewable Energy Heat Act in Germany obliges building developers to source a minimum percentage of the energy requirement for heating and hot water from renewable energy sources (Gassner, 2010).

Markets in renewable energy credits (RECs) have developed within some RPS schemes. The credits are assigned to eligible facilities on an energy unit basis (MWh) according to their output and are tradable (Fabri, 2009). The buyers are often utilities that need to meet the portfolio standard obligations, but RECs are also purchased by consumers who want to be ensured of the renewability and green marker of their energy.

Although RPSs can be found in various countries around the world, their popularity seems to have been greatest in the United States. However, in April 2013, 16 of the 29 states with renewable portfolio standards at the time were reportedly considering legislation to draw back mandates for utilities to buy renewable energy, after affordable shale gas became widely available in the markets (Martin, 2013). While such moves have mainly been directed at wind and solar power, they have the potential of proving detrimental to the geothermal energy industry if realized.

In addition to mandatory portfolio standards that stipulate penalties in the case of non-compliance, some countries have set non-binding targets for the share of electricity generated from renewables before a specific year, and many of these are related to the countries' commitments to reducing carbon dioxide emissions as a response to the threat of global warming. It is worth noting that where RPSs are in place, geothermal has in most, if not all, cases to compete with other renewables.

2.3 Tax credits

Various forms of tax credits exist to support geothermal development. Reed and Bloomquist (1995) inform that the 1978 Energy Tax Act established a 10% energy tax credit for investment by a business taxpayer in property used to produce, distribute or use energy from a geothermal deposit in the United States. This tax credit expired in 1990, but was later reauthorized. The American Recovery and Reinvestment Act of 2009 granted a federal renewable electricity production tax credit to eligible tax payers to generate electricity from geothermal resources through 2013 (IRS, 2009). Miethling (2011) notes, however, that small companies in the United States may have difficulties in making use of tax credits when facing a negative net income in the beginning of operations, and have therefore been forced into agreements with lending institutions to benefit from the credits.

In 2009, the Geothermal Energy Association published a study on US state and federal incentives for small power and direct-use geothermal production. It found that various tax credits were available at the federal and state levels at the time as shown in Figure 3 (Jennejohn, 2009). While the federal government only offered corporate tax incentives, the various states offered incentives through personal, corporate, sales, and property taxation. The implementation of these incentives varies significantly and the mechanics can be complex, which may result in difficult navigation for developers.

Peñarroyo (2010) reports that the Philippine Renewable Energy Act of 2008 provides various fiscal and non-fiscal incentives for renewable energy developers. These include an income tax holiday for the first 7 years of commercial operations of renewable energy facilities, special realty tax rates on equipment and machinery, net operating loss carry-over, accelerated depreciation, 0% VAT rate for the sale of renewable power, tax exemption of carbon credit sales, and tax credit on domestic capital equipment and services.

2.4 Direct support

Yet another way for the State to support geothermal development is through direct financial support in the form of grants and cost sharing. The US Department of Energy (DoE) has awarded grants for research and development, technical assistance, feasibility studies and demonstration projects, and provided cost sharing with industry on exploration, reservoir assessment, and reservoir engineering, in addition to releasing exploration data to the public (Reed and Bloomquist, 1995). Recently, DoE's Geothermal Technologies Program has granted millions of dollars to geothermal research and development projects in the US.

State	Personal Tax	Corporate Tax	Sales Tax	Property Tax	Rebates	Grants	Loans	Industry Support	Bonds	Production Incentives
Federal	-	+3	-	-	-	+3	+4	+	-	+
Alaska	-	-	-	-	-	+	-	-	-	-
Arizona	-	-	-	+	+3	-	-	-	-	-
California	+	-	-	-	-	-	-	-	-	+
Colorado	-	-	+2	+2	-	+	+	-	-	-
Hawaii	-	-	-	-	-	-	-	+	-	-
Idaho	-	-	+	+	-	-	-	-	+	-
Montana	-	+	-	+3	-	-	-	-	-	-
Nevada	-	-	+	+3	-	-	-	-	-	-
New Mexico	-	+	-	+	-	-	-	+	-	+
Oregon	-	+	-	+	-	-	+	-	-	-
Utah	+	+	+	-	-	-	-	+	-	-
Washington	-	-	+	-	-	-	-	-	-	+
Total	2	7	6	12	3	5	6	4	1	4

Legend:
- absence of that particular incentive in the respective state
\+ presence of one particular incentive/program within the state.
+# more than one incentive of that particular type are available within the respective state

Source: U.S. Department of Energy, GEA.

FIGURE 3: Overview of US federal and state level geothermal incentives in 2009 (Jennejohn, 2009)

Wahjosoedibjo and Hasan (2012) inform that in its 2011 State Budget, the government of Indonesia committed to allocate the equivalent of USD 145 million to a fund dedicated to geothermal development. The purpose is to attract investment by sharing costs for initial exploration and to provide potential developers and investor with sufficient and credible information on green field geothermal sites that will be offered during the tendering process of new areas. Besides reimbursing interested parties with exploration costs, the provision of high quality information on pre-selected green field geothermal sites should help to reduce unknowns and alleviate risk aversion.

The Indonesian plan is in line with Rybach's (2010) recommendation that governments would finance the exploratory, and preferably also the pre-feasibility, phases of geothermal development, letting investors take over when it is known where to go. This methodology is also in line with past methodology of the Icelandic government, which funded geothermal exploration activities for decades for the benefit of the public.

Rybach (2010) also reports on the substantial financial assistance of the Australian government to new geothermal projects in the country in order to foster progress towards the commercialization of geothermal energy resources.

2.5 Loans

Governments may back or provide loans to the geothermal sector directly. The Icelandic government backed foreign loans with favorable interest rates to municipalities in the decades of geothermal development after World War II, which the municipalities might otherwise not have been able to secure (Björnsson, 1995). The Icelandic Energy Fund was established in the 1960s to provide low-interest loans to municipalities, firms or individuals for geothermal drilling and to share the risk of drilling with developers (Björnsson, 1995; Björnsson et al., 2010). The loans normally covered 60% of drilling costs and could be converted into grants if the development of a new geothermal field proved unsuccessful, thus also functioning as insurance for the developer.

A number of loan programs have also been authorized by the US federal government through the years. According to Reed and Bloomquist (1995), the best known of these was the Geothermal Loan Guarantee Program, which was authorized under the Geothermal Research, Development, and Demonstration Act of 1974. Loans for up to 75 percent of project costs could be granted under the act, with the federal government guaranteeing the full amount. In 2009, various loan programs were available at the federal and state levels according to Jennejohn (2009), as depicted in Figure 3.

Goodman et al. (2010) suggest that geothermal energy should receive low interest rate loans in the EU, in line with those available for the development of some other renewable energy sources.

2.6 Insurance

Due to the inherent risk in drilling for geothermal resources, insurance may be coveted by investors that do not have pockets deep enough to absorb the economic setbacks associated with drilling failures. The idea behind the Icelandic Energy Fund, besides granting loans for exploration and drilling, has been to provide such insurance. This has been achieved by turning loans into grants in case of failed attempts to develop new fields. Miethling (2010) reports that Germany has installed a similar drilling insurance where a premium is paid on a loan, which is converted into a grant in the case of drilling failure.

Rybach (2010) informs that a governmental risk coverage system has been in place in France since 1981. A short-term risk guarantee covers all or part of an investment in a well in case of drilling failure and a long-term risk guarantee covers the risk of resource decline for up to 25 years. A risk guarantee system was also established by the Parliament of Switzerland in 1986 and implemented by the federal government in 1987 (Rybach, 2010). The guarantee extended to 50% of drilling and testing costs and in specific cases up to 80%. A new governmental risk coverage system was introduced in 2008, in which the maximum guarantee is 50% of the subsurface costs. Goodman et al. (2010) suggest that geothermal risk insurance should extend to the whole European Union (EU).

2.7 License fees and royalties

Goodman et al. (2010) advice to keep license fees and royalties for the use of geothermal energy to a minimum within the EU and to keep them in perspective with fees and royalties for higher value resources such as hydrocarbons. According to them, the fees should take into account the return on investment. As geothermal resources within most countries of the EU are of rather low quality compared to the high-temperature resources found in many of the leading geothermal countries, it follows that they are also of lower economic value. In this way, governments can support the development of geothermal resources.

2.8 Easement of import duties

Peñarroyo (2010) has informed that one of the ways in which the Philippine Renewable Energy Act supports renewable energy development is to relieve developers from tariff duties on imported machinery and equipment. El Salvador has also lowered tariff duties on imported equipment for geothermal power plants.

3. INTERNATIONAL SUPPORT FOR GEOTHERMAL DEVELOPMENT

In addition and complimentary to the State, there are various bi-lateral and multi-lateral agencies and organizations that support the development of geothermal resources, primarily in the developing countries. While these institutions cannot influence development through legal and regulatory tools that apply within States, such as feed-in tariffs, portfolio standards, and tax credits, their strong backing by donor countries and capacity for pooling resources makes them capable of making a big difference in the geothermal development of many countries, whether through direct support, finance, or through the creation of drilling risk insurance schemes.

3.1 Direct support

Direct support includes technical assistance, capacity building, and grants.

An example of a technical assistance project is the Geothermal Exploration Project, which is funded and implemented by the Icelandic International Development Agency (ICEIDA) and the Nordic Development Fund (NDF). The aim of the 13 million USD project is to assist East African Rift System (EARS) countries in completing the exploratory phase of geothermal development and build capacity and expertise in the field of geothermal utilization and related policy (ICEIDA / NDF, 2013). The project is a sub-project of the Geothermal Compact partnership led by the World Bank, which in 2012 started to explore with other donors the possibility of mobilizing additional concessional resources to fund test drilling programs, after the activities of the Geothermal Exploration Project have been successfully completed (Figure 4). This initiative, the Global Geothermal Development Plan (GGDP) is led by the Energy Sector Management Assistance Program (ESMAP, 2013), which is a global, multi-donor technical assistance trust fund administered by the World Bank and co-sponsored by 13 official bilateral donors. A step in this direction was taken in October 2013, when the Clean Technology Fund (CTF), a program of the Climate Investment Funds (CIF), approved 115 million USD for the Utility Scale Renewable Energy Program, which will initially focus on facilitating private sector engagement

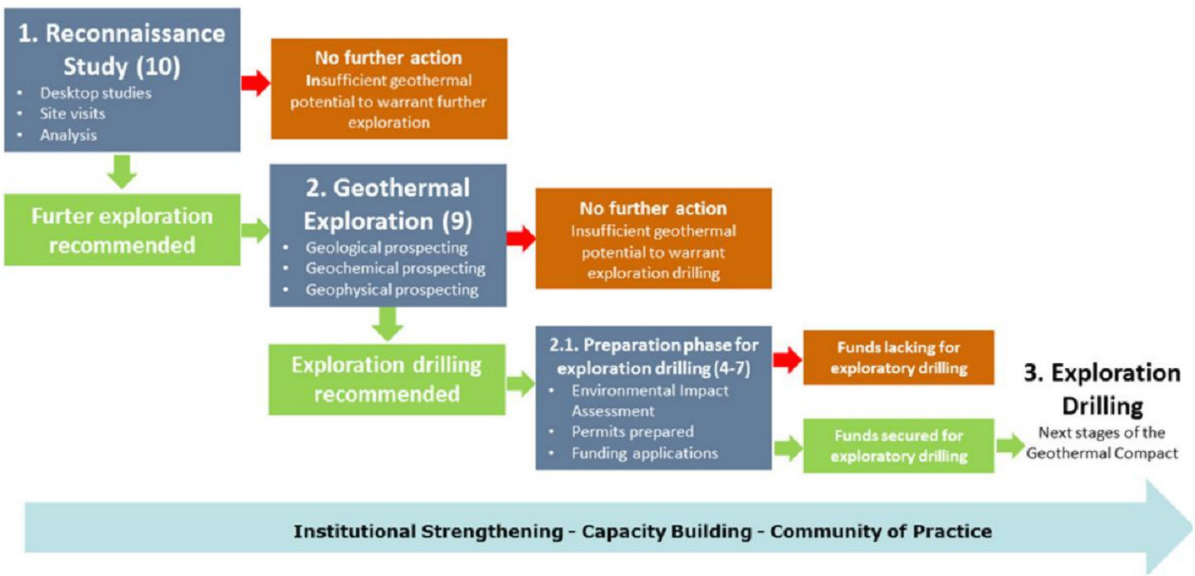

FIGURE 4: Workflow of activities within the Geothermal Exploration Project (color) precede exploration drilling, which may be supported through the GGDP or other channels (ICEIDA / NDF, 2013)

in geothermal resource validation through test drilling in four pilot countries: Chile, Indonesia, Mexico, and Turkey (ESMAP, 2014). The program is open to additional pledges to donors and is expected to expand to other countries, such as Ethiopia and Kenya. In the meantime, the funding of drilling activities in the EARS countries can potentially be aided through the Geothermal Risk Mitigation Facility (GRMF) or through other channels.

The GRMF was established by the African Union Commission on one side, and the German Federal Ministry for Economic Cooperation and Development (BMZ) and the EU-Africa Infrastructure Trust Fund via Kreditanstalt für Wiederaufbau (KfW) Entwicklungsbank on the other side, to fund geothermal development in East Africa (GRMF, 2014). The objective is to encourage public and private investors, as well as public-private partnerships to develop geothermal prospects for power generation in Eastern Africa by providing grants for two types of activity: surface exploration studies, and drilling and testing (GRMF, 2014). An example is a 5.6 million USD grant for initial drilling at the 1,000 MW Corbetti geothermal power project in Ethiopia (ThinkGeoEnergy, 2014).

Additional assistance to Africa comes from the Power Africa initiative, launched by the United States in 2013, to which 7 billion USD have been committed through 2018 in financial support and loan guarantees (USAID, 2014). The goal is to add more than 10,000 MW of clean, efficient electricity generation capacity through various collaborations and means, including technical assistance, grants, loans and risk mitigation insurance. Although the initiative is not specifically targeted towards geothermal development, Power Africa has already committed to an advisory role on the Corbetti project in Ethiopia.

In Latin America, the Japanese Trust Fund Consultancy financed a 0.9 million USD prefeasibility study for two selected sites in the Macizo Volcanico del Ruiz complex in Colombia, which was administered by the Inter-American Development Bank (IDB), and in 2011 the Global Environment Facility (GEF) provided a 2.7 million USD grant to Colombia, also through IDB, to promote investment in non-conventional renewable energy sources and lay the groundwork for a geothermal project at Macizo Volcanico del Ruiz (IDB, 2011).

Indonesia is tapping 400 million USD from Clean Technology Fund to develop approximately 800 MW of new geothermal generation supply at three sites, and to create risk sharing and finance facilities designed to accelerate investments in energy efficiency and renewable energy (CIF, 2014). Another example of direct support across borders in Asia is a pledge by the Government of New Zealand in 2012 to provide a 6.95 million USD technical assistance grant to support Pertamina Geothermal Energy's (PGE) 1000 MW geothermal investment program in Indonesia (World Bank, 2012).

These examples, which are by no means exhaustive, are indicative of the possibilities that governments and geothermal developers in the developing countries have in engaging multi-lateral and bi-lateral agencies, as well as foreign governments, for direct support of projects.

Regardless of the availability of funds, an able and committed workforce is needed for geothermal development to be realized. This has long been recognized internationally, as evident in the establishment of the International Institute for Geothermal Research at Pisa in 1970 (supported by the Italian Government and UNESCO), the Geothermal Training Course at Kyushu University in 1970 (supported by the Japan International Cooperation Agency), the United Nations University Geothermal Training Programme (UNU-GTP) in Reykjavik in 1978 (supported by the Icelandic Government), and the Geothermal Institute at the University of Auckland in 1978 (supported by the New Zealand Government and UNDP). Together these programmes have educated geothermal experts in the thousands, from a multitude of countries.

Recent examples of international support for geothermal capacity building include the education of geothermal experts from the EARS countries at UNU-GTP in Iceland, funded through the Geothermal Exploration Project, and the donation of 2.07 million USD to assist El Salvador in permanently establishing a regional geothermal training center for Latin America, based on two diploma courses already run at the University of El Salvador in 2010 and 2012. Of this amount, the Nordic Development Fund granted 1.25 million and the Inter-American Development Bank granted 0.82 million, with local commitments amounting to 0.77 million.

3.2 Loans

Development banks have been instrumental in the financing of many geothermal projects in Africa, Asia, and Latin-America. The World Bank's financing for geothermal development increased from 73 million USD in 2007 to 336 million USD in 2012, with projects underway in Indonesia, Kenya, Ethiopia, Turkey, Djibouti, and Nicaragua (ESMAP, 2013). The Inter-American Development Bank (IDB) took part in the financing of the 36 MW San Jacinto-Tizate geothermal project in Nicaragua, with a 40 million USD loan, and KfW Entwicklungsbank and its subsidiary Deutsche Investitions- und Entwicklungsgesellschaft (DEG) have contributed to the financing of power plants in Olkaria in Kenya (KfW, 2011).

Although these are but a few examples, they serve to provide an indication of financing support available from development banks for geothermal projects.

3.3 Insurance

As noted before, the risk inherent in drilling deep into the ground for resources that can only be inferred with indirect measurements prior to drilling and the high costs associated with those drilling activities present a large barrier to investment in geothermal projects. In order to increase certainty, governments can therefore support exploration and test drilling to prove geothermal resources, after which they can be passed on to developers for utilization. However, such an approach may not be viable in countries where State finances are restricted or where governments are unwilling to support geothermal exploration and resource quantification directly. Another approach to lower the barrier for investors to commit to geothermal projects is thus to alleviate their direct risk through insurance schemes.

There is considerable awareness of the need for risk mitigation insurance for geothermal drilling globally. In addition to direct grants for geothermal drilling already mentioned, which serve to reduce direct risk to investors, more conventional insurance schemes are warranted. In 2003, Munich Re group became the world's first insurer to develop a policy covering the costs of unsuccessful geothermal drilling projects (Munich Re, 2014). Since then, the group has insured various geothermal drilling projects in Germany and elsewhere, and entered into an agreement with the International Finance Corporation (IFC) to develop and pilot geothermal risk insurance in Turkey to reduce exposure to unproductive wells (IFC, 2014).

In 2012, Ngugi (2012) reported that the cost of wells in Kenya ranged between 3.5 and 6.5 million USD. Such significant costs for a single well suggest that drilling insurance can only be provided by entities with access to large funds, such as an international reinsurance group or international partnerships like the GGDP. The creation of such insurance schemes that are widely available to developers in various countries has the potential of significantly boosting the rate of geothermal development.

4. CONCLUSION

States and international development institutions have many tools for supporting the development of geothermal projects and these are used in myriad ways in many different countries. This support is of great importance to the growth of geothermal utilization world-wide. However, more can be done. Currently, a greater access to drilling risk mitigation schemes in a greater number of countries is needed. As suggested by the law of large numbers and the limited number of geothermal fields within any single country, the creation of such schemes should be launched and managed by international development institutions that have access to large funds and the possibility of pooling resources.

REFERENCES

Björnsson, J., 1995: Legal, regulatory and energy policy aspects of geothermal energy in Iceland. *Proceedings World Geothermal Congress 1995, Firenze, Italy*, 519-523. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/1-bjornsson.pdf

Björnsson, S., Gudmundsdóttir, I.D., and Ketilsson, J., 2010: *Geothermal development and research in Iceland*. Orkustofnun (National Energy Authority of Iceland), 39 pp. Website: http://www.nea.is/media/utgafa/GD_loka.pdf

Björnsson, S., Steingrímsson, B., Ragnarsson, Á., and Adalsteinsson, H., 2012: Master plan for geothermal and hydropower development in Iceland. *Proceedings of the "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador*, 13 pp. Website: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-14-18.pdf

California Energy Commission, 2011: *Renewables portfolio standards (RPS) proceeding docket # 11-RPS-01 and 03-RPS-1078*. Website: http://www.energy.ca.gov/portfolio/

CIF, 2014: *Indonesia*. Clean Investment Funds. Website: https://www.climateinvestmentfunds.org/cifnet/?q=country/indonesia

EIA, 2012: *Most states have renewable portfolio standards*. US Energy Information Administration. Website: http://www.eia.gov/todayinenergy/detail.cfm?id=4850

ESMAP, 2013: New funding to boost international support for geothermal energy. Energy Sector Management Assistance Program. Website: http://www.esmap.org/node/3527

Fabri, N., 2009: Geothermal REC contracts – Issues and solutions in today's market. *GRC transactions, 33*, 925-928.

Gassner, H., 2010: Feed-in tariffs, support policy and legal framework for geothermal energy in Germany. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 4 pp. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0309.pdf

Gipe, P., 2014: *Tables of feed-in tariffs worldwide*. Website: www.wind-works.org

Goodman, R., Pasquali, R., Dumas, P., Hámor, T., Jaudin, F., Kepinska, B., Reay, D., Rueter, H., Sanner, B., Van Heekeren, V., Bussmann, W., and Jones, G., 2010: GTR-H – geothermal legislation in Europe. *Proceedings World Geothermal Congress 2010, Bali, Indonesi*a, 8 pp. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0315.pdf

GRMF, 2014: *Geothermal Risk Mitigation Facility for East Africa*. Website: http://www.grmf-eastafrica.org/

Haraldsson, I.G., 2012: Legal and regulatory framework – Barrier or motivation for geothermal development? *Presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador*, 24 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-14-17.pdf

Haraldsson, I.G., 2013: Geothermal acticity and development in South America: Bolivia, Chile, Colombia, Ecuador, and Peru. *Presented at "Short Course on Conceptual Modelling of Geothermal Systems", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador*, 18 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-16-04.pdf

IRS, 2009: *Energy provisions of the American Recovery and Reinvestment Act of 2009*. US Internal Revenue Service. Website: http://www.irs.gov/newsroom/article/0,,id=206871,00.html

ICEIDA / NDF, 2013: *The geothermal exploration project*. Icelandic International Development Agency and Nordic Development Fund, project document ICE23066-1301, 30 pp. Website: http://www.iceida.is/media/verkefnagagnabanki/Geothermal_Exploration_Project_PD.pdf

IDB, 2011: *Colombia promotes geothermal energy with IDB support*. Inter-American Development Bank. Website: http://www.iadb.org/en/news/news-releases/2011-07-07/colombia-promotes-geothermal-energy,9451.html

IFC, 2014: *IFC and leading reinsurance firm Munich Re to reduce geothermal exploration risk in Turkey*. International Finance Corporation. Website: http://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/cb_home/news/feature_turkey_mar2013

Jennejohn, D., 2009: *State and federal incentives for small power and direct-use geothermal production*. Geothermal Energy Association, 42 pp. Web: http://www.geo-energy.org/pdf/Small_Power_and_Direct_Use_Incentives.pdf

KfW, 2011: *KfW Entwicklungsbank finances largest geothermal power plant in Africa*. Website: https://www.kfw-entwicklungsbank.de/International-financing/KfW-Entwicklungsbank/About-us/Pressemitteilungen/Pressemitteilungen-Details_9433-2.html

Martin, C., 2013: *U.S. states turning against renewable portfolio standards as gas plunges*. Bloomberg – Renewable energy world. Website: http://www.renewableenergyworld.com/rea/news/article/2013/04/u-s-states-turning-against-renewable-portfolio-standards-as-gas-plunges

METI, 2012: *Feed-in tariff scheme in Japan*. METI – Agency for Natural Resources and Energy. Web: http://www.meti.go.jp/english/policy/energy_environment/renewable/pdf/summary201207.pdf

Miethling, B., 2011: Different but similar: geothermal energy and the role of politics in Germany, Iceland and the United States. *Z Energiewirtsch Vol. 35*, 287-296. Website: http://www.springerlink.com/content/w31376444776h742/fulltext.pdf

Munich Re, 2014: *Insurance concepts for renewable energies for a low-carbon future*. Website: http://www.munichre.com/corporate-responsibility/en/solutions/reinsurance/concepts/default.aspx

Ngugi, 2012: What does geothermal cost? – The Kenya experience. *Presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador*, 13 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-14-13.pdf

OECD/IEA, 2011: *Technology roadmap – Geothermal heat and power*. International Energy Agency, France, 45 pp. Website: http://www.iea.org/papers/2011/Geothermal_Roadmap.pdf

Peñarroyo, F.S, 2010: Renewable Energy Act of 2008: Legal and fiscal implications to Philippine geothermal exploration and development. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 9 pp. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0305.pdf

Reed, M.J. and Bloomquist, R.G., 1995: National geothermal policy and regulation in the United States. *Proceedings World Geothermal Congress 1995, Firenze, Italy*, 629-633. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/1-reed.pdf

REN21, 2014: *Renewables interactive map*. Renewable Energy Policy Network for the 21st Century. Website: http://map.ren21.net

Rybach, L., 2010: Legal and regulatory environment favorable for geothermal development investors. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 7 pp. Website: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0303.pdf

Siddiqi, G., and Minder, R., 2012: Switzerland country report 2012. IEA Geothermal Implementing Agreement, 7 pp. Web: http://iea-gia.org/wp-content/uploads/2012/08/2012-Switzerland-Country-Report-IEA-GIA-with-Cover-Photo16Oct13-pdf.pdf

ThinkGeoEnergy, 2014: *Ethiopian project receives up to $5.6 million frm Geothermal Risk Mitigation Fund*. Website: http://thinkgeoenergy.com/archives/17890

USAID, 2014: *About Power Africa*. Website: http://www.usaid.gov/powerafrica/about-power-africa

Wahjosoedibjo, A., and Hasan, M., 2012: Geothermal fund for hastening the development of Indonesia's geothermal resources. *Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California*, 7 pp. Website: http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2012/Wahjosoedibjo.pdf

Watanabe, C., 2013: *Japan considering 21 geothermal plans after Fukushima, METI says*. Bloomberg BusinessWeek. Website: http://www.businessweek.com/news/2013-04-09/japan-considering-21-geothermal-plans-after-fukushima-meti-says

World Bank, 2012: Pertamina Geothermal Energy (PGE) prepares a globally unprecedented expansion of geothermal renewable energy with assistance from the World Bank and the Government of New Zealand. The World Bank Group. Website: http://www.worldbank.org/en/news/press-release/2012/06/18/pertamina-geothermal-energy-pprepares-a-globally-unprecedented-expansion-of-geothermal-renewable-energy

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

FROM CARBON FINANCING IN THE CONTEXT OF GEOTHERMAL DEVELOPMENT TOWARDS ADAPTATION TO CLIMATE CHANGE

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ABSTRACT

The concern on the effects of climate change is global. Scientific evidence has shown that its origin is the increasing greenhouse gas emissions from anthropogenic activities. The international community agreed that the solution is to mitigate climate change and adapt to this change.

The Clean Development Mechanism (CDM) contributes to the mitigation and provides opportunity for promoting the development of geothermal energy utilization in developing countries. Twelve geothermal projects have been registered in the CDM and four of them are from Central America. El Salvador has registered two geothermal electricity projects as CDM projects with about 212,881.0 Certified Emission Reductions per year (CERs/yr), which represent 96.5% of the total offer.

The main benefits identified in the CDM geothermal projects are: a) the contribution to mitigate climate change, b) contribution to sustainable development in the host country, c) improvement in project profitability, d) positive environmental publicity for the company, e) strengthening of the competitiveness of the company, f) reduced dependence on oil, g) contribution to fund adaptation, h) access to investment funds and i) capacity building in CDM.

Central America has low emissions of gases (0.08% of CO_2 in the world) and has high vulnerability to climate change; and hence, the main issue should be the adaptation to climate change. Geothermal project developers should include in their environmental management plan (EMP) measures that contribute to the reduction of the vulnerability in the local area of the project. In this way, geothermal projects not only would contribute to sustainable development but also to adaptation to climate change.

1. INTRODUCTION

The effect of climate change is a global problem. The international response provides two paths of solution: the mitigation of greenhouse gas emissions and the adaptation to its effects. This paper presents the potential for geothermal projects to participate in the CDM. At the same time, it presents the experience of El Salvador and the lessons learned from CDM. Finally, it gives the opportunity on how the developer of geothermal projects can contribute to the local adaptation to climate change.

2. GLOBAL EFFORTS TO CLIMATE CHANGE MITIGATION

Scientific evidence shows that increasing greenhouse gas (GHGs) emissions from anthropogenic activities is causing dramatic climatic changes such as elevating temperatures, rising sea levels, alterations in precipitation patterns and evolving of extreme climate events. There is more than 90% of certainty that global warming in the 20th century was due to the observed increase in these anthropogenic GHGs concentrations (IPCC, 2007).

According to the Intergovernmental Panel on Climate Change reported in its Fourth Assessment Report, the main greenhouse gases in the atmosphere are water vapour, carbon dioxide, methane, nitrous oxide, and ozone. The rise in carbon dioxide (CO_2) concentrations is mainly due to the use of fossil fuels; and increased concentrations of methane (CH_4) and nitrous oxide (N_2O) due to agricultural activities.

The international response to mitigate climate change began in 1992, where different governments in the world adopted the United Nations Framework Convention on Climate Change (UNFCCC). The main objective of the Convention is to achieve stabilization of atmospheric concentrations of greenhouse gases (GHGs) at levels that would prevent dangerous anthropogenic interference with the climate system, by an average of 5.2% in the period 2008-2012.

The Convention divides countries into two main groups:

- *Annex I Parties*: include the relatively wealthy industrialized countries that were members of the Organization for Economic Co-operation and Development (OECD) in 1992, as well as countries with economies in transition; and
- *Non-Annex I Parties*: mostly the developing countries.

In 1997, the Kyoto Protocol was adopted and gave new vision, with its legally binding constraints about reduction GHGs emissions, primarily through national measures. As an additional means of meeting these targets, the Kyoto Protocol introduced three flexible market-based mechanisms, which are:

- Emissions Trading (ET);
- Joint Implementation (JI); and
- The Clean Development Mechanism (CDM).

Under Article 12 of the Kyoto Protocol, the CDM is a mechanism which has two purposes:

- Assist non-Annex I Parties in achieving sustainable development and in contributing to the objective of the climate change convention; and
- Assist Annex I Parties in achieving compliance with their quantified emission limitation and reduction commitments under the Kyoto Protocol.

The CDM projects are designed to reduce GHGs emissions, as well as to transfer environmental protection technologies and promote these technologies to the host countries, see Figure 1.

3. PROBLEMS OF THE CLIMATE CHANGE IN C.A. REGION

The Central American region is located in a strategic position, which provides a natural link between North America and South America and separates the Pacific Ocean with the Caribbean Sea. The region is composed of seven relatively small countries: Guatemala, Belize, Honduras, El Salvador, Nicaragua, Costa Rica and Panama, which base their economies on agriculture and use of natural resources (Leonard, 1987). The biological richness of Central America is manifested in 20 lifezones, ranging from semi-desert to cloud forest, and with 8% of the world's known plant species and 10% of its vertebrates. The region has extremely steep terrains, ample variety of climate and perhaps a higher propensity for natural disasters than any other territory on the planet (Leonard, 1987).

Historically, the region has been identified by their socioeconomic vulnerability that is affected by droughts, cyclones and the El Niño/La Niña-Southern Oscillation (ENOS). The climate change is intensifying and expanding these vulnerabilities, and can cause an increased impact on the main economic activities in the region; such as agriculture and tourism, which are climate-dependent. These economic activities are representing a major proportion of income and employment in all the countries in the region (CCAD and SICA, 2010).

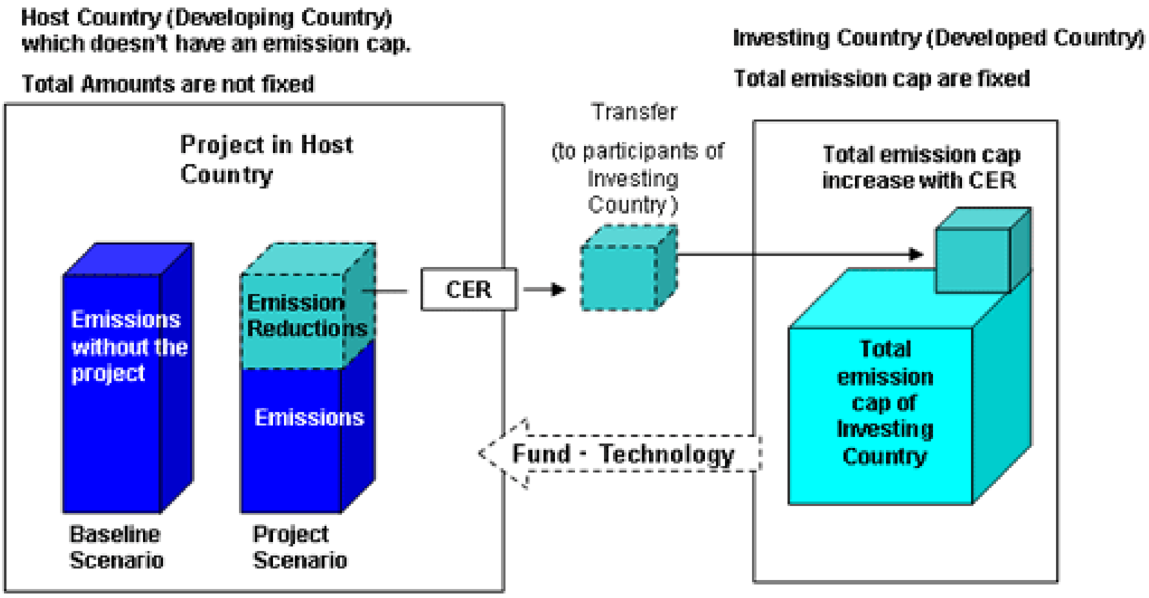


FIGURE 1: Clean Development Mechanism (JQA, 2007)

It doesn't matter that Central America continues to have one of the lowest shares of the GHG global emissions (0.08% of CO_2 in the world in 2007) as the effects of climate change will continue to increase in the region. In the past three decades, the number of disasters has grown at an estimated annual rate of 5% compared to the levels recorded during the 1970's. There is a consensus that the increasing intensity of hurricanes and other storms is related to climate change (United Nations, 2010 and The Word Bank, 2007).

According to GERMANWATCH (Harmeling and Eckstein, 2013; Kreft and Eckstein, 2014), the most affected countries in the world by the impacts of weather-related loss events in 2011 were Thailand, Cambodia, Pakistan and El Salvador. Between 2002 and 2011, El Salvador was affected by seven cyclones and two low-pressure systems, three of these extreme event caused losses of approximately 1,300 millions of dollars (equivalent to 6% of its Gross Domestic Product) (MARN, 2013). Furthermore, for the period of 1993 to 2012, Honduras, Myanmar, Haiti, Nicaragua, Bangladesh, Vietnam, Philippines, Dominican Republic, Mongolia, Thailand and Guatemala ranked the highest. Unfortunately, three of these countries belong to the Central American region and four have geothermal projects in the CDM.

The climate simulation for Central America under scenario B2 (medium-low global emissions) of the IPCC generated the mean annual temperature, stating that by 2020 and 2050, increase in temperature is up to 0.5°C and 1.3°C respectively, compared to the average annual temperature for 1980-2000. The region had suffered the impacts (shown in Figure 2) within the range of 0.5°C to 2°C (United Nations, 2010).

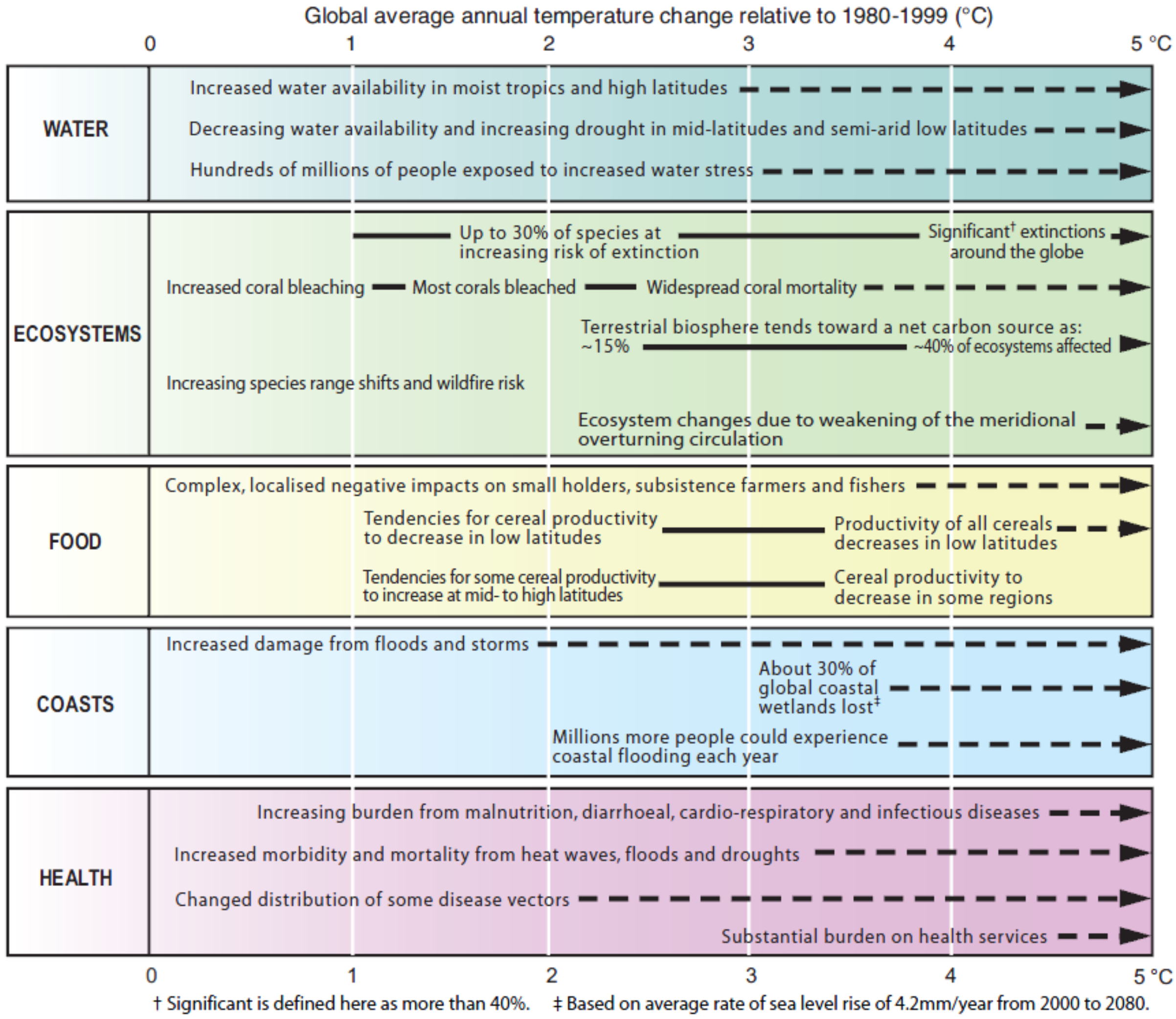


FIGURE 2: Impacts associated with global average temperature change (Bernstein et al., 2007)

In summary, the Central American region faces climate change with a high sensitivity to its impact and reduced resilience and adaptation capabilities. In this context, it is worth remembering the following definitions presented in the IPCC TAR (McCarthy et al., 2001):

- *Sensitivity*: The degree to which a system is affected, either adversely or beneficially, by climate related stimuli;
- *Resilience*: Amount of change a system can undergo without changing state; and
- *Adaptive capacity*: The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

The report by CCAD and SICA (2010) indicates that the response of the Central American region to face this problem is based on the Regional Strategy on Climate Change (RSCC).

This Regional Strategy contemplates actions to be taken in the following strategic and programmed areas:

- Mitigation;
- Vulnerability, adaptation to climate change and variability and risk management;

- Capacity building;
- Education, awareness, communication and citizen participation;
- Technology transfers; and
- Negotiations and international support.

4. SUSTAINABLE ENERGY AND CLIMATE CHANGE

The concept of sustainable energy can be defined as the provision of energy services affordable, accessible and reliable to meet the economic, social and environmental needs of society with an equitable distribution to meet these needs (Davidson et al., 2006).

In 2009, in Central America, there existed about 7.4 million of people without electricity access and this unsatisfactory situation is clearly a considerable constraint to its social-economic development (WEO, 2011; OFID, 2010); moreover 38% of electricity generation comes from fossil fuel (Montalvo, 2011). The dependence on fossil fuels not only increases the cost of electricity, but also is one of the main responsible for the global GHGs emissions. This fact allows to identify that there is a long way to go in the struggle against climate change and the urgent need to switch to an energy model to a low-carbon economy, in order to resume the path towards sustainable development.

Renewable energy projects and energy efficiency programs are making significant contributions in programmed area of Mitigation (reducing dependence on fossil fuel use and associated GHG emissions). Geothermal energy is one of the most promising among renewable energy sources, and has proven to be reliable and clean energy source compared to nuclear and fossil fuels. Therefore, its utilization for power generation and direct uses is increasing (Kömurcu and Akpinar, 2009). According to Bertani (2009), by 2050, geothermal electricity generation will be about 1000 TWh/yr and could be mitigated up to 1000 of million tons of CO_2/yr (calculation made based on the replacement of coal).

Central America has a total estimated geothermal potential of about 3500 MWe, which has an installed capacity of 506.8 MWe to date and by 2015 it is forecasted to increase to 885 MWe (Montalvo, 2011 and CEPAL, 2010). An opportunity for promoting and accelerating the development of geothermal energy utilization in developing countries is the CDM (Mutia, 2010). At present, Central America has already begun to benefit this mechanism.

According to the website of UNFCCC (2014), 12 countries (Chile, China, El Salvador, Guatemala, Honduras, Indonesia, Kenya, Malaysia, Mexico, Nicaragua, Papua New Guinea, and Philippines) are taking advantage of the Clean Development Mechanism (CDM) to generate an additional source of income to contribute to the economic viability of 29 geothermal power projects and 2 geothermal space heating projects. Of these 31 projects, it is expected to have an annual reduction near of 11 million tonnes of CO_2 equivalent. But only 10 have already received 7,227,982.0 of Certified Emission Reductions (CERs) in the period from 2005 to 2012 (which represents 8.0% of the offer). Five of these projects belong to the Central American countries indicating that the region has good participation in the CDM for geothermal projects and generated 19.6% of the CERs issued.

5. GEOTHERMAL PROJECTS AND CDM BENEFITS IN EL SALVADOR

Geothermal projects could be considered a potential CDM project and to qualify, these projects must meet the following requirements:

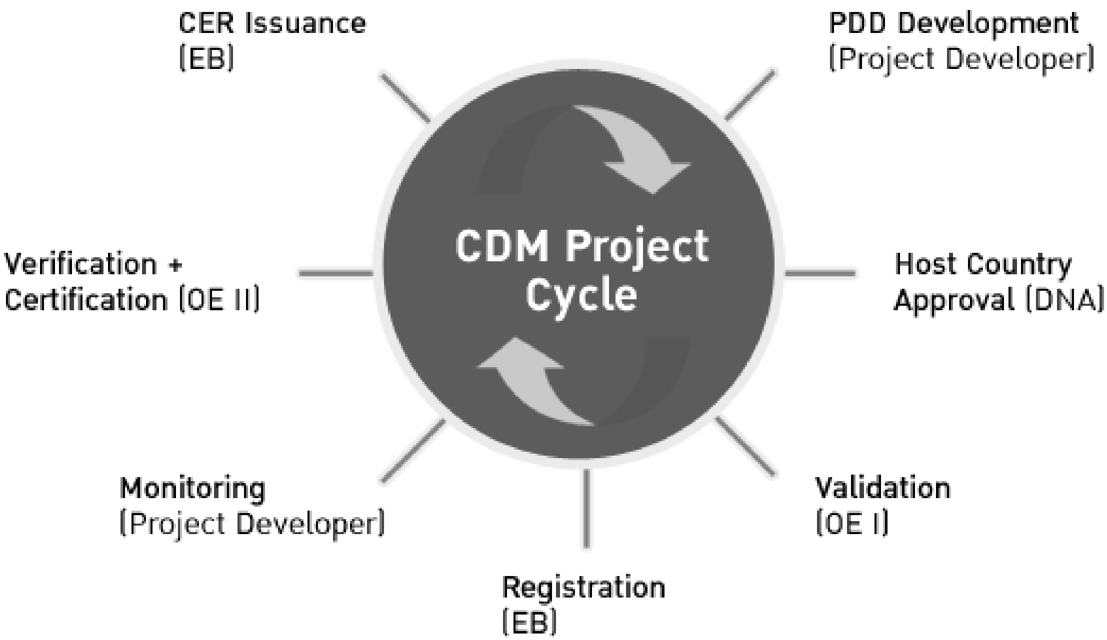
- The project host country must have ratified the Kyoto Protocol and a Designated National Authority (DNA);

- A letter of approval from DNA stating that participation of the project is voluntary, and that the project activity assists in achieving sustainable development of the host country;
- The project activity must demonstrate to have real, measurable and long-term benefits related to the mitigation of climate change;
- Early consideration of the project activity is to implement the CDM;
- The emission reductions must be additional;
- Does not give significant environmental impacts and undertakes public consultation; and
- Does not result to the diversion of official development assistance (ODA).

According to Loy (2008), in late 1999, LaGeo contracted consulting services to incorporate the geothermal projects to the CDM, which included the Berlin Geothermal Project Phase One and the Stabilization Project Ahuachapán, operating since 2000 and with an installed capacity of 66 and 23 MWe respectively. The study concluded that these projects were not eligible under the CDM because they did not meet the additionally requirements.

LaGeo attempted again to include another project called HFR (Hot Fractured Rock) and it was placed to validation in the CDM project cycle as it was already in the advanced stage (Figure 3). However, the project did not generate the required results so neither Emissions Reduction Purchase Agreement (ERPA) was signed nor it was registered in the CDM project.

El Salvador has registered two geothermal electricity projects as CDM projects, with about 165,000.0 CERs/yr and represents 74.8% of the offer. These are a) Berlin Geothermal Project, Phase Two and b) Berlin Binary Cycle power plant; both are already contracted until 2012. The general information of these projects is shown in Table 1.



CER: Certified Emission Reduction
DOE or OE: Designated Operational Entity (Independent agency that acts as a validator or verifier of CDM Projects)
DNA: Designated National Authorities
PDD: Project Design Documents

FIGURE 3: Clean Development Mechanism Project Cycle

TABLE 1: Geothermal CDM projects in El Salvador (UNFCCC, 2012)

Registered	Title	MWe Installed	Ref.	CERs Issued	CERs Awaiting issuance request	Period of monitoring reports issued
25 May 06 Ref. 297	Berlin Geothermal Project, Phase Two	44.0	0297	882,857	167,143	01 Jan 07 to 31 Dec 12
30 Nov 07 Ref. 1218	Berlin Binary Cycle Power Plant	9.2	1218	154,474	38,760	31 Nov 07 to 31 Dec 12

5.1 CDM benefits in El Salvador

The main benefits of CDM projects are listed in Article 12 of the Kyoto Protocol and related to the mitigation of climate change and contribution to sustainable development in the host country. The following are other benefits identified for these projects:

a) *Improvement of project profitability:*
The sale of CERs improves the feasibility of the project by providing additional revenue for the Project Proponent (PP). According to Rodriguez and Henríquez (2007), roughly 5-7% of the revenue streams can be accrued from a CDM certification of a geothermal project, having an impact of 1-2% on the internal rate of return.

b) *Positive environmental publicity for the company:*
The CDM provides an incentive not only economic but also an international recognition to the project by contributing measurable and long-term to climate change mitigation voluntarily. There are many publications which refer to CDM projects and their environmental achievements.

c) *Strengthening of the competitiveness of the company:*
The Project Proponent must implement control processes that should be verified by a third party (Designated Operational Entity - DOE) to ensure accuracy in the delivery of CERs on offer. This helps in identifying and incorporating improvement in the process.

d) *Reduction in dependence on oil:*
The energy generated by the geothermal projects helped reduce dependence on oil. Only in 2011, the geothermal CDM projects in El Salvador have prevented the purchase of 465,000 barrels approximately, and its respective impact on the national economy.

e) *Contribution to adaptation fund :*
Contribution to the adaptation fund for developing countries with 2% of total Certified Emission Reductions (CERs) issued on CDM project. Currently 7,356.0 CERs for adaptation fund have been given by the geothermal projects of El Salvador.

f) *Access to investment funds:*
Access to green or social responsibility funds has provided the search for investment opportunities in Latin America.

g) *Capacity Building in CDM:*
Training of staff involved in the CDM project has emphasized in global processes and methodologies.

5.2 Lessons learned from CDM

- Invest the time necessary to prepare and review the Project Design Document (PDD), if it meets the requirements and does not commit more than the required information. Does PDD correctly describe the actual project? Does PDD meet the CDM requirements?

- For geothermal projects, it is necessary to calculate project emissions due to release of CO_2 and CH_4 from the produced steam (PESy) to avoid offering of more emission reduction (ERy). In the case of "Berlin Geothermal Project, Phase Two" about 10% of the tons of emission as baseline is the project emission.

- During validation or verification process, most of the time depends on DOE, therefore Project Proponent should have an open communication with DOE (validator or verifier), and must have all the information. The Project Proponent must provide all information even confidential, so that the DOE could evaluate all the hypotheses.

- The monitoring report must follow the approach provided in the methodology and PDD. Communicate with your consultant if any deviation is detected. A deviation in the PDD could delay the verification process up to 3 months.

- The monitoring plan described in the PDD should be implemented by a team. The training of the team responsible for implementing the monitoring plan is essential in order to quantify correctly each of the variables to be used in the calculation of the emission reduction.

- The processes and methodologies are becoming increasingly complex with time. The project proponent should be aware of the changes and should be prepared to meet them.

- Identify gaps and opportunities for improvement before the actual validation or verification is pre-audited (pre-validation and pre-verification).

6. TOWARDS ADAPTATION TO CLIMATE CHANGE IN GEOTHERMAL FIELDS

Progress in the utilization of geothermal energy for electricity generation contributes to the significant reduction of the national emission factor in developing countries, which allows these projects to have a real contribution and measures related to the mitigation of climate change. Reduction in greenhouse gas emissions along with socio-economic and environmental benefits has helped identify geothermal projects that can contribute to sustainable development in the host country and be eligible for CDM.

Under Article 12 paragraph 8 of the Kyoto Protocol and the Marrakesh Accords, the Conference of the Parties (COP) shall ensure that a share (2%) of Certified Emission Reductions (CERs) issued for a CDM project activity is used to assist developing countries, which are particularly vulnerable to the adverse effects of climate change to meet the costs of adaptation. It is here where the CDM could contribute most significantly to meet the challenges of adaptation to climate change in developing countries.

In practice, UNFCCC has created the adaptation fund to finance concrete adaptation projects and programs that are driving developing countries. However, the CDM levy of 2% will not suffice to cover the growing adaptation needs in these countries; therefore the adaptation fund should also receive funding from other sources. According to The Adaptation Fund (until February 23, 2012), only 17 projects in different countries are receiving adaptation funds, of which just two projects (Honduras and Nicaragua) belong to the Central American region. The above is very small compared to the urgent adaptation needs of the region.

The Central American countries have such low emissions that should not be the main issue of the mitigation but should be the adaptation to climate change. The developments of geothermal projects are of great importance that should be executed even without CDM support; and many developing countries are making these efforts. Even without the CDM support, the geothermal projects must invest in adaptation to climate change in its geothermal fields. This is the way that Project Proponent should follow in order to give a greater contribution to sustainable development and climate change in the local area of the project.

In El Salvador, the Ministry of Environment and Natural Resources (MARN) has incorporated into its National Environmental Policy the reduction of vulnerability to climate change. It has also created National Strategy for Climate Change with three main areas:

a) National program priorities mitigation co-benefits;
b) Mechanisms to address recurring losses and damage from climate change; and
c) Adapting to climate change.

LaGeo has already started its studies in the Chinameca Geothermal Project and the environmental studies have incorporated greater emphasis on the evaluation of the social-economic and environmental sensitivity in order to identify vulnerability to climate change. This information has identified some measures that could contribute to reducing vulnerability and increase the resilience in the local people to climate events.

Some of the measures are listed below:

- Maintenance of existing ecosystems. The drilling pads are constructed in terrains that are usually coffee farms, therefore owners sell it completely. In practice a small portion is used for geothermal development and most can be allocated to the current ecosystem conservation.

- Restoration of damaged forest systems. All geothermal projects should make compensatory measures for the impacts generated such as planting 10 trees for every affected tree. This measure could be focused on the restoration of damaged forest systems.

- Construction of conservation work for soil stabilization and storm water management that works with a dual purpose: to protect the infrastructure of geothermal projects and reduce the vulnerability of the area to landslides and floods.

- Installation of a weather station in order to identify relevant information to be integrated into risk management of the area.

- Construction of rainwater infiltration systems on drilling pads to reduce runoff in the lower basin.

- Implement a wood-saving stove project to reduce deforestation and respiratory diseases in the area.

- Construction of individual rainwater- capturing systems to supply water the people in the rural area that are deprived of public water supply.

- Construction of storage tanks and distribution of spring water to supply water to rural communities in the area which have no public supply.

The above measures have been included in the Environmental Management Program (EMP) to be considered from the design of the project. As a result, the project will not only have a contribution to sustainable development, but also will include a local adaptive approach.

7. CONCLUSION

- Based on scientific evidence, it can be said that the problem of climate change has its origin in increasing greenhouse gas emissions from anthropogenic activities. The international community agreed that the solution is to mitigate climate change and adapt to this change. The Clean Development Mechanism (CDM) is a flexible mechanism of the Kyoto Protocol that contributes to the mitigation.

- The CDM is an opportunity for promoting the development of geothermal energy utilization in developing countries. Twelve geothermal projects have been registered in the CDM; seven have already received 2,610,299.0 CERs and short-term projects are waiting 1,826,367.0 CERs. Central America has 4 projects registered with an average of 285,000.0 CERs/yr.

- Developing CDM project requires the services of a professional with experience in the field. It should be kept in mind that each CDM project is different. By the lessons learned in this paper, it can help a project developer to reduce errors during the CDM project cycle.

- El Salvador has registered two geothermal electricity projects as CDM project activities with about 165,000.0 CERs/yr which represents 74.8% of the offer. The main benefits identified of the CDM geothermal projects are: a) contribution to mitigate of climate change, b) contribution to sustainable development in the host country, c) improvement of project profitability, d) positive environmental publicity for the company, e) strengthening of the competitiveness of the company, f) reduction in dependence on oil, g) contribution to adaptation fund, h) access to investment funds and i) capacity building in CDM

- Central American countries have such low emissions (0.08% of CO_2 emissions in the world in 2007), but they are very vulnerability to climate change, which should not be main issue for the mitigation but should be the adaptation to climate change.

- The project developer should give a greater contribution to sustainable development and climate change in local area of the project. One way is that the geothermal project developers should include in their environmental management plans (EMP) measures that contribute to the reduction of vulnerability in the local area. In this way, measures could be considered during the design of the project. As a result the project will not only have a contribution to sustainable development, but also will include the local adaptive approach.

REFERENCES

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., Hare, W., Huq, S., Karoly, D., Kattsov, V., Kundzewicz, Z., Liu, J., Lohmann, U., Manning, M., Matsuno, T., Menne, B., Metz, B., Mirza, M., Nicholls, N., Nurse, L., Pachauri, R., Palutikof, J., Parry, M., Qin, D., Ravindranath, N., Reisinger, A., Ren, J., Riahi, K., Rosenzweig, C., Rusticucci, M., Schneider, S., Sokona, Y., Solomon, S., Stott, P., Stouffer, R., Sugiyama, T., Swart, R., Tirpak, D., Vogel, C., and Yohe, G., 2007: *Climate change 2007: Synthesis report*. An assessment of the Intergovernmental Panel on Climate Change, 52 pp.

Bertani, R., 2009: *Long-term projections of geothermal electric development in the world*. Enel Green Power, Italy, 21 pp.

CCAD and SICA, 2010: *Regional strategy on climate change – Executive document*. Comisión Centroamericana de Ambiente y Desarrollo and Sistema de la Integración Centroamericana, Antiguo Cuscatlán, El Salvador, 95 pp.

CEPAL, 2010: *Centroamérica: estadísticas del subsector eléctrico*. México, D.F.

Davidson, O., Winkler, H., Kenny, A., Prasad, G., Nkomo, J., Sparks, D., Howells, M., and Alfstad, T., 2006: *Energy policies for sustainable development in South Africa. Options for the future*. Energy Research Center, University of Cape Town, Rondesbosch, South Africa, 225 pp.

Harmeling, S., and Eckstein, D., 2013: *Global climate risk index 2013. Who suffers most from extreme weather events? Weather-Related Loss Events in 2011 and 1992 to 2011*. Germanwatch, e.V., Germany, 28 pp.

IPCC, 2007: Cambio climático 2007: *Evaluación de la vulnerabilidad e impactos del cambio climático y del potencial de adaptación en América Latina.*

JQA, 2007: *What is CDM?* Japan Quality Assurance Organization. Website: www.jqa.jp/english/environment/cdm_what.html

Kreft, S., and Eckstein, D., 2014: *Global Climate Risk Index 2014. Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2012 and 1993 to 2012*. Germanwatch e.V., Germany, 28 pp.

Kömurcu, M.I., Akpinar, A., 2009: Importance of geothermal energy and its environmental effects in Turkey. *Renewable Energy, 34*, 1611–1615.

Leonard, H.J., 1987: *Natural resources and economic development in Central America: A regional environmental profile*. Transaction Books, Oxford, England, United Kingdom and New Brunswick, NJ, United States, 31 pp.

Loy, R., 2008: *LaGeo en el Mecanismo de Desarrollo Limpio (MDL)*. LaGeo, internal report.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., and White, K.S. (editors), 2001: *Climate change 2001: Impacts, adaptation and vulnerability.* Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, 1032 pp.

MARN, 2013: *Estrategia Nacional de Cambio Climático 2013*. San Salvador, El Salvador.

Montalvo, F.E., 2011: Current status of geothermal resources development in Central America. *Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador*, 10 pp.

Mutia, T. M., 2010: CDM projections for Kenya: Towards a green geothermal economy – the case of Olkaria and Menengai geothermal power projects. Report 21 in: *Geothermal training in Iceland 2010*. UNU-GTP, Iceland, 391-418.

OFID, 2010: *OFID and energy poverty challenges*. The OPEC Fund for International Development, Vienna, Austria, 40 pp.

Rodríguez, J.A., and Henriquez, J.L., 2007: Economics and financing for geothermal projects in Central America. In: Rodríguez, J.A., Lectures on geothermal in Central America. UNU-GTP, Reykjavik, Iceland, report 2, 40 pp.

United Nations, 2010: *The economics of climate change in Central America.*

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

COST AND REVENUES OF DIRECT USE APPLICATIONS

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ABSTRACT

Geothermal projects in general are riskier than conventional projects, not only because of the uncertainty regarding the geothermal resource but also because of the high investment costs involved in reaching the resource underground. It is legitimate for a project developer to wonder whether or not to undertake the long and risky process of developing a geothermal resource for direct use, with high upfront costs and long payback period, when one can use a standard technology with a standard source of energy that may prove more expensive in the mid to long term but is considered less risky.

The purpose of the paper is to discuss specific issues to be taken into account when determining feasibility of a geothermal direct use project or having an impact on its bankability. It also provides an overview of the components included in capital and operational cost of geothermal direct use applications and the types of revenues related to geothermal direct use. As direct use of geothermal resources may encompass a wide range of final products, the paper discusses when a project may become economically competitive.

1. INTRODUCTION

Direct use of geothermal resources has been implemented in various parts of the world in a successful manner, for instance in geothermal district heating systems in Reykjavik (Iceland), Izmir (Turkey) or Xinayang (China) or the Oserian greenhouse in Kenya. They also have been used successfully in bathing, industrial and fish farming facilities all around the world. When managed in a sustainable manner, geothermal energy can be a very interesting alternative source of energy.

Direct use of geothermal applications are rather unconventional although they may proceed from conventional processes. Their feasibility highly depends on the geothermal resource characteristics and whether its use can be achieved in an economically competitive manner or not. Investment costs may be much higher than in conventional projects whereas their operation costs are generally significantly lower. For instance in space heating applications, the heat is expected to be extracted from the geothermal resource at minor cost.

Parameters impacting the business case of geothermal direct use application include features uncommon in other conventional projects that are highlighted in the paper.

2. FEASIBILITY AND BANKABILITY OF GEOTHERMAL APPLICATIONS

2.1 Project development phases

Geothermal projects are rather unconventional projects. They always depend on the geothermal resource itself and on the nature of the application being considered. Although conventional equipment may be used, one cannot duplicate a solution and the project concept always has to be adapted and engineered to some extent to fit the specific geothermal resource characteristics.

The development process is furthermore lengthy and cannot be handled in a conventional manner for various reasons, e.g.:

- Lack of reliable resource information during the initial phases;
- High upfront costs and risks; and
- Availability of experienced professional.

Figure 1 below, although coming from an electricity production application, is still valid in principle for a direct use application. It describes how the project costs and risk profile are expected to evolve along with the project development stages.

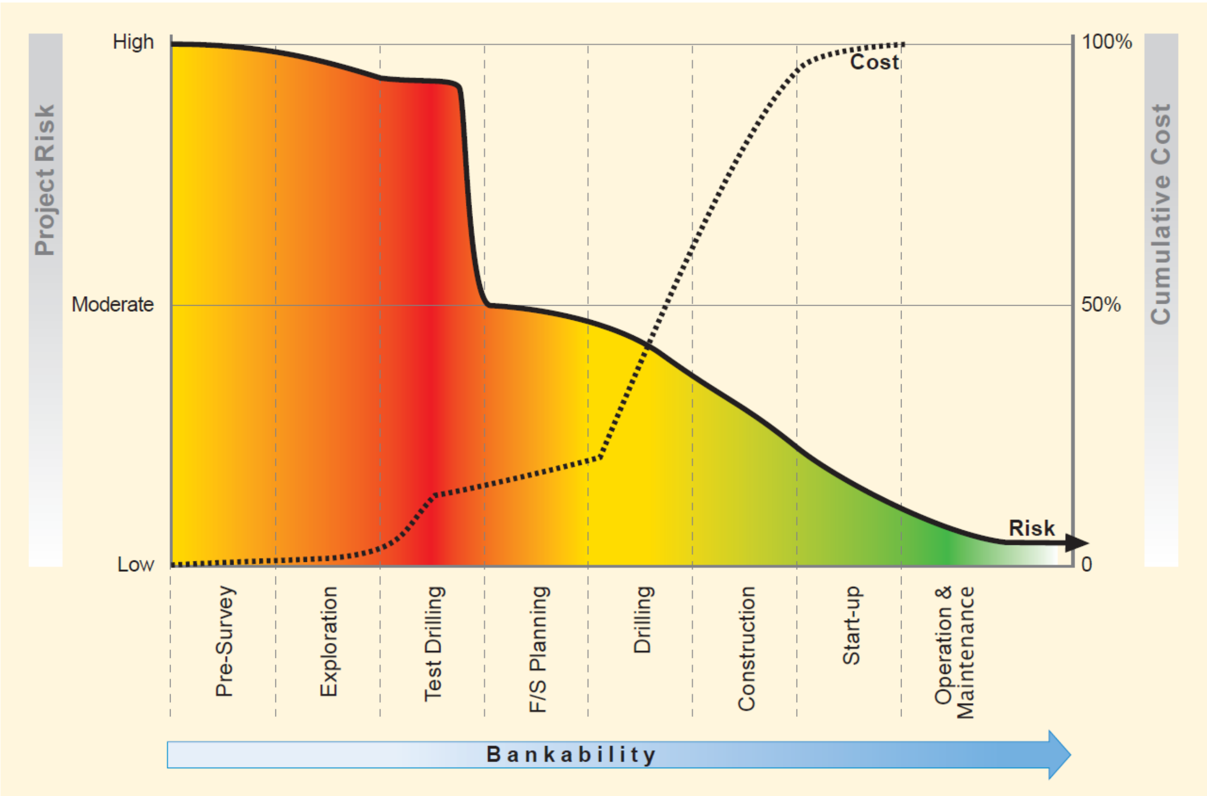

FIGURE 1: Project cost and risk profile at various stages of development – Electricity project (Gehringer and Loksha, 2012)

Geothermal projects imply high upfront costs with assessment of the geothermal resource and above all drilling of the first successful well(s). Whenever drilling is required, significant investment, and therefore financial risk, is required prior to establishing whether the resource is viable for the application considered or not.

Independent of the type of application, geothermal projects should always be developed in successive phases at the end of which the project developer decides to carry on with the project or not. This is a simple way to manage upfront risks, although it is to be noted that the approach alone will not eliminate the risks and that the project developer might have to investigate other tools or actions for further mitigation. Carefully planning the development activities and conducting a project in incremental steps will contribute to enhancing credibility of a project towards potential financiers and lenders.

The development stages can be divided into 4 major phases: 1) identification, 2) Exploration, 3) Design and construction, 4) Operation and maintenance. Figure 2 presents these phases and the main activities that may be undertaken during the development of a geothermal project.

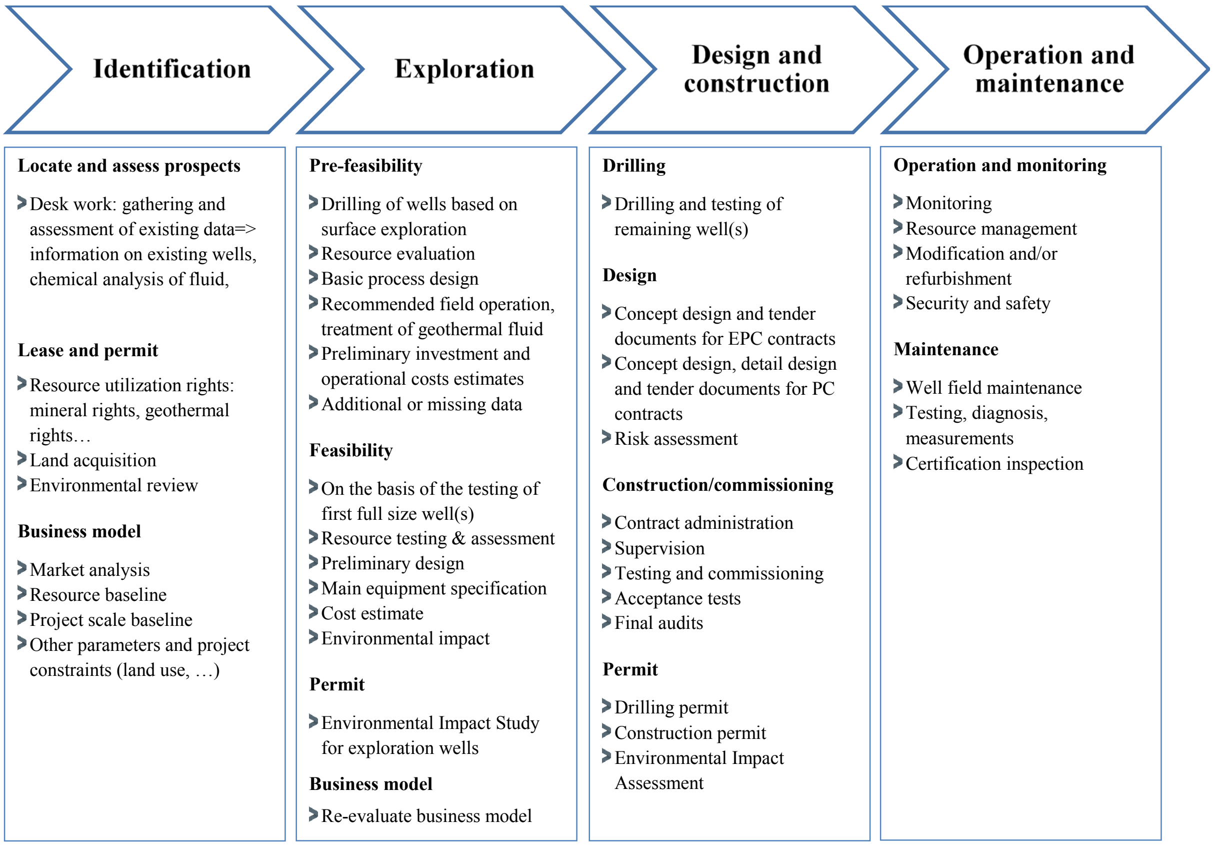

FIGURE 2: Typical activities that may be undertaken during development of a geothermal project

Experience has shown that it typically takes a few years to complete a full-size geothermal project. Various factors will impact the project duration. For instance, a green-field project with little information at hand regarding the resource might take longer time in its identification and exploration phases than a field which has previously been identified.

2.2 Bankability of a project and feasibility

A project is deemed bankable if lenders are willing to finance it. The feasibility study is a thorough study conducted once enough information on the geothermal resource is available. It is aimed at confirming or infirming the feasibility of a project by investigating various components of a project, i.a.:

- Resource assessment.
- Preliminary design for the use of the geothermal resource.
- Investment, operational and maintenance cost estimate.
- Development plan.

The operational and maintenance costs constitute, together with the expected revenues, essential input in the business model. Combined with a financial analysis aimed at validating the business model, the results of the feasibility may be gathered in a bankable feasibility study to undertake and complete the financing of a project.

3. TYPICAL CAPITAL EXPENDITURES - DESCRIPTION

The capital expenditures involved in the development of a geothermal direct use project can be viewed as separate components:

1. Exploration – early development.
2. Geothermal field development.
3. Downstream installation.

These components correspond more or less to the project stages described above. The key features and order of magnitude of these components may vary greatly from one project to the other, depending on the geothermal resource itself and on the nature of the application being considered. It is also what makes geothermal projects unconventional as one cannot fully duplicate a solution and it always has to be adapted and engineered to some extent to fit the specific geothermal resource characteristics.

3.1 Exploration – Early development

The early development phase concerns identification of the geothermal resource and its exploration.

The resource identification phase includes the collection and review of geothermal and other available information, including data regarding geology, geophysics and geochemistry of the presumed resource. Once the resource has been properly identified, the project developer decides whether to carry on with the project or not.

During the exploration phase, a pre-feasibility study is generally undertaken. The prefeasibility report is based on the surface exploration. If the outcome of the prefeasibility report is that the project is viable, the next phase will be drilling of exploration wells. Usually the exploration wells are full size wells that will become production wells if the drilling is successful. The location of the first exploration well is based on the surface exploration and locations of latter wells on the surface exploration, in addition to the outcome of testing of preceding wells. When exploration has proven that the capacity of the geothermal field is sufficient for a minimum size of economical viable power plant or other application, a feasibility report is made. On basis of that the project developer will decide if he continues with the project.

The phase may also include early environmental review and various activities related to leasing and permitting.

Direct investment costs involved at theses stage mainly concern the exploration well(s). It is to be noted that the well(s) may be used afterwards during operation.

Indirect costs may be accounted for separately, see section 3.4, and comprise:

- The activities and studies aimed at confirming the resource potential.
- Costs related to leasing and permitting.

3.2 Geothermal field development

The geothermal field is understood in the context of the paper to include all the underground elements and well heads.

Field development might begin during the exploration phase and generally continues in parallel with the activities related to the downstream installation. It consists of drilling production and reinjection wells as well as testing and preparing them for connection to the downstream components. Field development is conducted in accordance with the strategy established in earlier phases and is regularly revisited in light of current testing results as reservoir simulations will over time provide a more and more accurate picture of the geothermal resource and its capacity in the long term.

Field development is extremely important for the project as it allows verification of the preliminary resource assessment. It is also, as previously mentioned, the riskiest part of the project in terms of the investment involved and uncertainty regarding the outcome.

It is to be noted that the time and investment required to fully develop a geothermal field may vary considerably from one geothermal field to the other depending on parameters such as the wells depth, the resource geology and the availability and capacity of the drilling rig.

For projects requiring drilling, the bankable feasibility study is generally conducted simultaneously with the first exploration well and takes into account the testing results.

Direct investment costs involved at theses stage mainly concern:

- Infrastructure: roads, well pads…
- Drilling and well testing.
- Equipment required for the wells and their connection to the downstream components.

3.3 Downstream installation

The downstream installation encompasses the design, construction/installation and commissioning of all equipment, utilities and facilities required for the exploitation of the geothermal resource to the purpose of the project. The downstream components are above ground components starting from the geothermal field.

The components required for a direct use application will vary greatly depending on the application considered and may encompass:

- Gathering and re-injection pipelines along with mechanical and control equipment to handle and control the geothermal fluid: valves, de-aerators, filters, pumps etc.
- Mechanical and control equipment directly involved in the heat handling:
  - Heat exchangers, tanks, peak load boiler, transportation- and distribution pipes and end-users connection.
- Mechanical and control equipment directly involved in the application:
  - Heat exchangers, pump, temperature control.

Conceptual design is often being carried as the wells are being drilled and tested. The tender procedures can vary from one project to the other depending on their specificities. The utilities are generally tendered either as PC (Procurement and Construction) or EPC (Engineering, Procurement and Construction) contracts.

Direct Investment costs involved at theses stage mainly concern procurement and construction/installation of:

- Gathering and re-injection pipelines.
- Mechanical and control equipment to handle and control the geothermal fluid.
- Mechanical and control equipment directly involved in the application.
- Utilities and facilities.

3.4 Indirect costs

Indirect costs should also be accounted for. They may include:

- Engineering, supervision and commissioning.
- Project contingencies.
- Spare parts.
- Concessions, land costs.
- Official permits.
- Insurance…

4. TYPICAL OPERATION AND MAINTENANCE COST – DESCRIPTION

It is to be noted that the specific operation and maintenance costs of a geothermal direct use application are highly dependent on the type of application, its size and features. The components presented below only provide a general indication of operation and maintenance costs.

4.1 Personnel

Specific personnel may be required to operate and the costs associated should be taken into account.

4.2 Spare parts and consumables

Spare parts, as recommended by the manufacturer, should be accounted for here. In addition consumables may be required for e.g. lubrication oil replacement or to handle the geothermal fluid. Spare parts and consumables are usually accounted for on a yearly basis as a given percentage of investment cost of the downstream components.

4.3 Maintenance

Usually, the yearly maintenance costs may be estimated to the percentage of the installation cost, for wells, pumps, well heads and the collection pipes or as a percentage of the total installation cost. Scheduled maintenance may be required yearly, eventually resulting in production stops and impacting the revenue stream to some extent.

4.4 Overhead, licences, taxes and insurances

Administration costs or the costs associated to running and operating an office should be included here together with various insurances, taxes and licenses required to operate.

4.5 Well replacement

Depending on the project and geothermal field characteristics, well flow rate may decrease over time and well replacement may be accounted for.

5. REVENUES

The revenues will highly depend on the type of application and product(s) resulting from the direct use of the geothermal resource. The geothermal resource may provide:

- Energy or heat at a given level of enthalpy.
- Water or geothermal fluid at a given rate.
- Chemicals, gases and minerals at given concentration.

The part played by the geothermal resources in the revenues varies greatly depending on the nature of the direct use application. In some cases, energy or water is directly sold to the end-users whereas in other cases, the geothermal resources contribute to part of the process for production of a completely different end-product. Cascaded use may also be an option under consideration, complicating somehow the picture to determine the costs.

The end products, or the product sold by the project developer after using the geothermal resources in its process, may be (list non exhaustive):

- Energy for space heating, snow melting or industrial applications.
- Hot water or geothermal fluid for swimming-pools, aquaculture, agriculture, industrial applications and also for space heating depending on the metering and tariff methods.
- Agricultural products: vegetables, fruits, potted plants and dried food or goods.
- Products from fish farming.
- Salt, minerals.
- End products from various industries in which geothermal resources may play a given part.

Revenues of the geothermal direct use application owner will directly be linked to the end product delivered by the application.

6. GEOTHERMAL RESOURCES: ECONOMICALLY COMPETITIVE?

In a general manner, geothermal direct use applications are associated with consequent investment costs. On the other hand, operation and maintenance costs are usually significantly much lower than in conventional projects. The geothermal fluid mainly needs to be pumped from the field whereas in projects using fossil fuels, the energy cost is much higher.

A break-even analysis may be conducted for each specific application to determine how high the investment cost of the geothermal system may be before the project stops becoming economically competitive.

Although geothermal resources may be considered economically competitive for the direct use application being considered during the development of a geothermal field, the chances of success of such projects are highly dependent on how the project developer manages to guarantee its revenues to make-up for the high investment costs. A plant or a user using today or planning on using the geothermal resource may cease its activities before the infrastructure developed around the geothermal resource has been paid-off. Conventional source can eventually be removed and sold to be used somewhere else whereas the components of a geothermal system are more difficult to move and use in other contexts.

It is probably one of the most common obstacles to the development of geothermal projects and project developers may ask themselves: Why go through the long and risky process of developing a geothermal resource for direct use, with high upfront costs and long payback period when one can use a standard technology with a standard source of energy that may prove more expensive in the mid to long term but is considered less risky?

The answer lies among others in careful planning, expert advice and local and national schemes that aim at mitigating the risks and encourage the sustainable development of this alternative source of energy.

7. CONCLUSION

Geothermal resources are an attractive option for various direct uses, i.a. space heating, industrial uses, agriculture, fish farming, etc. Geothermal energy is, when managed in a sustainable manner, a very interesting alternative source of energy. Such resources may be developed with the help of geothermal experts in a successful manner as has been proved in various cases around the world.

Project developers may overcome challenges associated with the high investment costs by, among other things, placing emphasis on the early development phases aimed at confirming the geothermal field characteristics and capacity. Following extensive exploration activities, a bankable feasibility report is considered to provide indication on the economic feasibility of a project with sufficient level of certainty. This approach is very similar to the front-end loading approach well known in various industrial sectors and contributes to mitigation of the high upfront risks.

After that, uncertainty related to the high investment costs and the guarantee to have a client for the products delivered by the geothermal system is probably one of the major drawbacks when it comes to have financiers deciding upon the financing of a project. The challenges in this regards may require a lot of effort to solve.

Finally, there is undeniably a lot of promotion work to be done with the consumers, financiers and project developers to contribute to using geothermal resources in direct applications on a larger scale.

REFERENCES

Gehringer, M., and Loksha, V., 2012: *Geothermal handbook: Planning and financing power generation*. The International Bank for Reconstruction and Development / The World Bank Group, Washington DC, United States, Energy Sector Management Assistance Program technical report 002/12, 164 pp. Web: http://www.esmap.org/Geothermal_Handbook

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

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FINANCIAL MODELING OF GEOTHERMAL POWER PROJECTS

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ABSTRACT

A financial model is an essential tool that helps to define key financial parameters of a project on the basis of which investors and financiers commit resources to a project, and governments, utilities or off-takers sign onto the project. The investors require knowing what funds they need to raise to make the project a reality and what the return is for their efforts. Financiers on their part wish to ascertain that the project will fully service the loan taken and make payment promptly when they fall is due. The approving authorities pursue value for money and therefore seek the most cost effective tariff.

Some of the information sought by the various stakeholders especially tariffs and return on investment cannot easily be determined. These parameters are derived best using financial models. The outputs of financial models typically take the format of pro forma financial statements which are prepared according to various accounting standards.

The data input into the model largely mirrors the key strategic decisions required for the project implementation. These strategic decisions relate to the resources to be committed to the project, their sources and the costs associated with them. For a geothermal project, it also reflects the assumptions made on the resource characteristics and project development costs. Putting together data that is representative for a geothermal project is the main challenge in carrying out a financial modelling exercise.

Optimizing models through computer based programing shows that the models can further help refine the implementation strategy and assist in evaluating impacts when changes occur in the assumptions made. For this reason, models are also useful tools for monitoring the project through the various development stages.

1. INTRODUCTION

A financial model is anything that is used to calculate, forecast or estimate financial numbers. Models can therefore range from simple formulae to complex computer programs that may take hours to run (Financewalk, 2014). From the inception of a project, investors who act as the project sponsors and providers of equity, want to know how much money they will need to raise to make a project a reality and what will be their benefits if they undertook the project. On the other hand, lenders who support the projects by providing debt wish to affirm that the project will generate sufficient money to fully service the loans taken for their development in addition to promptly making payments when they fall due. Governments, utilities and off-takers only accept projects whose tariff is cost effective compared to alternative similar projects. Figure 1 shows the screening curves used to prioritize power projects using alternative sources under the least cost power studies in Kenya. From this figure, Kenya should only implement imports as the least cost source of power. Excluding imports for strategic reasons, only projects falling on the thick line in the figure are acceptable subject to the plant utilization.

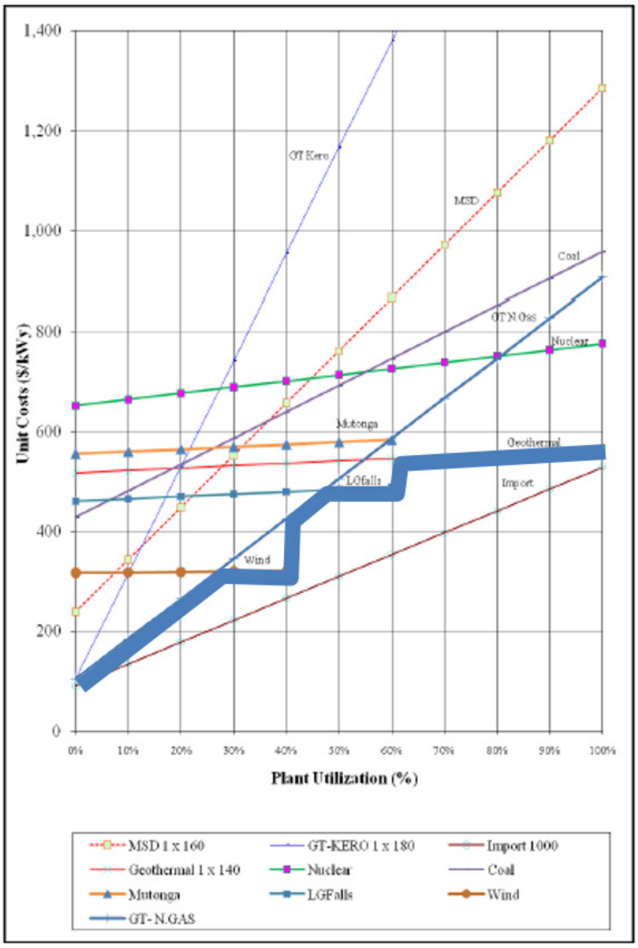

FIGURE 1: Screening curve (KenyanMinistry of Energy, 2011)

A mostly representative set of financial performance data for a geothermal project cannot be easily derived. This arises from the fact that almost all geothermal resources are different and one cannot relate geothermal projects to one another to make accurate decisions. In addition, different project sponsors have different opportunities. Some have rigs and personnel within their organizations while others will hire. Further, the information sought by the various stakeholders is intricately related to the various costs and cost drivers. The cost drivers also behave differently under different conditions. Some of the cost and cost drivers include geothermal resource temperature and pressure, permeability and well output, enthalpy, level of non-condensable gases, adopted technology, required infrastructure, cost of financing as well as the underlying terms, cost of equipment, government policies and also macro-economic factors. At the inception of a project, it is therefore confounding to accurately determine the value of the bulk tariff, return on investment and pattern of cash flows and how they are affected by the various cost drivers without employing a financial model.

Three types of financial models are prepared in the life of a geothermal power project. The project inception model is prepared to demonstrate that the project financial prospects are attractive. It is normally a high level generic model prepared by the project team mainly based on assumptions made from general experience. The feasibility study financial model is more definitive. It is prepared by a third party. It is constructed mainly from extrapolated real data especially data relating to the resource. It is prepared after exploration and appraisal drilling. These two models are prepared for decision making points and are targeted at top management and financiers. A third and detailed model is prepared for the project development and execution team. It reflects much more details on the assumptions made, projected cost and budgets, strategy adopted and technology chosen. The model is a working document that is updated often as real data is obtained and decisions are arrived at. Its life continues from the strongly assumption based project inception financial model to the plant commissioning where real historical data is reflected. Optimizing models through computer based programing shows that the models can further help in refining implementation strategy and help to evaluate impacts of changes in the assumptions made. For this reason they are useful tools for monitoring the project through the various development stages.

A valuable financial geothermal model is one which integrates accurately all the costs throughout all phases of development and presents the resulting information in a manner to help various users make the appropriate decision. It should resolve the need for a competitive priced tariff, while indicating adequate cash flow to meet the project's, lenders' and investors' financial requirements.

2. FORMAT OF FINANCIAL MODEL

The output of the financial models typically takes the format of proforma financial statements. The statements, prepared annually in most cases, present the result and financial position of a company by a certain date. Four statements, namely income statement, statement of financial position (balance sheet), cash flow statement and statement of owners' equity are commonly prepared. However, for the purpose of analysis, the statement of the owner's equity is normally disregarded. The statements are adopted from the accounting profession and have been developed over a long period of time. In general, financial statements are designed to meet the information needs of investors. The investors have to make a decision whether a certain investment is viable and therefore worthy of committing personal financial resources to the investment. To afford comparability between entities, the statements are prepared in accordance with various standards including the General Agreed Accounting Principles (GAAP), International Financial Reporting Standard (IFRS) and other standards adopted by various countries (Investopedia, 2014).

2.1 Income statement

2.1.1 Template

The objective of the income statement is to establish the profitability of a business venture. It is founded on the matching principle. The principle requires that a company relates expenses incurred within a specific period to the revenue accruing over the same period in order to report the company's profitability during the specified period. Figure 2 presents the most typical template of an income statement. The main elements of a financial statement are revenue, expenses, depreciation, interest and tax. The gross profit, operating profit alternatively called earnings before interest and tax (EBIT) and net profit or Profit after tax (PAT) are some of the information obtained from the income statement.

PKN COMPANY
INCOME STATEMENT FOR THE PERIOD ENDING XX

		20X2	20X1
	REVENUE	82.29	82.29
	EXPENSES		
	O&M	5.35	5.35
	STEAM FIELD MANAGEMENT	0.68	0.68
	TOTAL EXPENDITURE	6.04	6.04
EBDIT	OPERATIONAL PROFITS	6.26	76.26
	DEPRECIATION	13.24	13.24
EBIT	EARNING BEFORE INTEREST & TAX	63.02	63.02
	INTEREST	1.96	2.27
EBT	EARNINGS BEFORE TAX	61.06	60.75
	TAX	18.32	18.23
PAT	PROFIT AFTER TAX	42.74	42.53

FIGURE 2: Sample income statement

2.1.2 Revenue

Revenue is the sales arising from the activities of a business venture. For a power project, it is a product of the net exported power and the agreed tariff.

2.1.3 Operating expenses

The operating expenses encompass all cost directly and indirectly associated with the generation of the sold energy. These include staff cost, spares, oils, cooling water where applicable, security and other administrative costs.

The cost also includes reservoir maintenance costs such as undertaking a steam status report, scaling management measures, well interference testing using tracers and pressure monitoring as well as maintenance of road and steam gathering systems. Often, costs of drilling and connection of make up wells are included as an expenses rather than capital. This is not standard as these costs may be appropriately described as capital costs. However, including them as expenses reduces the tax payment and improves cash flow.

2.1.4 Depreciation expense

Depreciation expense is that portion of the capital assets allocated to a specific period and used in the generation of revenue based on the matching accounting principle. There are various methods of determining depreciation. The two most common include a straight line depreciation and fixed percentage deduction. Computation of the capital cost includes interest during the construction period.

2.1.5 Interest

Interest expense is the cost of debt allocated to the period in consideration. The interest computation are determined by the amount of the principle loan, grace period provide and the loan tenure.

2.1.6 Tax

Tax is a compulsory contribution to state revenue, levied by the government on business profits or added to the cost of some goods, services, and transactions. For the purpose of the income statement, the business profit tax applies. The tax is computed on fixed tax rate. However, where tax based incentives are provided, the incentives may be deducted from the computed tax.

2.1.7 Computation

The net profit is computed as shown in the formula below:

$$Net\ profit = Revenue - total\ expenses - depreciation - interest - taxes \tag{1}$$

2.2 Cash flow statement

2.2.1 Template

The cash flow statement mainly accounts for the "physical" cash available to the organization whether at hand or in the bank. The amount of cash within an organization defines how much it can meet its financial obligation. An organization could register book profits but may become bankrupt if it runs out of funds to carry on day to day business. On the other hand, cash exceeding the organization's day to day needs represent a lost opportunity to invest the same and have a better return. The GAAP is founded on an accrual principle. The accrual principle recognizes income or expenditure upon a sale or purchase transaction regardless of whether the transaction was on a credit basis. Therefore a cash flow statement tracks transactions involving cash and provides a cash balance in the possession of an entity at a given time. Figure 3 shows the typical structure of a cash flow statement. The statement is divided into three major segments, the cash flow from operations, from investment activities and from financing activities.

ABC COMPANY
CASH FLOW STATEMENT FOR THE PERIOD ENDING XX

	20X2	20X1
A: Cash flow from operating activities		
Net profit	113	76
Adjustment for		
Depreciation	68	63
Other adjustments	-	-
Operating profit before working capital changes	181	139
Adjustment for		
Trade and other receivables	8	(45)
Inventories	(17)	(27)
Trade payables	42	(32)
Net cash flow from operating activities	395	174
B: Cash flow from investing activities		
Investment in assets		
Purchase of fixed assets	(146)	(168)
Sale of fixed assets	-	-
Net cash flow from investing activities	(146)	(168)
C: Cash flow from financing activities		
Proceeds		
Long term borrowing	192	139
Overdraft	-	-
Short term borrowing	-	154
Payments		
Long term borrowing	(88)	(100)
Short term borrowing	(128)	-
Dividend paid	(38)	(39)
Other	(101)	(94)
Net cash flow from investing activities	(163)	60
Cash flow summary		
Cash and cash equivalent at beginning of year	72	6
Net cash flow from operating activities	395	174
Net cash flow from investing activities	(146)	(168)
Net cash flow from investing activities	(163)	60
Net cash	86	66
Cash and cash in hand at end of year	158	72

FIGURE 3: Sample cash flow statement

2.2.2 Cash flow from operating activities

Net profit, depreciation, other non-cash deductions, and changes in working capital are elements that are included in the cash flow from operational activities. The first item in the cash flow from operating activities is the net profit obtained from the income statement. The net profit is based on the matching and accrual principles. This means that some non-cash items are included in the determination of the net profit. These include depreciation as well as production tax credit where such incentives are granted. They are added to determine the cash arising from operations.

Working capital is that portion of the financing that is locked in the business and is used to support the business by paying bills that become due such as salaries, spares and consumables, stationary and other administrative and office expense. Some of the spares and consumables may be provided at credit and energy sales may also be on credit. Creditors and financiers evaluate the working capital of an organization as it serves to tell whether the company will pay its debts. The working capital therefore stands for several very important concepts; it serves as a measure of the ability of the firm to meet its most immediate financial obligations, it reflects the company's policy on credit and debt servicing, it reflects capital inherently retained by the business that will require financing and it also serves as a measure of financial efficiency by management during the operations and maintenance phase (Pandey, I.M., 2005).

Not all the net profit declared is therefore cash. Sales or revenue may have been sold on credit and some of the materials may have been bought on debt while some of the cash generated may have been investment in spares and consumables held in the stores. Thus an analysis is undertaken to correct that portion declared as net profit that is not physical cash (credit) or costs financed through debt or cash spent to stock items.

An estimation of working capital needs is complex requiring a wide range of considerations. Assuming a percentage of either total project cost or annual revenue is common practice.

2.2.3 Cash flow from investing activities

Initial capital expenditure, plant overhaul and make-up wells' cost and salvage value entail cash flow from investing activities (Pandey, I.M., 2005). Capital expenditure consumes cash and are the key aspects under this category. Proper accounting takes overhaul and makeup wells as capital expenditure. However, some analysts factor in these cost expenses and include them in the income statement. Tax reduction is the main motivation for such modelling. Salvage value is the residual cost after the plant is decommissioned. The sale of the decommissioned plant generates revenue to its owners. The difference in the cash inflows and outflows make the net cash flow from investing activities.

2.2.4 Cash flow from financing activities

The owners' financial contribution (equity), all kinds of debts that may include overdraft, long term loans, grants and other forms of cash incentives such as carbon credit contribute cash to the project while dividend payments takes away cash from the project. The difference of the cash inflows and outflows make the net cash flow from financing activities.

2.2.4 Computation

The net cash at end of a period is generally computed as shown in the formula below:

$$Net\ cash\ = PAT + Dep. - \Delta\ NWC + E + D -\ CAPEX - Rep. - Div + B/F \qquad (2)$$

where PAT = Profit after tax;
$Dep.$ = Depreciation;
$\Delta\ NWC$ = Change in net working capital;
E = Equity;
D = Debt;
Rep = Debt repayments;
$Div.$ = Dividend paid; and
B/F = Cash balance brought forward from previous period.

2.2.5 Free cash flow

Free cash flow may be viewed as the surplus funds that is available for distribution to equity and debt providers (Wikipedia, 2014). It is the most useful concept in calculating the project's and investor's internal rate of return. It is given by the following equitation:

$$FCF \ = EBIT\ (1-T) + Dep. - \Delta\ NWC - CAPEX \tag{3}$$

where T = tax rate.

2.3 Statement of financial position (balance sheet)

2.3.1 Template

The statement of financial position reveals the sources of financing for the project and their total value and matches the same with the value of the various classes of assets held by the organization. Figure 4 shows a typical balance sheet template. The elements are categorized into two major groupings, the assets and the equity and liability.

XYZ COMPANY
STATEMENT OF FINANCIAL POSITION FOR THE PERIOD ENDING XX

	20X2	20X1
Current Assets		
Cash	126	114
Short term investment	42	20
Trade receivables	60	50
Inventory	38	28
	266	212
Fixed Assets		
Long term investments	28	44
Machinery	200	140
Buildings	240	80
Land	14	14
	482	278
Total Assets	748	490
Current Liabilities		
Creditors	40	30
Bills payable	20	10
Short term loans	60	30
	120	70
Long term Liability		
Long term loans	250	130
Equity		
Paid share capital	220	160
Premiums	24	0
Reserves and Surplus	134	130
	378	290
Total Equity and Liability	748	490

FIGURE 4: Sample of a statement of financial status

2.3.2 Assets

Assets are properties both tangible and intangible that an entity acquires using funds provided by the owners and creditors. The assets are further classified as current assets which are those assets that can be turned to money within one year and fixed assets which are assets procured for the purpose of carrying out the business.

The current assets include cash at hand and in the bank, accounts receivables or debt owed to the entity, inventory which includes consumables and spares used in the carrying on of the business, and any short term investments.

Fixed assets include land, buildings, equipment and machinery, vehicles and all other items used in the carrying out of business. Intellectual properties as well as copyrights fall within this category.

2.3.3 Equity and liability

Equity and credits/debts represent capital provided to the entity to conduct it business. Equity comprise owners' capital and where the firm is a limited public or limited company, equity may be in the form of paid up shares, premiums, surplus and reserves.

Liability may be further classified as current liability which is debt that will fall due within a year or long term liability. Liability may be in the form of supplier credit, overdraft/short term loans or long term loans.

The total value of assets is always equal to the total value of equity and liability. The main computation is given by the equation:

$$ASSETS = LIABILITY + EQUITY \quad (4)$$

3. INPUT DATA

Putting together representative data for inputting into the model is the main challenge in carrying out a financial modelling exercise. The data largely mirrors the key strategic decisions required for the project to be implemented. These strategic decisions relate to the resources to be committed to the project, their sources and the costs associated with them for the entire project's economic life. The costs to the project can be grouped into two major categories, capital and expenses. Capital cost in general are costs that accumulate during the project formulation and construction while expenses are direct and indirect costs incurred and accruing annually charged against revenue generated each year after the plant is commissioned. The expenses are directly dispensed off annually through the income statement. However, the capital expenditure is dispensed by depreciating them over time (Pandey, I.M., 2005).

The factors that drive costs of geothermal development comprise of infrastructure, plants and equipment, raw materials and consumables, nature of the resources, opportunities and other factors of production. The cost drivers can generally be categorized into eleven groups namely investment policy, project site specific costs, level of investment, plant design, construction and installation, operation and maintenance, financing and risk, taxes, investment incentives, macro-economic factors and assumptions made about the resource.

4. INFORMATION OUTPUT

Various groups of people take interest in a geothermal project. Governments, municipalities and utilities see an opportunity for serving their constituencies, investors realize business opportunities in order to make money, financiers seize the opportunity to issue loans, project management teams see employment and consumers seek cost effective services. All these groups seek different information from a project. Therefore a financial model is generally designed to provide information to serve the various groups. Collectively, the stakeholder wishes to know the tariff, capital requirement, internal rate of return, profitability, debt levels, liquidity levels, operating performance, cash flows, and projected financial performance.

4.1 Required capital and cash flow

The project cost is of interest to the investors, financiers and the project management team. The value is used to assess investors ability to provide equity, is a reference for setting debt ratio and for establishing testing of the viability of a business venture. Where the cost is spread over a number of periods, it is used to plan financier disbursement schedules.

4.2 Bulk tariff (Levelized Cost of Energy)

The cost of generating geothermal electricity is normally expressed on a kWh basis otherwise referred to as the levelized unit cost of electricity. Levelized Cost of Energy (LCOE) is the constant unit cost (per kWh or MWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life (Black and Veatch). It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel and cost of capital. It is a very useful industrial tool for comparing technologies with different operating characteristics. It is on this cost basis that the geothermal projects are evaluated for investment, approval and financing by prospective investors, governments, consumers or regulators and bankers or credit providers.

The LCOE is determined through an iterative process during modelling.

4.3 Financial performance

The project's financial performance is a key concern to all stakeholders. Capital budgeting tools are used to evaluate financial performance of a project vis-à-vis alternative projects. The capital budgeting tools include break even analysis, payback period, net present value analysis and the internal rate of return.

Further to the capital budget tools, ratios are used to interrogate the model. The most commonly used ratios are profitability, debt service, leverage, and liquidity ratios.

5. COMPUTER MODELING

A spreadsheet software such as Microsoft Excel or similar software is most frequently used as the platform for financial modelling. A proper understanding of geothermal cost factors, skill in MS-Excel and basic financial and accounting knowledge will enable the development of a geothermal financial model with an adequate level of accuracy. Incorporating an iterative computer program helps greatly in understanding the behaviour of the key parameters and their effect on the tariff, total capital requirement and internal rate of return.

6. MODEL OPTIMIZATION

The primary target of a financial modelling exercise is to determine the lowest tariff, lowest capital requirement and the highest profit possible with stable cash flows. Ngugi (2012) has shown that the various geothermal project cost factors impact the tariff and capital cost in different ways. Some have a direct relation while others an inverse relation. Table 1summarizes the effect of the various cost drivers on the tariff and total capital expenditure. For this reason, Ngugi has postulated that for a set of financial model input data there is an optimal point where certain values for each of the drivers give the lowest tariff.

7. MODEL ACCURACY

There is an inherent risk associated with data obtained from a financial model. This is because the various cost factors are intricately interlinked and the fact that certain key factors are assumed. It is recommended that a sensitivity analysis be performed to evaluate the impact of changes in any of the assumed factors.

TABLE 1: Relationship between cost drivers, tariff and capital expenditure

Cost drivers	Relationship tariff	Relationship to capital expenditure
	Relationship	Relationship
Well output (1.5-21 MW)	inverse	inverse
Debt interest (0-12%)	direct	direct
Payback period (5-12 years)	inverse	None
Drilling cost (US$ 3.5 -9.5 million at 1.5 MW)	direct	direct
Project size/fix costs (20-400 MW)	inverse	inverse
Leverage (40-80%)	inverse	direct
Return on equity (12% - 22%)	direct	none
Plant capital cost (US$ 1.5 -3 million)	direct	direct
Loan term (7 -25 years)	inverse	none
Early generation (wellhead, 0-60% of designated plant size)	inverse	inverse
Operation & Maintenance cost (US$ 0.005 – 0.009)	direct	none
Steam decline (0-3%)	direct	none

8. CONCLUSIONS

A financial model is an essential tool that helps stakeholders evaluate the attractiveness of a project. The model provides them with information that they need to make decisions. The stakeholders wish to know the tariff, capital requirement, internal rate of return, profitability, debt levels, liquidity levels, operating performance, cash flows and projected financial performance. The information sought by the various stakeholders is intricately interlinked with the various costs and cost drivers. It is therefore difficult without a model to adequately derive that information.

The models typically take the format of proforma financial statements. Three statements, namely income statement, statement of financial position (balance sheet), and cash flow are commonly prepared when modelling. The primary target of a financial modelling exercise is to determine the lowest tariff, lowest capital requirement and the highest profit possible with stable cash flows. A valuable financial geothermal model is one which integrates all the costs through all the phases of development and presents the resulting information in a manner to help various users make appropriate decisions. For every set of data used in modelling, an optimal point can be obtained where certain values for each of the cost/cost drivers give the lowest tariff.

There is an inherent risk associated with data obtained from a financial model and it is recommended that a sensitivity analysis be performed on the effects of possible changes to the input data.

REFERENCES

Financewalk, 2014: *What is financial modelling?* Website: http://www.financewalk.com/2013/financial-modeling-2/

Investopedia, 2014: *Definition of 'Accounting Standard'.* Website: http://www.investopedia.com/terms/a/accounting-standard.asp

Kenyan Ministry of Energy, 2011: *Updated least cost power development plan, study period 2011-2031.* Ministry of Energy, Republic of Kenya, 203 pp.

Black and Veatch: *Levelized cost of energy calculation – Methodology and sensitivity*. Web: http://csep.efchina.org/report/20112844913435.70772110666485.pdf/Levelized%20Cost%20of%20Energy%20Calculation_BV_EN.pdf

Ngugi, P., 2012: What geothermal costs? - The Kenya experience. *Paper presented at "Short Course on Geothermal Development and Geothermal Wells", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador*, 13 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-14-13.pdf

Pandey, I.M., 2005: *Financial management* (9th edition). Vikas Publishing House PVT Ltd, New Delhi, India, 784 pp.

Wikipedia, 2014: *Free cash flow*. Website: http://en.wikipedia.org/wiki/Free_cash_flow

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

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RISKS AND RISK MITIGATION IN GEOTHERMAL DEVELOPMENT

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ABSTRACT

Geothermal projects are designed to be within time, budget, planned specification and legal and regulatory provisions while meeting the project objectives. The geothermal development is exposed to various risks of varying degrees throughout all its phases and stages of development. The resource risk distinguishes geothermal projects from others projects. This persists through all phases and stages of development. It takes several forms including resource existence and size, suitability, sustainability and utilization challenges. Other risks include way leaves, market, financing, commercial and macro-economic risks.

Comprehensive and detailed surface studies, numerical simulation and interference tests during resource utilization are cheaper ways that inform the possibilities of occurrence of various forms of resource risk and provide information for formulation of resource risk mitigation strategies. Coupled with reservoir monitoring and incremental development, resource risk can be managed effectively. Undertaking a baseline environmental and social studies can avoid project disruption and law suits against the project. Deliberate engagement of the host community can bring about the positive understanding of the project and buy in.

Conservative assumptions and use of time and financial contingencies are essential in deriving a tariff that safeguards investors' interest, use of generation tax credit, concessional financing such as green funds and carbon credit help improve project financial competitiveness, power purchase agreement shield the investor from the market risk inflation and foreign exchange risks.

1. INTRODUCTION

The objective of undertaking a geothermal power project is to generate power for consumers on a value for money basis, generate return for the investor over the hurdle rate and service debts from lenders and suppliers when they become due, while still making sufficient funds to meet operational and maintenance cost. For these goals to be met, a demand for the power must exist, a resource characteristics are suitable and can sustainably be exploited for the economic life of the project within the legal and environmental framework has to be identified, a matching proven technology to develop and exploit the resource must exist at a competitive price, investors, lenders, off-takers and technologists must be available for the project to take effect. The probability that the project will be implemented according to plan and meet the desired goals without a hitch or glitch is highly unlikely. Therefore forestalling risks, estimating impacts and defining responses to emerging issues is an essential aspect of project management. Risk may be defined as the chance that an investment's actual return will be different than expected.

Risk involves a state of uncertainty where some of the possible outcomes are undesirable (Hadi et al., 2010). Figure 1 (red) shows the resource uncertainty versus investment cost (blue) for the various geothermal development phases and stages. The figure show that the uncertainty decreases overtime and as the project progress. However, the uncertainty is not totally eliminated. On the other hand the investment cost progressively increases as the project progresses.

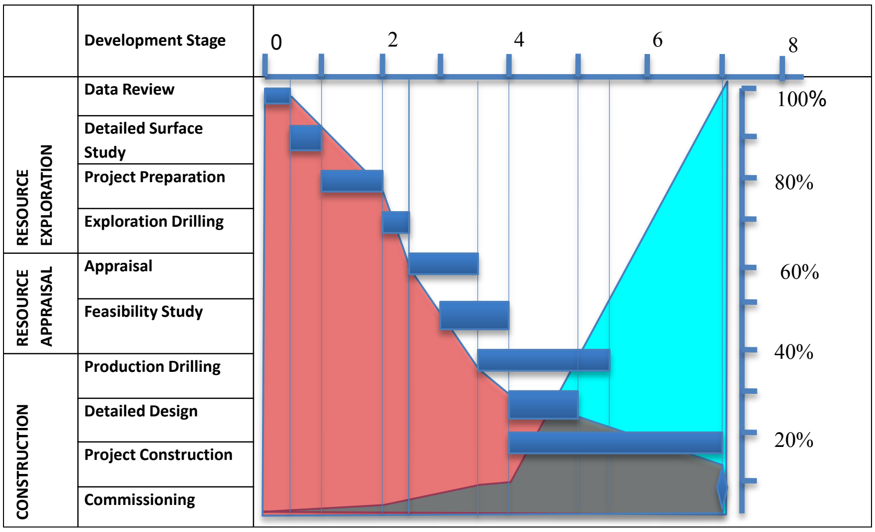

FIGURE 1: Development resource uncertainty and investment cost against project progress

2. LAND ACCESS AND WAY LEAVES

Like all other physical projects, land is a required for the geothermal project to establish the wells, road infrastructure, the power plant and the power evacuation system. As human populations increase, land which is a constant production factor continues to become scarce and precious. Geothermal development therefore is in competition with other land uses. Land access and way leaves is one of the most sensitive aspects of the geothermal project especially because it causes the project to results in resettling people out of the project area.

Land negotiation can be protracted stalling or delaying the project. Implementing an attractive resettlement package, providing adequate time to procure land and deliberate strategic stakeholder communication programs are vital for the success of the project. Ultimately, government support may be necessary when a need arises for compulsory acquisition of land (Government of Kenya, 1982).

3. RESOURCE RISKS

The one risk that distinguishes a geothermal project from all other power projects is the resource risk. All other risks are generally well understood, can be quantified and therefore addressed. Every geothermal field is unique. In addition, sections of a geothermal field may exhibit different characteristics and or different development challenges. In Kenya for instance, the three geothermal fields so far drilled do not bear similar reservoir characteristics. In particular, the greater Olkaria geothermal field, has different section of the fields have exhibited different characteristics and within the same sections it has been observed that some wells have different chemistry, well output, temperature, pressure, enthalpy and drilling challenges. The resource risk is not only confined to the resource exploration and appraisal development stage but in general persists throughout the entire economic life of the project although of varying degrees. The resource risk falls into several categories some of which are existence, resource size, suitability, and utilization challenges.

3.1 Existence

It is not sufficient that a geothermal prospect possesses magnificent surface manifestations such as geysers, fumaroles, hot springs, steaming and altered grounds or mud pools. To prove commercial viability of a resource, drilling of deep wells is required. Infrastructure such as roads, water system and other supporting facilities are required for drilling of exploration wells. Further, funds are required for drilling of wells, mobilization and demobilization of drilling equipment. The mobilization and demobilization costs may be sizable. This is the first stage of the project that requires significant funds. At this stage, uncertainty of the outcome is highest. To increase the probability of successfully drilling a discharging well, various studies are undertaken. The studies are aimed at estimating or predicting the existence of a heat source, reservoir temperature, existence of reservoir fluids and recharge mechanism and geological structures to support evolution of a geothermal reservoir and depth of the reservoir.

The studies that are undertaken include geological and hydrogeological studies, gravity measurement, resistivity measurement, sampling of fumaroles gas seepages, chemistry of borehole fluids and temperature measurement. The encountering magmatic gases indicate possible existence of a heat source, geothermometry analysis undertaken with the chemistry of the sampled fluids provides insight to the possible reservoir temperature, micro-seismic activities may indicate where the fluid movement exists (target for drilling) and the possible reservoir depth and resistivity anomalies may indicate the possible areal size of the resource. High seepage of reservoir gases may indicate possible high permeability a precursor for large output wells and chemistry of the sampled fluids indicate the upflow within the system or possible development problems such as scaling. Temperature gradient measurements are used to estimate top of the reservoir. Geophysical measurements also help indicate the top of the reservoir thus aid in designing well casing programs.

It is the strength of convincing detailed surface studies tha exploration wells are sited. In the event that none of the three wells typically drilled at this stage are productive, then further development is halted until a review of the data is undertaken. On the other hand, if one well discharges fluid, the resource is said to be proven. It is common practice to assume a low success rate for the exploration wells to reflect the level of risk in a financial model.

To motivate privates sector and governments to invest in this stage of development, the African Union Commission with the support of donor community have devised a grant termed Geothermal Risk Mitigation Fund (GRMF) available only to a few countries in Eastern Africa. The grant is designed to meet part of the infrastructure cost as well as the cost for the drilling of exploration well. An additional component may be available to the investors if the project progresses to appraisal drilling.

3.2 Suitability

It is not uncommon for wells that have discharged fluid to be plugged because the fluids they produced are corrosive, or remain idle due to temperature inversion or cyclic discharge as well scaling. There are generally three technologies employed in the exploitation of the geothermal resource for electric power generation namely steam turbine/ flush technology, binary technology and a hybrid model.

Temperature, pressure, enthalpy and permeability are the major criteria for suitability of a resource. The higher the temperature/pressure, the better is the resource. Low yielding wells with low temperature increases capital investment because a larger number of wells would be required for a particular plant size. Permeability influences the well capacity which is a product of fluid mass and enthalpy. High mass flow and enthalpy results in wells with high potential power potential. Large amounts of non-condensable gases, corrosive nature of fluids and potential to develop scaling reduces the value of the resource.

The cost of drilling accounts for the greater resource development cost and is further influenced by the depth of the resource. Deep seated resource or high drilling costs can inhibit the development of a resource.

Investing in studies which lead to siting of high yielding wells with high temperature/ pressure and avoiding drilling in areas with potential for scaling improves financial performance for the project. Conservative assumptions on well productivity are essential when projecting capital cost and tariff.

3.3 Size

After drilling a successful discovery well, there remains a great uncertainty as to what resource area exists with exploitable fluid characteristics (Sanyal and Koenig, 1995). Resistivity measurements used to make initial resource size estimates are known to deviate from reality (Hadi et al., April 2010). Figure 2 shows a typical resistivity profile used for siting wells. Further appraisal wells are drilled in order to delineate the areal area of the resource and to confirm suitability of the resource. Conceptual models updated using data from exploration wells can greatly improve the success of siting subsequent wells. However, the risk of drilling unsuccessful well remains significantly high. Provision for failed wells in the financial models is necessary to accommodate this risk.

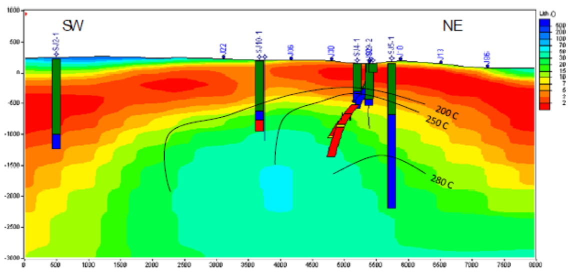

FIGURE 2: Resistivity profile used for siting wells (Hadi et al., 2010)

3.4 Sustainability

The economic life for geothermal power projects is typically 20 to 30 years. For the entire period, steam/ brine has to be guaranteed. Ordinarily, the steam pressure and or well yields decline slightly before stabilizing. Potentially all fields can degenerate significantly by way of decline in pressure/ well yield, adverse fluid chemistry change (Sanyal and Koenig, 1995), or incursion by cooler fluids. Together, these factors either require additional capital investment to make-up for steam/ brine decline or increase operational costs.

Selection of turbine inlet pressure versus wellhead pressure is essential to provide allowance for decline. Development of well calibrated numerical reservoir model to tract well output, resource quality and reservoir response under various exploitation scenarios will provide great insight to the probability of adverse reservoir occurrences. Undertaking incremental development will limit capital exposure to loss arising from these types of risk while providing adequate time to study and understand the resource response to utilization. Integration of hot and cold reinjection as informed by the numerical simulation can greatly help to avert pressure decline and check well yield decline. A reservoir monitoring program that includes well productivity testing, downhole temperature measurement, enthalpy measurement and fluid chemistry analysis is a must during resource utilization.

The financial model used for project evaluation and approval should include make-up wells, and undertake a sensitivity analysis on profitability under various development scenarios.

3.5 Development and utilization challenges

Even after a commercial resource has been discovered through drilling and delineated, some production wells within the delineated area will have dismal performance. Some will have cold inversion, cyclic pressure regime and below average yields. Others may show scaling tendency.

Experience has shown that there is a learning curve required in optimally developing a resource. In Kenya, Olkaria greater geothermal field has been under development for the last 60 years since the drilling of the first two well in 1956 – 1958. Over this period, observations have shown different sections of the greater Olkaria geothermal system to have very attractive characteristics while others with non-commercial characteristics. In the early stages of Olkaria development, the field was drilled to the shallow steam dominated reservoir section. These wells over time have shown noticeable decline in yield. On the other hand, it has become apparent that deeper wells have demonstrated better yields.

Geothermal resources are by nature fractured. Fractured systems are good for well yields but result in increased drilling cost. Major loss of drilling fluid circulation causes problematic drilling due to poor hole cleaning and extended cementing jobs. Sloughing formation can significantly increase drilling cost thereby compromising project profitability or leading to abandonment. Experience in drilling serves to reduce drilling challenges and costs.

Scaling increases the operational cost due to use of chemical inhibitors or mechanical cleaning. Entrained solids within steam can create challenges of deposits on steam turbine members, non-condensable gases can create stress related cracking or premature failure of equipment. Selection of materials for the construction of the plant and its accessories is therefore very important.

4. TECHNICAL RISKS

Financiers are risk averse and they would be cautious when faced with untested technology that may jeopardize recovery of their credit/investment. Technology is used to explore, access by drilling and utilize geothermal resource in power generation. Geothermal conventional steam turbines and binary technology are now fully reliable. Selection of manufacturers who have a successful history and long term business outlook is a prerequisite. Experienced geoscientists and drilling personnel are essential for success of the project. Use of experts is useful for peer review. Warrants and guarantees are instruments used to shield investors.

5. SOCIAL AND ENVIRONMENTAL RISKS

Environment and social economic issues (Naito, 1995) are very sensitive and can lead to a viable project not being approved, being denied financing and disbursement of funds. It is one area that many world governments control and regulate through legislation and have governmental bodies monitoring on a continuous basis. For electricity generation projects in Kenya, an environmental permit must be issued by National Environmental Management Authority (NEMA). Further, most financial institutions will require an environmental audit during project appraisal and implementation with a requirement to meet certain standards. Most financial institutions have employed specialists with environmental and social expertise for this purpose.

It is customary to carry out baseline environmental and social studies alongside detailed surface exploration studies. Upon successful surface exploration, a social environmental impact assessment study would be carried out before commencement of any site development. Prior to project ground breaking and during the life of the project investor representatives will engage host communities on a continuous basis by holding open gatherings to build project awareness, receive concerns, complaints and community based proposals for corporate social responsibility. In addition, weather stations are erected within and outside of the project area to monitor various factors of the project that could affect the environment. In addition, various environmental audits are carried out regularly to establish data and basis for corrections where standards are not met. Incorporating mechanism to comply with environmental regulations benchmarked to international standards is the best way to mitigate this risk.

6. MARKET RISK

Ultimately except where government provides subsidies, the end user pays for all the costs arising from electricity provision and therefore their need for power, willingness and ability to pay are influencing factors for a successful project. Besides demand, access to the market may be curtailed by lack of the necessary infrastructure including transmission and distribution network. It is the demand for affordable electricity that drive developments and in the absence of this demand the project assets will be without any return.

The feasibility study includes undertaking electricity supply and demand analysis and forecast as a basis for justifying further development. In addition, a long term power supply contract (Power Purchase Agreement) on a take or pay basis transfers the market risk from the investors and lenders to the off taker.

7. FINANCING RISK

All other types of risk eventually translate to financial risks. Investors and debt providers therefore have to identify and evaluate risk before they can commit financial resource to the project.

Additionally, project implementers have to be aware of and contend with the risk associated with their choice of debt providers. Kenya has largely relied on bilateral and multilateral financial institutions for financing its power projects. In a number of cases, this financing has disaster. In point from the 1990’s, is where a geothermal project stalled for 10 years essentially because the government then was perceived as not subscribing to various political ideologies acceptable to the financier’s sponsors. Even though the steam was available and tendering documents had been prepared, the Country could not raise funding from its traditional partners leading to the prolonged delay. In another instance, a project solely financed from a bilateral arrangement with only one financier on board stalled. Disbursements of funds to the project were stopped midstream, while all contractors and consultants were on site, simply because there was social agitation fronted by some non-governmental organization. The ensuing uncertainty lasted several years and during that period, the project accrued huge standby costs. Consequently, project became a loss making venture. A classical case was where the project capital cost tripled and the projected implementation time went from about two year to seven years. This arose from the financier demand that a study be made to ascertain steam which was already availability at the wellhead. The financier declined to allow an award for building an additional unit to the contractor who had constructed the previous two units, yet they were on site waiting to demobilize. The financier directed that a fresh competitive bid be undertaken and opportunity of constructing the third unit at a cheaper price lost and the project rendered loss making. In one other case, a financial delayed disbursed until the project had progressed 70% thereby inconveniencing the borrower.

Keen interest that certain financiers place on social resettlement programs can attract unjust enrichment from undeserved compensation. In one project in Kenya, certain people migrated into the project area, when they became aware that an appraisal program had successfully been carried out, and that the lender would require their full compensation for resettlement as a condition for funding.

About 25 years ago, arising from perceived corruption within the government, along with the unexplained murder of the a senior government official, a key lender declined to serve as principal financier for further geothermal development in Kenya and refused to negotiate a new credit until action was taken. As a result the geothermal development suffered delays (Geothermex Inc., 2010).

Typically geothermal projects have long lead times and the capital outlay is largely upstream. Further, the earlier stages of development are mainly financed using equity which is expensive as compared to debt. The high upfront costs combined with long lead times can influence cost of financing in a manner not favorable the project (Gehringer and Loksha, 2012). Further, capital budgeting tools used to compare projects namely IRR and payback period may show that geothermal projects are unfavorable.

Matching your financers' lending criteria vis-à-vis your project and country issues as the foregoing shows is crucial for the success of a project. Pooling lenders rather than using one lender spreads the risk of financiers' failures. It is important to have contingent measures to meet financing gaps in the absence of lenders or delay in disbursement.

Concessional financing through cheap loans from governments, green funds, carbon credits, tax holidays and generation tax credit where available help to improve the competiveness of geothermal projects thus making them attractive to financing.

8. OFF-TAKER DEFAULT RISK

Figure 3 shows the transaction model for the first 100 MW Menengai Project in Kenya used by Geothermal Development Company (GDC). The model shows the various key parties involved in the transaction. Off-take risk encompasses the risk of failure by the off-taker to take power due to reasons concerning dispatch, transmission line congestion, line failure and the risk that the off-taker may be unable to make the agreed payment in a timely fashion (Gehringer and Loksha, 2012).

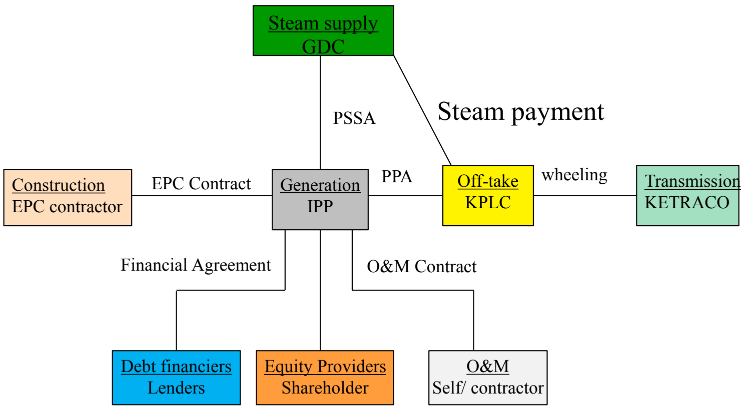

FIGURE 3: Transaction model used by Geothermal Development Company of Kenya

This risk is borne by the off taker in addition to the market risk. The off-taker through the power purchase agreement is obligated to procure a form of guarantee to safeguard against its failures. The guarantee may be in the form of bank guarantee, letter of credit or for government agencies they may procure partial risk guarantees. The power purchase agreements in Kenya are structure on a take or pay basis. Further, the off-taker is tasked to procure a sovereign guarantee or letter of comfort that becomes applicable should the off-takers default result in termination of the power purchase agreement.

9. POWER GENERATOR DEFAULT RISK

The obligation of the power generator falls into two categories, the fuel supply and energy conversion or power generation. Fuel supply entails availing steam or brine by way of prospecting, assessing and drilling while energy conversion entails designing and construction of the power plant, operating and maintaining it over the power purchase agreement period. As it were, the generator bears the resource risk, construction, operations and maintenance risks. In addition, by entering in a power purchase agreement, the generator is liable for liquidated damages in the event they do not meet their obligation as stipulated in the power purchase agreement.

The construction risks can be in the form of delays or time overruns, budget overrun or plant underperformance or malfunctions during commissioning. Time overruns and plant underperformance attract penalties while budget overrun strain the project capital needs and erode profitability. The plant design, construction delays and underperformance risks are passed over by the generator to a qualified engineer-procure- construct (EPC) contractor through a lump-sum, time based and turnkey contract. Time and budget overruns are also mitigated by providing contingencies.

The investors risk paying penalties during periods of plant downtime. Proper operations of power plant ensures revenues for all. However, prolonged breakdown and other downtime can compromise a return on investment and the ability of the plant to service its loan and generate sufficient funds to keep it in good operating conditions. The risk of operation and maintenance is therefore real and lasts for a long time. To mitigate the risk, adequate budgets and stock of spares and consumables are required. Proper preventive and maintenance schedules undertaken in time are essential. Outsourcing overhauls can help reduce risks and attractive personnel benefits can help recruit competent staff and retain them.

The generator will employ various insurance instruments to transfer risks related to their default.

10. FORCE MAJEURE

Force majeure are event that occur without being caused by any action or inaction by any of the contracting parties or there agents which prevent one or all parties from fulfilling their obligations under the contract. These events include war, strikes, crime, hurricane, flooding, earthquake and volcanic eruptions. For such events to be declared an act of forced majeure, the cause must not be as a result of a failure of the party declaring it, nor must it be predictable or preventable.

The effects can be temporary and possible to remedy without serious erosion of projected economic benefits. In this case each party involved takes liability of the losses arising from the force majeure. Certain obligations are waived especially relating to time aspects but the parties continue with the project. Where possible the parties insure such risks. Where the project can be remedied but the economic conditions of the project have been adversely eroded, the aggrieved party may seek buyout. Abandonment is an option where the project cannot be rescued.

11. INSTITUTIONAL RISKS

Both investors and the financiers will be concerned with the capacity of the institutions in the entire electricity generation and distribution value chain including contractors and lenders. Figure 3 shows the value chain for the Menengai first 100 MW project. GDC will avail steam which the independent power producer (IPP) will convert to electricity. The IPP will further contract an EPC contractor to construct the plant for them and seek funding from prospective lenders. The electricity will be sold to

Kenya Power and Lighting Company Limited (KPLC), the off take power, and power will be evacuated using Kenya Electricity Transmission Company Limited (KETRACO) transmission infrastructure. Any of these organizations can cause the failure of the project. The key concern in evaluating the organization's risk includes the experience of the organization to undertake its role, the financial capacity to undertake the projects and to endure financial shock that may arise during the project implementation and the human resource capacity to undertake, manage and operate the projects. Use of joint venture partnerships and consultants can alleviate financial and human capacity deficits.

12. MICRO-ECONOMIC RISKS

In Kenya, generation costs are pegged to the US dollar in order to shield both the power off taker and the generator from currency exchange risks. However, the consumers pay for the electricity in the local currency. The cost of the exchange rate variation is assessed on a monthly basis which is then billed to the consumers directly.

Over time inflation erodes money value such that a fixed amount of money will buy fewer goods in the future. If left unaddressed, inflation can erode the investors return on investment and may lead to poor management and maintenance of the power plants. In Kenya, the cost of inflation is an aspect of the power purchase agreement and is adjusted on an annual basis.

13. CHANGE IN LAW RISK

Imposition of legal requirements such as expansion or increase in taxes and royalties after the power purchase agreement has been signed whose compliance would result into material difference in the investors return can compromise the project financial integrity. Provisions are provided in the power purchase agreement that should such events occur the investor shall qualify for a review of the tariff.

14. LEGAL AND REGULATORY RISKS

All investments will result in various business transaction and contractual relationships. Potentially all these transactions and relationships could give rise to disputes necessitating arbitration and or court adjudication. Therefore investors and financiers would be concerned whether justice can be served and be enforced by evaluating institutions and national policies.

Countries that uphold independent judiciaries, enter into varies treaties and memberships of international bodies provide comfort to investors and lenders. Investors may avoid investing in countries where the risk is very high.

15. POLITICAL RISKS

The 25 year economic life of a geothermal project will see several changes of government. Elections particularly in Africa often times result in civil disobedience and may at times degenerate to civil war. Incoming governments are likely to formulate new policies if only to make political statements or may altogether vary policies seriously impacting existing and future developments. Investors and financiers seriously worry over whether they will be able to repatriate their investment to their country of origin, convertibility of the local currency to other currencies without making serious exchange losses or restriction and whether investment owned by foreigners will not be expropriated by rogue governments. Investors and financiers would require transparent and fair taxation policies. Further these policies should be long term and predictable.

Countries that seek political stability and put in place transparent systems for decision with checks and balances reduce the political risk. Partial risk guarantees and political risk insurance are used to safeguard against this risk.

16. CONCLUSIONS

The overarching goal of a geothermal development is the successful implementation of the project that will generate a good return to its owners as well as meeting its other financial obligations. The geothermal development is exposed to various risks of varying degrees throughout all its phases and stages of development. The resource risk is one of the major risks in a geothermal development. It persists through all phases and stages of development and takes the form of resource existence and size, suitability, sustainability and utilization challenges. Other risks include way leaves, market, financing, commercial and macro-economic risks.

Studies, in particular comprehensive detailed surface studies, numerical simulation and interference tests are very useful for informing the possibilities of occurrence of the various forms of resource risk. This enables formulation of resource risk management strategies. Incremental development and reservoir monitoring are highly recommended to ensure resource sustainability. A deliberate and purposeful baseline environmental and social studies, host community engagement and diligent environmental management program are essential for reducing project interruption. Incorporating green funds, resource risk mitigation grants and carbon credit help the project to be financially competitive against other sources of energy. The feasibility study includes establishing electricity supply and demand. Insurance, partial risk guarantee, sovereign guarantee and letter of comfort are some of the instruments used to mitigate against some of the development risks. Power purchase agreement help shield the investors from the market risk, inflation and foreign exchange risk.

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REFERENCES

Gehringer, M., and Loksha, V., 2012: *Geothermal handbook: Planning and financing power generation*. The International Bank for Reconstruction and Development / The World Bank Group, Washington DC, United States, Energy Sector Management Assistance Program technical report 002/12, 164 pp. Web: http://www.esmap.org/Geothermal_Handbook

Geothermex Inc., 2010: *An Assessment of Geothermal Resource Risks in Indonesia*. Report prepared for the World Bank, 2-18. Web: http://www.ppiaf.org/sites/ppiaf.org/files/publication/REPORT_Risk_Mitigation_Options_Indonesia.pdf

Government of Kenya, 1982: Geothermal Act. *Laws of Kenya*. Website: http://www.kenyalaw.org:8181/exist/kenyalex/actview.xql?actid=CAP.%20314A

Hadi, J., Quinlivan, P., Ussher, G., Alamsyah, O., Pramono, B., and Masri, A., 2010: Resource risk assessment in geothermal greenfield development; An economic implications. *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 5 pp. Web: http://www.geothermal-energy.org/pdf/IGA standard/WGC/2010/0709.pdf

Naito, T., 1995: Project finance for geothermal power projects. *Proceedings World Geothermal Congress 1995, Firenze, Italy*, 2883-2887. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/4-Naito.pdf

Sanyal, S.K., and Koenig, J. B., 1995: Resource risk and its mitigation for the financing of geothermal projects. *Proceedings World Geothermal Congress 1995, Firenze, Italy*, 2911-2915. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/4-Sanyal2.pdf

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

FEASIBILITY STUDY:
COST ESTIMATION FOR GEOTHERMAL DEVELOPMENT

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ABSTRACT

In this paper, capital costs and cost affecting factors of each project stage from exploration, drilling, power plant construction to operation and maintenance are evaluated. Investment costs for typical geothermal development suggest extreme variability in the cost of components when all project costs (exploration and confirmation, drilling an unknown field, power plant and transmission line) are considered. The variability of the specific capital cost is inversely affected by the resource temperature and the mass flow rate. Based on the geothermal resource quality considered for each technology, the estimated cost for single flash ranges from 2,912 to 5,910 USD2010/kW, for double flash from 2,500 to 6,000 USD2010/kW, and for the organic Rankine cycle the cost ranges from 2,302 to 11,469 USD2010/kW. The range of results matches the costs presented in literature where the temperature range is concentrated, for example in the case of the flash systems, when temperature range is reduced to 200-300°C from 160-340°C, and in the binary system when temperature range is reduced to 140-180°C from 100-180°C. Larger size development of geothermal power plants gives more cost effective values than smaller power plant sizes due to economies of scale. The cost of development for small geothermal power projects depends significantly on drilling cost, transmission cost and resource quality. A critical case is small ORC development: the specific capital cost rises quickly, as resource temperature and mass flow rate decrease (as a result of small power output).

1. GEOTHERMAL DEVELOPMENT PROJECT PHASES

The geothermal development processes are fairly similar in geothermal areas around the world with corresponding modifications and innovations (Dolor, 2006). According to Cross and Freeman (2009), the primary stages of a geothermal developmental cycle are exploration, resource confirmation, drilling and reservoir development, plant construction and power production. Based on this approach, this analysis proposes a four stage breakdown as illustrated in Figure 1.

The four phases of the geothermal energy project shown in Figure 1 could be used as a baseline plan for future feasibility models. In this paper, capital costs and cost affecting factors of each project stage from exploration, drilling, power plant construction to operation and maintenance are evaluated.

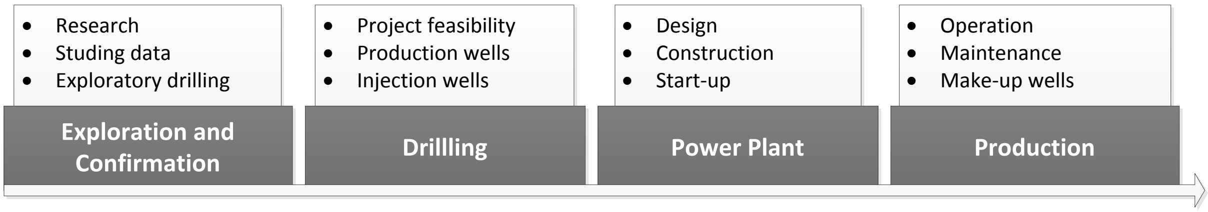

FIGURE 1: Geothermal developmental project phases

2. EXPLORATION AND CONFIRMATION

According to the consulting firm Mannvit (2011), geothermal exploration is *the bridge between early stage ideas for geothermal development and fully committed planning and startup of geothermal production. In the broadest sense, geothermal exploration involves proving the viability of geothermal energy as a practical means of generating power and/or heat in a particular location. The knowledge obtained through exploration is the basis for an assessment of energy producing potential and the subsequent creation of engineering plans and construction cost estimates.*

Resources defined during the exploration phase can be divided into three sub-phases: regional reconnaissance, district exploration, and prospect evaluation. The costs involved in geothermal exploration and development have been widely researched and published. A good deal of this work was summarized by the Geothermal Energy Association on behalf of the US Department of Energy (Hance, 2005). This study points out that the geothermal developers provided exploration cost estimates averaging 173.1 USD/kW. The confirmation phase is defined as drilling additional production wells and testing their flow rates until approximately 25% of the resource capacity needed by the project is achieved. An average cost of 346 USD/kW was suggested when the confirmation phase was considered in tandem with the exploration phase. Using 2010 USD values as an input in the present analysis, the cost in USD/kW was inflated according to the US BLS (2011) inflation calculator.

3. DRILLING

Cost related to drilling is usually the single largest cost and a highly risky component in any geothermal development. Given the circumstances, it is expected that the cost of drilling will be very variable; while this is certainly true to some degree, there are general tendencies. This analysis of drilling costs in Central America is based on the statistical method for estimating drilling investments in unknown geothermal fields presented by Stefansson (2002) who made a statistical study of drilling results in 31 high temperature fields around the world. Using these world average results, and combining them with data from Central America (Bloomfield and Laney, 2005), it is possible to estimate the expected value and its limits of error for drilling investment in this region.

Stefansson (2002) stated that the average yield of wells in any particular geothermal field is fairly constant after passing through a certain learning period and gaining sufficient knowledge of the reservoir to site the wells so as to achieve the maximum possible yield. The average power output (MW) per drilled kilometer in geothermal fields is shown as a function of the number of wells in each field.

TABLE 1: Average values for 31 geothermal fields (Stefansson, 2002)

Average MW per well	4.2 ± 2.2
Average MW per drilled km	3.4 ± 1.4
Average number of wells before max. yield achieved	9.3 ± 6.1

For this estimation, it is assumed that the average depth of the wells is 1,890 m, and that the average cost of such wells is 3.24 million USD as presented in Table 2 (drilling costs in Central America as reported by Bloomfield and Laney, 2005).

TABLE 2: Drilling costs from 1997 to 2000 for Central America and the Azores in 2010 USD (Bloomfield and Laney, 2005)

Depth interval (km)	Number of wells	Total cost (MUSD)	Average depth (km)	Average cost/well (MUSD)
0.00-0.38	1	0.33	0.21	0.33
0.38-0.76	8	12.34	0.60	1.54
0.76-1.14	0	0.00	0.00	0.00
1.14-1.52	5	12.87	1.31	2.57
1.52-2.28	24	77.13	1.77	3.21
2.28-3.04	20	81.57	2.55	4.08
3.04-3.81	3	13.62	3.35	4.54
Total			1.89	3.24

The average yield of the 1,890 m wells is 3.24 x (3.4 ± 1.4) = (6.43 ± 2.6) MW, and the cost per MW is 3.24 / (6.43 ± 2.6) = 0.5 (+0.46/-0.21) MUSD/MW.

According to Stefansson (2002), this cost per MW is relatively insensitive to the drilling depth (and drilling cost) because the yield of the wells refers to each km drilled; for the first step of field development, the learning cost has to be added to the cost estimate. This cost is associated with drilling a sufficient number of wells in order to know where to site the wells for a maximum yield from drilling. As shown in Table 1, the average number of wells required for this is 9.3 ± 6.1 wells.

Assuming that the average yield in the learning period is 50%, 4.6 ± 3.0 wells are adding to the first development step. Incorporating the average cost per well, shown in Table 2, the additional cost is 15.07 ± 9.7 million USD. The estimation for expected drilling investment cost is calculated as follows:

$$Drilling\ cost\ million\ USD = (15.07 \pm 9.7) + [(0.5 + 0.46/-0.21) * MW] \quad (1)$$

Using 2010 USD values, the cost of wells has been inflated according to the US BLS (2011) inflation calculator.

4. POWER PLANT

Equipment purchase cost estimation is the key driver of the capital cost estimation for a given power plant project. There are three main sources of equipment estimation data: vendor contacts, open literature, and computerized estimating systems (Westney, 1997). In this section, the prices of the main geothermal power plant equipment are collected in the form of correlating equations found in the literature (heat exchangers, compressor, pumps, etc.), communication with developers (turbines and separators) and vendor quotes (cooling tower). The prices are given in terms of appropriate key characteristics of the equipment, such as area (m2), pressure (kPa), and power (kW). Factors for construction materials and performance characteristics other than the basic ones are also included.

4.1 Heat exchangers

The three geothermal systems (SF, DF and ORC) analyzed require a variety of heat transfer steps to produce a suitable prime mover fluid. In order to evaluate the cost of these components, and before selecting the estimation method, it is necessary to define the size and design of the component. This requires the appropriate duty factor, temperature and pressure differences.

Equipment sizing

In this analysis, the Log Mean Temperature Difference (LMTD) method is applied to calculate the heat transfer area A (Equation 2). Heat transfer in a heat exchanger usually involves convection in each fluid and conduction through the wall separating two fluids. In the analysis, it is convenient to work with an overall heat transfer coefficient U that accounts for the contribution of all these effects on heat transfer. The rate of heat transfer $\dot{Q}$ between the two locations in the heat exchanger varies along the heat exchanger. It is necessary to work with the Logarithmic Mean Temperature Difference ΔT_{lm} (Equation 3), which is an equivalent mean temperature difference between two fluids for an entire heat exchanger (Cengel and Turner, 2005).

The overall heat exchange surface expressed as a function of $\dot{Q}$, U and ΔT_{lm} can be written as:

$$A = \frac{\dot{Q}}{U\ \Delta T_{lm}} \tag{2}$$

where

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{3}$$

In Equation 3, ΔT_1 and ΔT_2 represent the temperature differences between the two fluids at the inlet and outlet. Table 3 shows the overall heat transfer coefficients used in the analysis of a heat exchanger.

TABLE 3: Overall heat transfer coefficients (Valdimarsson, 2011)

Fluids	U (W/m² K)
Water – Water	2000
Steam – Water	2000
Water – Isopentane	1200
Isopentane – Isopentane	1200

Estimated equipment cost

Numerous methods in relation to the cost of heat exchangers can be found in the literature. Most of them are presented in the form of graphs and equations for FOB purchase cost as a function of one or more equipment size factors. The equipment cost equation presented by Seider et al. (2003) is incorporated into the calculations here. The equations are based on common construction materials, and for other materials a correction factor is applied. The input parameters are: heat exchanger surface area A_f in ft, design pressure P_d in psig, heat exchanger type and material of construction.

The base cost (C_B) can be calculated as follows:

$$C_B = \exp\{11.0545 - 0.9228[\ln(A_f)] + 0.09861[\ln(A_f)]^2 \quad for\ fixed\ head \tag{4}$$

$$C_B = \exp\{11.967 - 0.8197[\ln(A_f)] + 0.09005[\ln(A_f)]^2 \quad for\ kettle\ reboiler \tag{5}$$

This base cost calculation counts for certain base case configurations including a carbon steel heat exchanger with 100 psig (690 kPa) pressure with a heat exchanger surface between 150 ft^2 (13.9 m^2) and 12,000 ft^2 (1,114.8 m^2). Correction factors for a different specific heat exchanger are introduced, and the FOB purchase cost for this type of heat exchanger is given by

$$C_P = C_B \; F_P \; F_L \; F_M \tag{6}$$

For different materials the factor F_M is introduced:

$$F_M = a + \left(\frac{D}{100}\right)^b \tag{7}$$

For different operating pressure the factor F_P is introduced:

$$F_P = 0.9803 + 0.018 \left(\frac{P_d}{100}\right) + 0.0017 \left(\frac{P_d}{100}\right)^2 \tag{8}$$

The base heat exchanger purchase cost equation is based on the CE index cost in mid year 2000 (CE=394).

Correcting equipment cost for inflation

Because the cost literature reflects equipment from some time in the past, it is necessary to correct for the cost of inflation. There are several inflation or cost indices in use; here the Chemical Engineering Plant Cost Index (CE index) is used in this analysis. The Chemical Engineering magazine (CHE) publishes the CE index regularly for correcting equipment costs for inflation; the CE indices for December 2010 are used in this analysis (CHE, 2011).

In order to obtain the current cost value of equipment C_2 we use an inflation index I_2 as given by Equation 9.

$$C_2 = C_1 \; \frac{I_2}{I_1} \tag{9}$$

4.2 Turbine – Generator

If a new piece of equipment is similar to one of another capacity for which cost data is available, then it follows that the estimated cost for turbines can be obtained from a scaling factor by using the logarithmic relationship known as the six tenths factor rule. According to Peters et al. (2003) if the cost of a given unit at one capacity is known, then the cost of a similar unit with X times the capacity of the first is approximately $(X)^N$ times the cost of the initial unit. The value of the cost exponent *N* varies depending upon the class of equipment being represented; the value of n for different equipment is often around 0.6. The typical value of cost exponent *N* for the steam turbine included in this analysis is 0.6.

Input parameters: cost and power of known turbine, capacity of estimated turbine.

$$\frac{Cost\ of\ equipment_2}{Cost\ of\ equipment_1} = \left(\frac{Capacity\ equipment_2}{Capacity\ equipment_1}\right)^N \tag{10}$$

This method is used in combination with the cost indices. Personal conversations with geothermal developers indicate that recent references (2010) used in the estimated purchasing cost for a turbine generator in a single flash process is around 13 million USD for 30 MW, and for double flash an additional 15% of the SF cost is considered. In a recent ORC development in Costa Rica, Marcos (2007) quoted a turbine cost of around 4 million USD for 7.5 MW.

4.3 Compressor

The FOB purchase cost for a typical centrifugal compressor is based on an equation from Seider (2003) where the base cost is given as a function of consumed power. The input parameters are: consumed power P_c in HP and material of construction.

The base cost (C_B) is calculated as:

$$C_B = \exp\{7.2223 + 0.80[\ln(P_c)] \qquad for\ centrifugal\ compressor \tag{11}$$

This base cost calculation counts for certain base case configurations including an electrical motor drive and carbon steel construction. For other materials, a correction factor F_M is included. For geothermal purposes, stainless steel is used ($F_M = 2.5$).

$$C_P = C_B \;\; F_M \tag{12}$$

The base purchase cost equation for the compressor has a CE index of 394. To correct the equipment cost for inflation, compressor CE indices (CE=903) for December 2010 are included (CHE, 2011).

4.4 Pumps

The technical literature for the cost of equipment offers several equations for calculating the approximate cost for centrifugal pumps, but the limitation is the flow range that the cooling water pumps operate in the geothermal power plant. The FOB purchase cost for the centrifugal pump is based on the equation equipment cost presented by Walas (1990). The input parameters are: flow rate Q_{cw} in *gpm* and material of construction.

The base cost for a pump (C_B) is calculated by:

$$C_B = 20\ (Q_{cw})^{\ 0.78} \qquad for\ vertical\ axial\ flow \tag{13}$$

Base cost calculations do not include the cost of the motor and are only valid for a flow range between 1,000 *gpm* and 130,000 *gpm*. The material correction factor for stainless steel is ($F_M = 2$). The cost of the motor is calculated by Equation 14. The input parameter is consumed power P_c in HP. The cost of the motor (C_P) is calculated as:

$$C_P = 1.2\ \exp[\ 5.318 + 1.084\ \ln(P_c) + 0.056\ \ \ln(P_c)^2\ ] \tag{14}$$

These cost calculations are for a motor type which is totally enclosed, fan-cooled and 3,600 rpm.

4.5 Cooling tower

An online vendor quote is easy to get from many companies (e.g. Cooling Tower Systems, Delta Cooling Tower, Cooling Tower Depot). The only requirements are the cooling tower design and operating conditions. In this analysis, the six tenths factor rule is applied, and the cost reference is based on the cost quoted by Cooling Tower Depot (2011). The typical value of cost exponent *N* for the cooling tower included in this analysis is 0.9 (Bejan et al., 1996).

4.6 Separation station

A personal conversation with geothermal developers indicated that the cost estimation of a separator can be made based on the mass flow rate capacity of the station. Recent references (2010) gave a cost of 400,000 USD for a mass flow rate capacity of 200 kg/s. Based on this information, in this study the calculation for another separator capacity was obtained using the six tenths factor rule.

4.7 Comparison of PEC between SF, DF and ORC

A comparative study of specific purchased equipment costs (USD/kW) between cycles is presented in Figure 2. The resource temperature (°C) and the mass flow rate (kg/s) have a major influence on the plant size (kW) for the SF, DF and ORC power plants. The size determines the cost of various components such as the turbine and heat exchangers which are the major components reflected in the purchasing costs of the main equipment of ORC, SF and DF power plants. An increase in the geothermal resource temperature results in an increase in the efficiency of the power plant and a decrease in the specific cost of equipment.

The temperature of the geothermal resource also affects the selection of the power plant technology. The ORC has the advantage over flash cycles when used for power production from low temperature resources. In the economic evaluation of the purchase costs of main equipment as a function of the resource temperature, it can be seen (Figure 2) that the specific PEC of ORC for temperatures below 180°C is lower than that of SF and DF. However, the specific PEC of ORC rises as temperature drops.

From the same geothermal fluid flow rate, the DF cycle can generate more power than the SF cycle but at an overall increase in cost because of the extra equipment. However, the specific PEC for DF can be lower than for SF for the same fluid rate and higher temperature resources, and for the same temperature resource and higher mass flow rate, which is also associated with power plant size. DF power plants present lower specific PEC than SF for a resource temperature above: 220°C for a mass flow rate of 300 kg/s; 200°C for a mass flow rate of 600 kg/s; 180°C for a mass flow rate of 1000 kg/s.

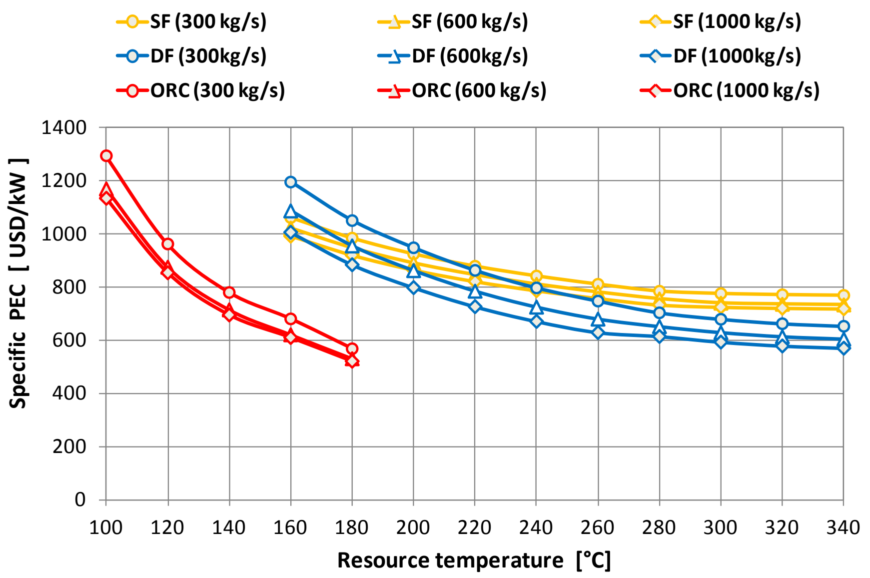

FIGURE 2: Comparison of specific PEC from SF, DF and ORC power plants

4.8 Equipment and construction

The estimation of the total equipment and construction cost is based on the purchase of the main equipment cost which was calculated in the last section. The factor method proposed by Bejan et al. (1996) calculates the cost components of the fixed capital in terms of a percentage of the purchase equipment cost (% of PEC) and direct cost (% of DC). Table 4 shows the calculation of equipment and construction costs.

TABLE 4: Estimation of equipment and construction cost in terms of PEC and DC

Equipment and construction cost estimation	**% factor**
Purchase equipment cost (PEC)	
Installation of main equipment	33% of PEC
Piping	10% of PEC
Control and instrumentation	12% of PEC
Electrical equipment and materials	13% of PEC
Land	10% of PEC
Engineering and supervisor	25% of PEC
Total direct cost (DC)	
Construction costs	15% of DC
Total	

4.9 Steam gathering

The connection between the wells, the separation station and the power plant network is defined as the steam gathering system or steam field piping. The cost of steam field piping typically depends on the distance from the wells to the power house, the flowing pressure and the chemistry of the fluids. According to Hance (2005), valves, instrumentation, control and data acquisition must be included because they can be significant; the piping and controls can vary from 111 to 279 USD/kW. Using 2010 USD, the estimated cost USD/kW has been inflated according to the US BLS (2011) inflation calculator.

4.10 Power transmission lines

Power transmission lines are expensive; therefore, geothermal power plants need to construct them near the resources. Distance, accessibility and capacity of transmission play key roles in the cost of constructing transmission line. The unit cost per kilometer based on flat land/rural setting, engineering and construction costs, for 69 and 115 kV double circuits, the cost is between 0.66 and 0.92 MUSD/km; for a 230 kV double circuit, the cost is between 0.79 and 0.91 MUSD/km (Ng, 2009). Using 2010 dollar values, the estimated cost USD/km has been inflated according to the US BLS (2011) inflation calculator. Scaling economies are particularly important for transmission costs. Differently sized power plant projects should have similar transmission requirements. Specific transmission costs for larger projects will be 10 times smaller since this cost will be shared out over a much larger power output (Hance, 2005). In this analysis a fixed distance of 10 km is assumed for calculating the power line transmission cost in all scenarios.

5. OPERATION AND MAINTENANCE

Power plant and steam field O&M costs correspond to all expenses needed to keep the power system in good working order. Most articles present O&M cost figures which exclude make up drilling costs.

In this study, however, 2.8 UScents/kWh is used as the total average O&M cost presented by Hance (2005); this O&M cost includes power plant maintenance, steam field maintenance and make up drilling costs. Using 2010 USD values, the O&M estimate cost has been inflated according to the US BLS (2011) inflation calculator.

6. CAPITAL COST OF GEOTHERMAL DEVELOPMENT

Capital cost for geothermal development includes exploration, drilling and power plant. Most of the estimations are based on related literature, which present average cost figures. Geothermal developers can achieve better accuracy if they can acquire updated market information.

Table 5 shows a summary of costs for scenario 1 (SF, 300 kg/s, 240°C) calculated as explained in previous sections. The capital costs estimated according to this methodology for a different geothermal resource (mass flow and temperature) and different power plant technology will be used as input in the financial modeling. Figure 3 illustrates the breakdown of the total capital cost of geothermal development for scenario1. This includes all the costs associated with total investment where the plant cost is approximately 50%, the drilling cost is 27%, exploration and confirmation costs total 8%, the power line transmission cost is 8% and the steam gathering system cost is 7%.

TABLE 5: Estimated cost of geothermal power plant development for single flash scenario 1 (27.7 MW): 300 kg/s and 240°C

Category	**Sub-category**	**Nominal value**	
		Value	**Units**
Exploration	Exploration	173	USD/kW
	Confirmation	173	USD/kW
	Total exploration	346	USD/kW
Drilling	Known field	504	USD/kW
	Unknown field	1,047	USD/kW
	Total drilling	1,047	USD/kW
Power plant	Steam gathering	279	USD/kW
	Equipment and construction	1,964	USD/kW
	Transmission power line	840,000	USD/km
	Total power plant	2,546	USD/kW
O&M	**Total O&M**	2.8	USD¢/kWh

6.1 Capital cost of single flash power plant

Figure 4 shows the specific capital cost (SCC) of SF in USD/kW for exploration and confirmation, drilling and power plant as a function of the resource temperature for different mass flows. The SCC decreases as the resource temperature increases from 160 to 340°C. SCC for SF power plants varies from 3,474 to 2,028 USD/kW for 300 kg/s; from 2,928 to 2,002 USD/kW for 600 kg/s; from 2,736 to 2,000 USD/kW for 1,000 kg/s. SCC for SF drilling varies from 2,090 to 721 USD/kW for 300 kg/s; from 1,295 to 610 USD/kW for 600 kg/s; from 977 to 566 USD/kW for 1,000 kg/s.

6.2 Capital cost of double flash power plant

Figure 5 shows the specific capital cost (SCC) of DF in USD/kW for exploration and confirmation, drilling and power plant as a function of the resource temperature for different mass flows. The specific costs decrease as the resource temperature increases from 160 to 340°C. SCC for DF power plants varies from 3,761 to 1,745 USD/kW for 300 kg/s; from 3,070 to 1,616 USD/kW for 600 kg/s; from

2,736 to 1,594 USD/kW for 1,000 kg/s. SCC for DF drilling varies from 1,893 to 701 USD/kW for 600 kg/s; from 1,196 to 600 USD/kW for 600 kg/s; from 1,025 to 560 USD/kW for 1,000 kg/s.

6.3 Capital cost of organic Rankine cycle power plant

Figure 6 shows the specific capital cost (SCC) in USD/kW for exploration and confirmation, drilling and power plant as a function of the resource temperature for different mass flows. The specific costs decrease as the resource temperature increases from 100 to 180°C. SCC for ORC power plants varies from 3,020 to 1,325 USD/kW for 300 kg/s; from 2,729 to 1,223 USD/kW for 600 kg/s; from 2,646 to 1,215 USD/kW for 1,000 kg/s. SCC for ORC drilling varies from 8,103 to 1,305 USD/kW for 300 kg/s; from 4,302 to 902 USD/kW for 600 kg/s; from 2,781 to 741 USD/kW for 1,000 kg/s.

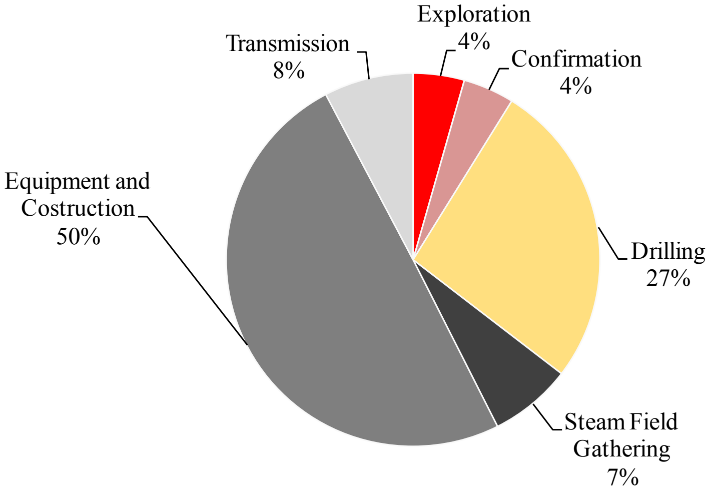

FIGURE 3: Cost breakdown for SF geothermal development in % of total; scenario 1: (27.7 MW): 300 kg/s and 240°C

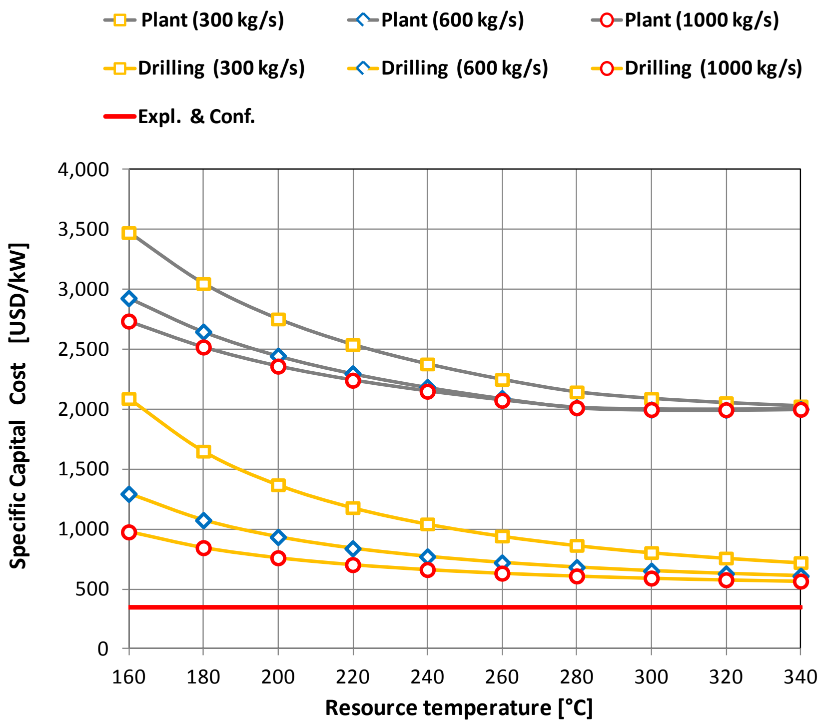

FIGURE 4: Specific capital cost of geothermal development for SF power plant

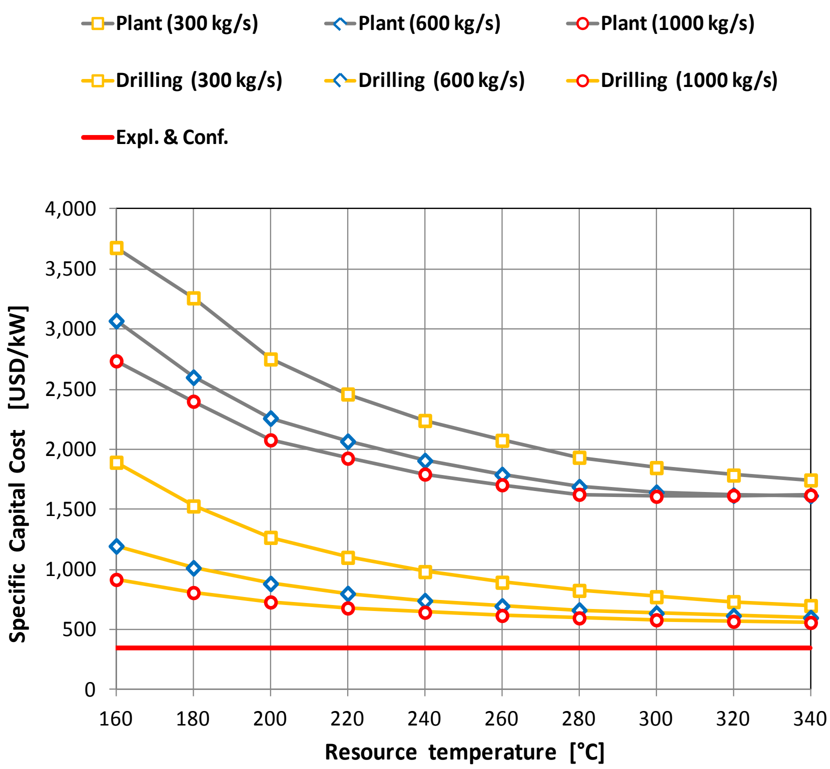

FIGURE 5 Specific capital cost of geothermal development for DF power plant

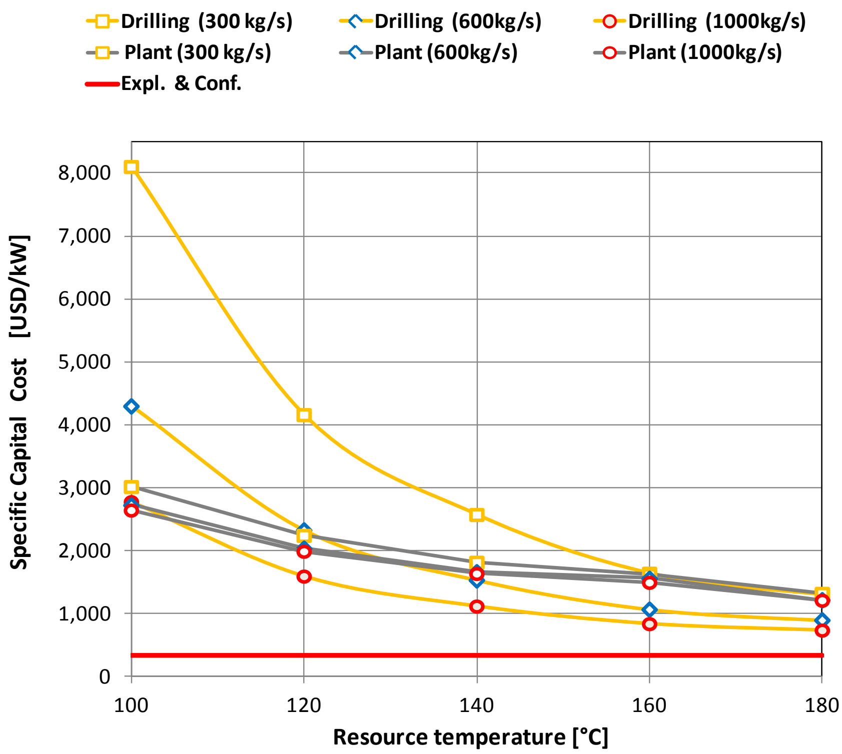

FIGURE 6: Specific capital cost of geothermal development for ORC power plant

6.4 Comparison of capital costs between SF, DF and ORC

Figure 7 compares the specific capital cost as a function of the resource temperature for different mass flow rates and power plant technologies. As shown in the figure, all the technologies in this study anticipate that a larger sized power plant has more cost effective values than smaller sized plants as reflected by scaling economies.

The specific capital cost (SCC) for ORC ranging between 11,400 and 2,300 USD per installed kW, for the resource temperature (100-180°C), and mass flow rate (300 kg-1,000 kg/s) was examined. The SCC of ORC rises quickly, exponentially, as the resource temperature and mass flow rate decrease (as a result of small power output). This occurs because the cost is affected by drilling and transmission line costs. For 300 kg/s at 180°C, the cost of drilling is 35% and transmission lines 13% of the total; at 100°C, drilling costs are 52% and transmission lines 26% of the total.

The SCC for SF, which ranges between 5,910 and 2,940 USD per installed kW, and the SCC for DF, which ranges between 6,000 and 2,500 USD per installed kW at resource temperature (160-340°C) and mass flow rate (300-1,000 kg/s), were examined. The SCC of DF presents lower values than SF for a resource temperature above 200°C at all the mass flow rate scenarios. For resource temperatures between 220 and 180°C, the SCC of SF presents lower values than DF. Finally, for resource temperatures between 180 and 160°C, the SCC of ORC has lower values than either SF or DF.

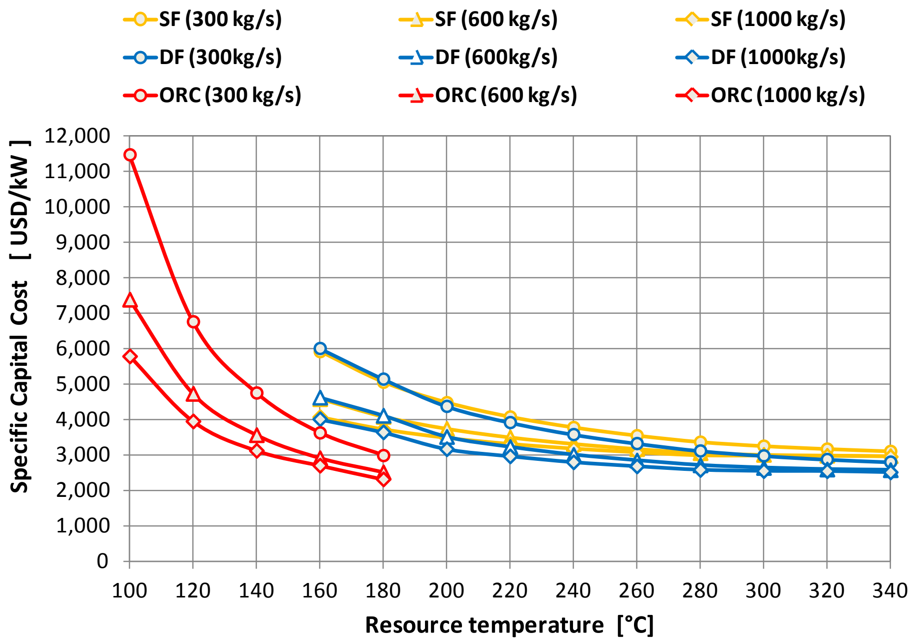

FIGURE 7: Comparison of specific capital costs of geothermal development

6.5 Literature review of capital costs of development

The main limitation for estimating costs is the acquisition of up-to-date data on prices for geothermal power plants, primarily because of the proprietary nature of this information. Source data for Figure 8 are taken from two sources: 1) the "Next Generation Geothermal Power Plants" (EPRI, 1996), where the estimation of cost is for nine geothermal projects in the USA located at different resources with various temperature characteristics; from research by EPRI, Hance (2005) reports that the apparent cost increase of the steam power plant corresponding to the 274°C resource temperature project is explained by other site and resource characteristics; 2) the "Assessment of Current Costs of Geothermal Power Generation in New Zealand (2007 Basis)" (SKM, 2009), a study which developed a band of estimated specific capital costs for geothermal resources in New Zealand settings from an analysis of 32 assumed scenarios. Using 2010 USD values, the costs have been inflated according to the US BLS (2011) inflation calculator.

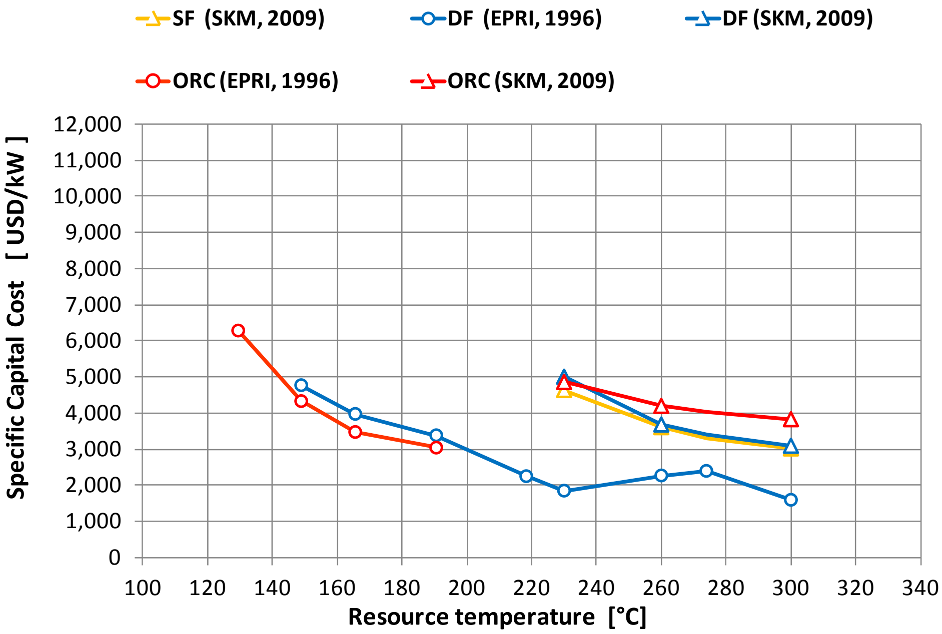

FIGURE 8: Literature review (EPRI, 1996; SKM, 2009): specific capital cost of geothermal developments as function of resource temperature (2010 USD); Note: the specific capital cost from: a) EPRI (1996): 129-300°C resource/50 MW plant size. b) SKM (2009): 230°C resource/20 MW plant size; 260-300°C resource/ 50 MW plant size; values from low enveloped wells; 0.7 as NZD/USD exchange rate (year 2007)

Table 6 illustrates data from a few authors about the specific capital costs of geothermal development for SF, DF and ORC power plants. Hance (2005) has drawn attention to the fact that even though some articles may present average cost figures for geothermal power projects, the cost figures provided frequently hide from view the extreme variability of the cost of components, financing costs and almost none consider the cost of transmission. Research by SKM (2009) observed that further useful discussions on factors affecting the cost of geothermal power development were presented by Sanyal (2005) and Hance (2005), but SKM emphasized that "the details in those papers are specific to the USA and these costs are now significantly out of date, having been largely gathered over the period 2000 to 2003".

TABLE 6: Literature review: specific capital costs of geothermal development (2010 USD)

Technology	Specific capital cost (USD/kw) (2010 USD)		Author
	Min	Max	
Non specified	1,896	2,962	(Sanyal, 2005)
ORC	3,400	4,240	(World Bank, 2006)
ORC	3,040	6,283	(EPRI, 1996)
ORC	2,481	3,848	(EPRI, 2010)
Flash	2,090	2,600	(World Bnk, 2006)
Flash	3,049	4,065	(Cross and Freeman, 2009)
Flash	1,974	3,038	(EPRI, 2010)
Dual flash	1,595	4,740	(EPRI, 1996)

REFERENCES

Bejan, A., Tsatsaronis, G., Mora, M., 1996: *Thermal design and optimization*. John Wiley & Sons, Inc, New York, NY, United States, 522 pp.

Bloomfield, K.K., and Laney, P.T., 2005: *Estimating well costs for enhanced geothermal system applications*. Idaho National Laboratory for the US DOE, Idaho Falls, Idaho, USA, 101 pp. Web: http://geothermal.inel.gov/publications/drillingrptfinal_ext-05-00660_9-1-05.pdf

BLS, 2011: *CPI inflation calculator*. Website: *http://www.bls.gov/data/inflation_calculator.htm*

Cengel, Y.A., and Turner, R.H., 2005: *Fundamentals of thermal-fluid sciences* (2^{nd} edition). McGraw-Hill, New York, NY, United States, 1206 pp.

CHE, 2011: *Economics indicators*, *118-4*, April 2011. Website: http://www.che.com/

Cooling Tower Depot, 2011: *Online tool for design, pricing, selection and optimization of cooling tower.* Website: http://www.ctdepotinc.com/content/cooling-towers

Cross, J., and Freeman, J., 2009: *2008 geothermal technologies market report*. National Renewable Energy Laboratory, report TP-6A2-46022, 46 pp. Web: http://www1.eere.energy.gov/geothermal/pdfs/2008_market_report.pdf

Dolor, F.M., 2005: Phases of geothermal development in the Philippines. *Papers presented at "Workshop for Decision Makers on Geothermal Projects and Management", organized by UNU-GTP and KengGen, Naivasha, Kenya*, 10 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-01-05.pdf

EPRI, 1996: *Next generation geothermal power plants*. Prepared for U.S. Department of Energy, Bonneville Power Administration, Southern California Edison Company, and Electric Power Research Institute, report EPRI TR-106223, 184 pp.

Hance, C.N., 2005: *Factors affecting costs of geothermal power development*. Geothermal Energy Association, Washington DC, United States, 12 pp.

Mannvit, 2011: *Geothermal exploration*. Website: *http://www.mannvit.com*

Marcos, A.G., 2007: *Technical-economic feasibility analysis of a geothermal power plant based in Latinoamerica*. Universidad Pontifica Comillas, Spain, BS thesis, 120 pp.

Ng, P., 2009: Draft unit cost guide for transmission lines. *Presented at Stakeholder Meeting, Folsom, CA, United States,* 7 pp. Website: http://www.caiso.com/2360/23609c2864470.pdf

Peters, M.S., and Timmerhaus, K.D., 2003: *Plant design and economics for chemical engineers* (5th edition). McGraw-Hill Companies, Inc., New York, NY, United States, 1008 pp.

Sanyal, S., 2005: Cost of geothermal power and factors that affect it. *Proceedings World Geothermal Congress, Antalya, Turkey*, 10 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0010.pdf

Seider, W.D., Seader, J.D., Lewin, D.R., 2003: *Product and process design principles: Synthesis, analysis, and evaluation* (2nd edition). Wiley, New York, NY, United States, 820 pp.

SKM, 2009: *Assessment of current costs of geothermal power generation in New Zealand (2007 basis)*. Sinclair Knight Merz, Auckland, New Zealand, 82 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/AGEC/2009/Quinlivan_2009.pdf

Stefansson, V., 2002: Investment cost for geothermal power plants. *Geothermics, 31-2*, 263-272.

Valdimarsson, P., 2011: Geothermal power plant cycles and main components. *Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador,* 24 pp. Web: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-12-35.pdf

Walas, S.M., 1990: *Chemical process equipment: Selection and design*. Butterworth-Heinemann Ltd., Boston, MA, United States, 755 pp.

Westney, R., 1997: *The engineer's cost handbook tools for managing project cost*. Marcel Dekker, Inc., New York, NY, Unite States, 749 pp.

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UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo
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BANKABLE GEOTHERMAL PROJECT DOCUMENTS

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ABSTRACT

Geothermal projects are financed with equity, grants and loans. The lenders finance the projects if they are attractive and when they pass a test of bankability. A project proposal is likely to be accepted if it has sufficient collateral, future cash flow, and high probability of success, acceptable to institutional lender and where all risks are identified, practical mitigation measures put forward and the risks are properly allocated to various parties involved in the project.

A feasibility study document undertaken by an experienced third party is the most authoritative technical bankable document. Detailed surface study under certain circumstance may be admissible. A power purchase agreement on a take or pay contract terms is most important document from a commercial point of view. Government guarantees are strong indicators of government support which impact the projects positively.

1. INTRODUCTION

Bankability is a loose term that may be defined as the ability to attract financing from commercial sources (World Bank, 2012) while a bankable document is a project proposal that has sufficient collateral, future cash flow, and high probability of success, acceptable to institutional lender for financing (Business dictionary, 2014) A bankable document may also be considered as a document which outlines the technical risks inherent in a project, delineates methods of eliminating those risks, and quantifies the potential economic returns that can be attained at various commodity prices. Bankability generally depends of four broad criteria namely creditworthiness, legal, economic and technical viabilities.

The essence of bankability is the assessment of a project to assure that the project objective will be met and undertake a risk assessment to reassure risks are adequately mitigated. The lenders carry out the bankability check as a means to reduce credit risk while the equity investor seeks to secure levels of return on investment (Hampl et al., 2011).

Bankable documents are prepared by the project sponsor in support for a loan, grant or credit application.

2. PROJECT CONCEPT NOTE

The project concept note is the owner's perception of the project, how it will be organized, implemented, financed and will perform financially.

2.1 Ownership or project sponsor

The project note will declare who the owner(s) of the project is. The banks are keen to evaluate the institutional risks associated with the owners which focus on financial capability, experience, managerial and organizational capacity. Therefore the project concept note has a profile of the owner detailing their legal establishment, financial strength and business interests.

2.2 Project brief

The concept note will also provide a brief project description. The brief would include location, objective, project size, scope and status. Indication of existing infrastructure such as roads, communication systems, major towns/cities which would provide social amenities and serve as load centers as well as the nearest point to connect to transmission lines are aspects that help rate the project.

2.3 Project justification

Every project is designed to meet a social need. The reason which makes the project a necessity should be stated. Geothermal project may be implemented to meet future power needs arising from growing demand or to arrest high tariff where geothermal project is implemented to replace more expensive power or to achieve a power mix that best suits a country. All these three reasons have been the motivation behind the drive for expansion of geothermal in Kenya. The least cost power development plans indicate that Kenya's peak demand will increase to at least 19000MW by the year 2030. To meet the increasing demand, the Country has committed to develop at least 5000 MW additional generation capacity from its vast largely untapped geothermal resources. On the other hand, the Country's hydro and thermal generation capacity comprise over 80% of the existing interconnected grid electricity system. This combination makes electricity supply vulnerable in that hydro is prone to the frequent droughts that have hit the Country from time to time while thermal generation is subject to frequent adverse fuel price variations. Geothermal on the other hand has very high available and is independent of the weather cycles. Lastly, the Country's bulk tariff as deduced from the Kenya Power and Lighting Company 2011/12 annual statements indicate the individual tariff from different generators ranges from US$ 0.048 per KWh (co-generation) to US$ 0.41 per KWh (emergency power) while geothermal is priced at US$ 0.097 per KWh). The low geothermal bulk tariff has pushed the drive for increasing geothermal generation capacity.

2.4 Project execution strategy

The method, approach and way that the various activities comprising the project will be accomplished need to be defined adequately in order for a project to be understood by other parties. Figure 1 shows the transactional arrangement of a project under implementation sponsored by Geothermal Development Company of Kenya. The figure identifies the parties that are involved in the project, their anticipated roles and types of contracts to define the relationships between the parties.. The execution strategy helps to evaluate the effectiveness and efficient of the implementation plan, risks associated with the project and hence risk allocation to the parties.

2.5 Time line

The concept note will provide the major milestones to be accomplished during the implementation of the project. In addition, key target dates to achieve the milestones should be given. As a minimum,

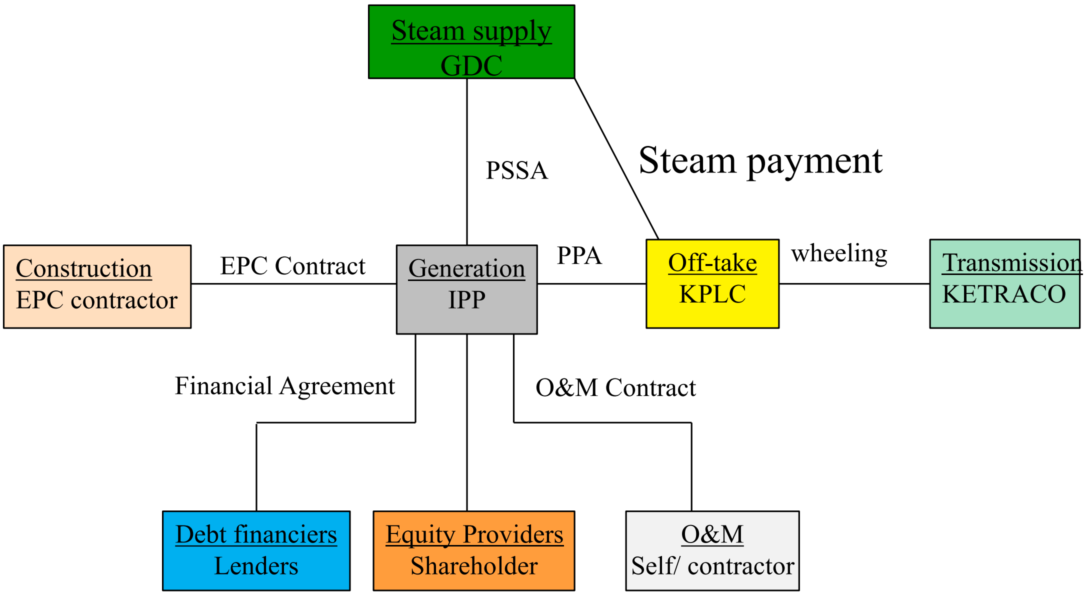

FIGURE 1: Transaction model used by Geothermal Development Company of Kenya

the dates of the key decision point should be provide. The decision points include, when detailed surface study will be done, exploration and appraisal drilling, feasibility study, commencement of the construction of the power plant and the commissioning. This information help all in planning, monitoring the project progress and evaluating time related risks.

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2.6 Budgets

The project budget provides information on the total capital cost required for the project and should be indicated in the proposal. A detailed cost break down showing various budget items and the amount required for each year of development is most helpful. This helps in planning disbursement schedules from the various financiers. In addition, the data is used to evaluate whether the project cost are under or overestimated and whether adequate contingencies have been factored in.

The second component of the budget is the operation and maintenance requirements. While in general this cost are financed from the revenues, the data is necessary in the preparation of the financial models that help evaluate the financial performance of the project.

2.7 Financing plan

A financing plan should be provided in the proposal. One major question answered by the project concept note is how the project sponsor anticipates the project financial requirements will be met. The financing plan in addition match source of financing and budget items to be financed. This information is helpful in evaluating the reliability of the sources identified and in determination of the cost of financing from the individual sources and combined.

2.8 Financial model

The proforma financial statements should be attached to the proposal. A financial model of geothermal power project is essential in defining the various parameters required to enable investors make decisions for or against the project, convince financiers to commit resources to the project and government, utilities or off-takers to sign on the project. Financial models typically take the format of proforma financial statements.

2.9 Basic financial performance appraisal

A basic assessment of the project financial performance should be included in the project proposal. The objective of setting aside financial resources to an individual investment including the granting of loans is aimed at ensuring the limited resource are allocated to the most economic activity. There is an opportunity cost associated with committing financial resource to a specific project. For this reason, both investors and lenders use various tools to choose between alternative and competing projects. Some of these tools include internal rate of return, payback period and breakeven point. In addition, financial ratios are used to evaluate the financier performance of a project. A basic assessment of the project will provide comparative information to provide a perspective of the project financial performance.

2.10 Assumptions

The proposal should clearly state the assumptions made in preparing the proposal. The data provided in the proposal is as good as the assumptions made. If the assumptions change, the proposal information also changes. The assumptions typically made include well output, cost of various activities, performance levels such as number of drilling per rig per year, success rate and terms of financing.

3. PRE-FEASIBILITY STUDY

Detailed surface study is the first comprehensive technical report produced in relation to the project prospect. The detailed surface study cover geological and hydrogeological studies, gravity measurement, resistivity measurement, sampling of fumaroles gas seepages, chemistry of borehole fluids and temperature measurement at shallow depth. Infrared and micro-seismic studies may also be undertaken.

A high quality study is very useful in helping design the technical decisions such as wells casing programs and give insight to the likely problems that are likely to arise when the project is implemented. The study does give an indication of the temperature/ pressure expected and hence the possible technology to employ, like hood of scaling, size of resource, resource depth. In addition, the study help site the exploration wells. On the basis of the study, the initial project concept note may be prepared.

The document however, is not admissible as a bankable document except where governments back the document with sovereign guarantees or private investors with balance sheet financing. Most of the conclusions of the detailed surface study are inferred and therefore may actually differ from reality. For this reason under project finance (limited recourse) arrangement, the documents would be considered highly risky.

Risk associated with exploration drilling has been identified as a risk that deters private sector participation at the early stages of geothermal resource development, thus accounting to a great extend for the low geothermal development. Recent efforts (Combs, 2006) are exploring possibility of providing financial instruments aimed at accelerating development at these very early stages of development. If successful, the detailed surface studies may become bankable.

4. FEASIBILITY DOCUMENT

Feasibility is the most authoritative technical bankable document when it is prepared by third party reputable and experienced firms. It should establish sufficient quality and technical standard to produce the desired level of reliability. In a project finance arrangement, the lenders bear the full project risk. The feasibility document therefore is subjected to rigorous and all aspects of the project receive the highest level of scrutiny from the financiers. The document is prepared when well data is available.

4.1 Data collection and re-interpretation

The main concern here is to analyze the real data obtained during the drilling and well discharge activity so as to make a decision on the characteristic of the resource in terms of type (steam or water dominated) the temperature/ pressure, well discharge fluid chemistry, non-condensable gases, scaling potential and well productivity behavior. This information is important in evaluating the suitability of the resource, the size and the possible utilization challenges.

4.2 Exploitation models

Sustainable exploitation model is one of the key answers that a feasibility study must provide. Computer numerical simulation model is prepared and calibrated using historical data. Various exploitation models are run and the response of the project reservoir response is noted. The scenario that best fits the project in terms of project size and PPA period is chosen if the runs shown resource sustainability.

4.3 Preliminary design

A preliminary design of the project is prepared based on the chosen utilization model. The preliminary design would include well sites for the projected number well of steam/ binary wells and hot and cold reinjection wells. In addition, a preliminary steam gathering network would be designed. The power plant location would be provided and the power plant operation characteristics chosen.

4.4 Power system study and design

The feasibility study should answer the question of demand, existence of infrastructure to transmit and distribute the power to the market. The document will recommend the method of connecting to the existing system, the routing of the proposed connection lines and environmental scoping associated with the line.

4.5 Financial and economic models

The firms undertaking the feasibility study will further undertake a financial model based on the preliminary design. The input cost should be reflective of the market situation as close as possible. The key concern would be to evaluate financial viability of the project. Where governments obtain concession financing, an economic analysis of the project would be necessary.

4.6 Environmental Scoping

It is common in Kenya to require that the firm undertaking the feasibility study also provide a chapter on suggested areas of environmental consideration when undertaking a full environmental and social impact assessment.

5. POWER PURCHASE AGREEMENT

Power purchase agreement is one of the' must have' bankable document for the private investment. Perhaps due to their strategic nature, the power sectors worldwide are largely controlled by government agents through independent commissions, utilities, municipalities or government ministries. In addition, transmission and distribution networks, infrastructure put in place by other parties, are necessary for the producer of electricity to reach the consumers. The electricity market is therefore not a free market and even if the market were free, the investment requirement is so inhibitive to gamble. Ultimately except where government provides subsidies, the end user pays for all the costs arising from electricity provision. The power purchase agreement (PPA) therefore assures the investors as well as the lenders of the right to the market for the period of the PPA. Further, it assures investors and lenders that in the absence of the market, the risk is transferred to the power off-taking party. Without the PPA regardless of how good the project proposal is, private investor will find it difficult to raise funds from financial institutions. Where the government is the investors as well as the off taker, the PPA is not necessary.

The PPA are designed to assign the market (generation capacity), roles and responsibilities, rights including the right of step-in by the lenders, define the nature of contract, take or pay being the most popular, set the term of the PPA, project milestones, agree on the dispatch and operation procedures, penalties to be levied against default, procedure and manner of treating forced majeure, termination, and allocate risks.

6. GOVERNMENT GUARANTEES

Government guarantees have very positive impact on bankability of a geothermal project. Government guarantee may be sovereign or a letter of comfort both which are instruments obligating the government to step in and meet certain obligation if any government agent involved in a power project default. The document may cover such risks as default of the agents, political risk and termination in the case where termination occurs due to default of the government agent. While the instruments are designed to be called on as a last result, issuing of the same strongly indicate government commitment which has a very positive impact on the bankability of the project proposal.

7. EPC CONTRACT

The engineer-procure-construct (EPC) contract is another of the key documents that make a project proposal bankable. The bulk of the investment funds are expended during the construction stage of the development. It is imperative that the plants and equipment are constructed installed and commissioned within time, on budget and meeting the design functional characteristics. The risk during construction is borne by the investors. Therefore the EPC contract transfers the risk from the investor to the EPC contractor. The selection of the EPC contractor is essential for the success of the project.

Key clauses relate to project cost preferably lump sum cost, payment structure and milestones, completion tests, minimum functional specifications, support services, provisions for cost escalations, copyrights, training manuals, spare parts, warranties, penalty provisions and LDs, force majeure, arbitration / liquidated damages, jurisdiction (Subramanyam P., 2012).

8. ESIA AND ENVIRONMENTAL LICENCE

Another of the must have document for a project to be bankable is the environmental certificate/licence. It is true for Kenya as it is in many other countries that one cannot commence the project with an environmental licence. In Kenya, it is typical to undertake two ESIA one for the drilling activities and another for the power plant. The latter is undertaken as a follow up of the feasibility study environmental scoping. The process of approving the ESIA allows a period for the public to raise concerns or objection to the project. The major development financial institutions further display the ESIA on their website for a period before they can consider providing financing.

9. SUPPORTING DOCUMENTS

From a Kenyan context, a ratification of the PPA by the Energy Regulatory Commission is required in addition to obtaining a generation licence. Loans obtained by the Government would require an opinion from the Attorney General. Projects implemented under the public private partnership would require Cabinet approval.

10. CONCLUSION

Bankability may be viewed as a measure of the attractiveness of a project to the extent that it can attract financing from lending institutions. The criteria of measuring bankability is based on the project ability to generate adequate revenues to sustain itself while serving debts and meeting its investors financial expectation, existence of a resource that can be utilized using matching proven technology and where risks of technical nature are properly mitigated, existing power market and where inflation, currency exchange rate and interest rates are favorable to enable the project to be undertaken profitably and on where there is no legal or regulatory requirement that can stop the project to be undertaken.

Determination of bankability of a project entails evaluation of documents submitted by the project sponsor for application for financing of the project. The documents include the project proposal or concept note, detailed surface study (under certain conditions), feasibility study, power purchase agreement, government guarantees, EPC contract, ESIA and environmental licence among others.

A project proposal is likely to be accepted if it has sufficient collateral, future cashflow, and high probability of success, to be acceptable to institutional lender and where all risks are identified, can be mitigated and properly allocated to various parties involved in the project.

Bankable documents are prepared by the project sponsor in support for a loan, grant or credit application.

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REFERENCES

Business dictionary, 2014: *Bankable. Definition.* Website: http://www.businessdictionary.com/definition/bankable.html

Combs, J., 2006: *Financial risk management instruments for geothermal energy development projects.* United Nations Environment Programme, Consultation Meeting on Climate Change Finance, Working Group 3, 80 pp.

Gehringer, M., and Loksha, V., 2012: *Geothermal handbook: Planning and financing power generation*. The International Bank for Reconstruction and Development / The World Bank Group, Washington DC, United States, Energy Sector Management Assistance Program technical report 002/12, 164 pp. Web: http://www.esmap.org/Geothermal_Handbook

Hampl N., Lüdeke-Freund, F., Flink, C., Olbert, S., and Ade, K., 2011: *The myth of bankability - Definition and management in the context of photovoltaic project financing in Germany.* Goetzpartners and Colexon, Germany, 28 pp.

Subramanyam, P.G., 2012: *Advanced project financing – Structuring, bankability and contractual issues*. Slides presented at the Institute of Company Secretaries of India, 46 pp.

Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

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HOW DO FINANCIAL ASPECTS OF GEOTHERMAL COMPARE WITH OTHER ENERGY SOURCES?

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ABSTRACT

How does geothermal energy compare with other conventional sources of energy? Under which conditions does the harnessing of a geothermal resource become economically competitive? These are legitimate questions for entities undertaking the development of a geothermal energy project. The paper deals with cost analysis of geothermal power production. It provide insights on the main parameters influencing a business model for such projects and proposes a comparison with other energy sources.

1. INTRODUCTION

Each geothermal power plant is unique because each geothermal field is unique. Comparison of electrical energy from geothermal resources is a therefore complex as various parameters may have significant impact on the components of the "geothermal field-power plant" complex. Geothermal power plants are never plain "plug and play" units and always require a minimum of engineering to harness energy in the most efficient and sustainable manner. Geothermal projects are in this regard more complex than conventional power projects.

Geothermal fields suitable for harnessing energy may have temperature ranging from 120°C to 350°C. Drilling cost will vary greatly from one project to the other depending on the location, the underground features and how deep the resource is to be found. Furthermore, not all drilled wells may be successful and their performance may go from a few hundred kW up to 20 MW or even more. The risks involved in reaching the resource are significant and geothermal project are generally characterized by high upfront cost risks.

As a geothermal project usually takes 5-10 years to come to a full development, it is important to have from the beginning a good notion of the range within which geothermal energy may be economically competitive.

The paper discusses the investment, operation and maintenance costs of geothermal projects and proposes a comparison of energy prices from various sources.

2. COST OF GEOTHERMAL PROJECTS

2.1 Investment cost

Typical investment costs include (list non exhaustive):

- Preparation:
    - Civil works, roads, planning;
    - Environmental impact assessment;
- Exploration cost;
- Geothermal well field development:
    - Drilling of wells and well testing;
    - Gathering system for supply to the power plant:
        - Geothermal well pumps (pumped brine);
        - Piping;
        - Steam separation;
        - Well field control;
    - Reinjection system:
        - Piping;
        - Pumping;
        - Reinjection control;
- Power plant:
    - Civil structures, turbine hall, cooling tower basin etc.;
    - Mechanical installation;
    - Electricity and control;
- Indirect cost:
    - Engineering supervision and commissioning;
    - Owner's costs;
    - Leasing and permitting; and
    - Interest during construction.

Typical distribution of investment costs for geothermal power plants is presented in Tables 1 and 2 below.

Typical investment costs are:

- 3.650 USD/kW gross for steam plant 50 MW using 250°C geothermal fluid; and
- 5.300 USD/kW gross for binary plant 10 MW using 150°C geothermal fluid.

TABLE 1: Cost distribution for a typical geothermal steam plant (50 MW 250°C)

Cost Item	**%**
Preparation	2
Exploration	8
Geothermal well field development	50
Power plant	30
Indirect cost	10
Total	**100**
Total installation cost, USD pr. kW Gross	**3,650**

TABLE 2: Cost distribution for a typical geothermal brine plant (10 MW 150°C)

Cost Item	**%**
Preparation	2
Exploration	5
Geothermal well field development	44
Power plant	39
Indirect cost	10
Total installation cost, USD pr. kW Gross	**5,300**

2.2 Operation and maintenance costs

Typical operation and maintenance costs include:

- Personnel;
- Spare parts and plant consumables;
- Scheduled maintenance;
- Overhead and insurances; and
- Well replacement.

Operation and maintenance costs may vary greatly from one plant to the other depending on the size and type of plant, its location and the plant operation philosophy selected at the design stage by the plant owner.

Modern geothermal power plant operation is foreseen to be mostly automatic and unmanned. Sensors and surveillance will be provided to raise alarm on plant malfunctioning, working fluid leakage, in case of fire or unauthorized plant visitors, etc. During start-ups and scheduled shut-downs, operator attendance is however always required. Following automatic shut-down due to malfunctioning, operator attendance is also required to remove/correct the fault and reset the respective computer system modules.

Geothermal power plants are usually equipped with various human machine interfaces and PLC software to operate the plant and display trend diagrams and records plant parameters and alarms. The overview screen, at least, is visible from remote location and, in case malfunctioning occurs, fault alarms become visible/audible too. Plant start-up, warming-up, synchronization and loading follows an automatic programmed routine and same applies to plant shut-down, scheduled or forced. A daily plant operator visit is nevertheless necessary to look after systems and perform preventive maintenance and inspection tasks such as checking for noise, vibrations, leakages, strainer conditions, liquid levels, safety valves, etc.

About 1 to 2 weeks scheduled shut-downs are foreseen each year for general maintenance and 5-8 weeks every 3-6 year for major maintenance-related shut-downs. This influence the maintenance cost and also the expected utilization hours.

General maintenance includes inspection of the plant, instrument calibration, generator cleaning, strainer cleaning, mechanical seal inspection, insulation tests, etc. The geothermal wells, the gas separator and control valves are checked for scaling and cleaned. Outdoor maintenance is required on buildings and painted steel parts, equipment and piping supports, area fencing, etc.

Typical plant operation and maintenance costs are presented in Table 3. In general the cost is in the range of 1.5-2.5 % of the total installation cost.

TABLE 3: Operation and maintenance cost for a geothermal steam plant

Plant output	MW	1
Annual Gross electricity production	MWh	8,000
Fixed annual operational cost	**$/MW**	**43,000**
Supervision of machinery	$/MW	8,000
Maintenance work	$/MW	25,000
Supervision of reservoir	$/MW	10,000
Variable operational cost	**$/MWh**	**4.30**
Operation supplies	$/MWh	0.70
Maintenance drilling	$/MWh	3.30
Total O&M cost for 1 MW	**USD /year**	**75,000**

Similar values can be derived for binary plants.

2.3 Net electricity production

Geothermal power plants generally use their own electricity production to cover the parasitic load. The parasitic load is not listed as operational cost; it only reduces the amount of energy sold to the grid.

The parasitic power for a geothermal steam plant is in the range of 2-5 % but can reach 20-40% for some binary plants.

In normal operation mode, each unit should run and stay on line for more than 8000 hours/year, allowing 1 to 2 week for annual scheduled maintenance and up to 7 days/year of unforeseen outages. Also, as mentioned before major shut-downs for maintenance purposes should be programmed for 5 – 8 weeks every 3-6 year.

3. COMPARISON WITH OTHER TECHNOLOGIES

The feasibility of a geothermal power project does not only depend on the technical issues previously introduced. Decision on the development of a geothermal project will also be dependent on the economic justification of the geothermal resources involved in the project. Table 4 proposes an overview of typical costs for various types of power plants:

- Geothermal:
  - Steam turbine plants: harnessing energy from geothermal fluids at temperature above 180°C.
  - Binary plant: the binary technology allows for production of electricity from low temperature resources that could otherwise not be used for such purpose, typically at reservoir temperatures below 180°C.
- Medium speed diesel: this type of power plant typically operates on heavy fuel.
- Steam turbines: typically operating on coal for the purpose of this paper.
- Combustion turbine typically operating on gas for the purpose of this paper.
- Nuclear.
- Wind: similarly to geothermal power plants, wind turbines are site specific.
- Hydro:
  - Large dam hydropower plants, designed to have a high capacity factor.
  - Other hydropower plants, with smaller dams and a lesser capacity factor.

TABLE 4: Typical costs for power plants and

Plant	Investment cost MUSD/MW	Annual operational and maintenance cost		Typical load factor
		Fixed USD/MW	Variable USD/MWh Gross	
Geothermal, steam	3.60	43,000	4.3	90 – 95
Geothermal, binary	5.30	43,000	1.0	85 - 95
Large wind	2.00	35,000	2.0	35 – 40
Nuclear	4.05	90,000	15.0	80 – 90
Large hydro	2.80	15,000	1.0	80 - 90
Gas Turbines	0.80	12,000	90.0	50 - 60
Coal	2.10	70,000	60.0	70 - 80
Diesel	1.50	60,000	120.0	30 - 40

Typical capacity, or load, factors are also indicated for each type of power plant in Table 4. The capacity factors indicated depend on availability of the source, for intermittent renewable sources of energy such as wind or hydropower, and on the fuel costs. Geothermal power plants are generally considered one of the power production means with the highest capacity factor as the energy may be available 24 hours a day almost all year round and may in some cases be above 95%.

It is possible to compare the economics of different energy sources by considering the various cost elements such as: investment cost, fuel cost, operation and maintenance costs, economic lifetime and efficiency. An Equity Research on “Alternative Energy” conducted by Credit Suisse in 2009 aimed at comparing Levelised Cost of Electricity for various sources of energy, see Figure 1. According to these estimates, geothermal plants are the least expensive form of power.

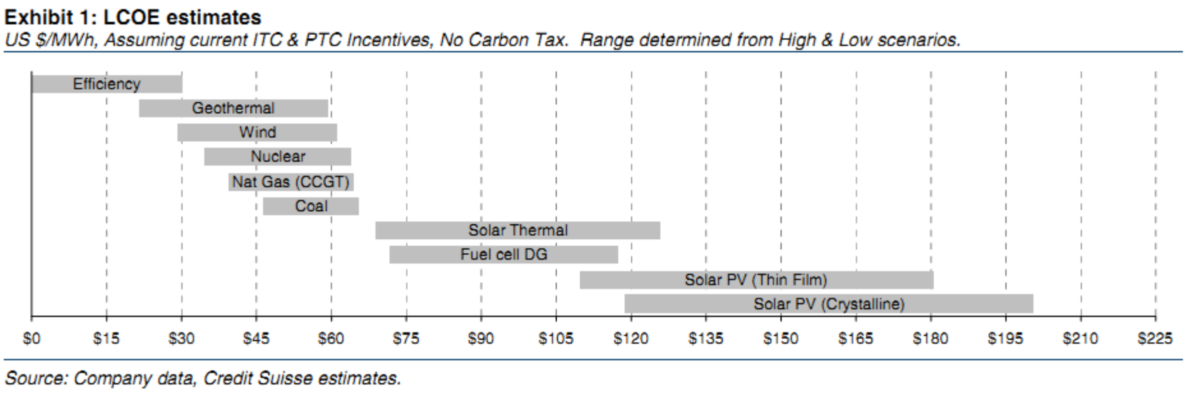

FIGURE 1: LCOE estimates for various sources of energy (Credit Suisse, 2009)

Countries may develop and maintain a least cost development plan for a given timeframe with the purpose to identify the resources that are the most economically feasible. The result of such exercise is often shown in the form of so-called screening curves that show the total costs associated with the development of each plant per kW as a function of the capacity factor. These curves are an interesting tool for comparing various types of power plants in different capacity factor context.

4. CONCLUSION

Geothermal electricity, while limited in scalability and geography, compares well with other options and scores among the least expensive sources of energy. Investment costs for geothermal power plants are high, 3-7 MUSD/MW, compared to other technologies whereas the operation and maintenance costs are low, due to the fact that once the plant has been installed, no fuel or little external source of energy is required to run the plant. This is among the main reasons why geothermal power plants are considered competitive. They furthermore generally contribute to cut CO_2 emissions and reduce dependence on fossil fuels.

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ECONOMIC BENEFITS OF GEOTHERMAL SPACE HEATING FROM THE PERSPECTIVE OF ICELANDIC CONSUMERS

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ABSTRACT

Geothermal resources provide a low-cost option for heating Icelandic buildings. This is evident when the cost of geothermal space heating is compared to the cost of heating with imported oil and domestic electricity, both of which are used by residents of areas where geothermal resources are not to be found. The comparison reveals annual savings that amount to 1.1-4.3% of the total income from employment in 2005. A comparison of district heating prices in Europe shows that Icelandic consumers pay the lowest price per energy unit.

1. INTRODUCTION

Over the course of one century, geothermal space heating has grown from being non-existent in Iceland to reaching 90% of the population. The first farm was connected to a hot spring in 1908 and the first geothermal district heating system was established in Reykjavik in 1930, in times when coal was the main heating fuel. In the following decades, the district heating system was expanded, but oil gradually became the heating fuel of choice for those inhabitants of the capital area who did not have the benefit of a geothermal connection. By 1960, oil had mostly taken over from coal and by the early 1970s, the district heating system had expanded to reach nearly all the inhabitants of Reykjavik. However, oil continued to be used for heating in the countryside. This was felt heavily by the Icelandic economy during the oil crises of the 1970s and early 1980s, which served to motivate the Icelandic Government to encourage further development of geothermal resources for space heating through policies and attractive loans. The resulting expansion of geothermal heating over this period is evident in Figure 1. While the lowest hanging fruit were harvested first, the Government and municipalities have continued to encourage the exploration and use of geothermal resources for space heating in areas of lesser population density and/or inferior resource quality, resulting in gradual increase in geothermal space heating from the mid-1980s up to the present.

Although geothermal resources are widely spread in Iceland, there are parts of the country where they are hard to find or non-existent. In those areas, electrical heating has mostly taken over from oil (Figure 1). In 2011, the electricity mix consisted of hydro (72.7%) and geothermal (27.3%) (Baldvinsdóttir et al., 2013).

Such wide access to geothermal resources for space heating in a cold country that needs year-round heating is of great benefit to the national economy and to consumers. The aim of this paper is to describe these benefits to Icelandic consumers, and to this end, the cost of geothermal space heating is compared to the following scenarios:

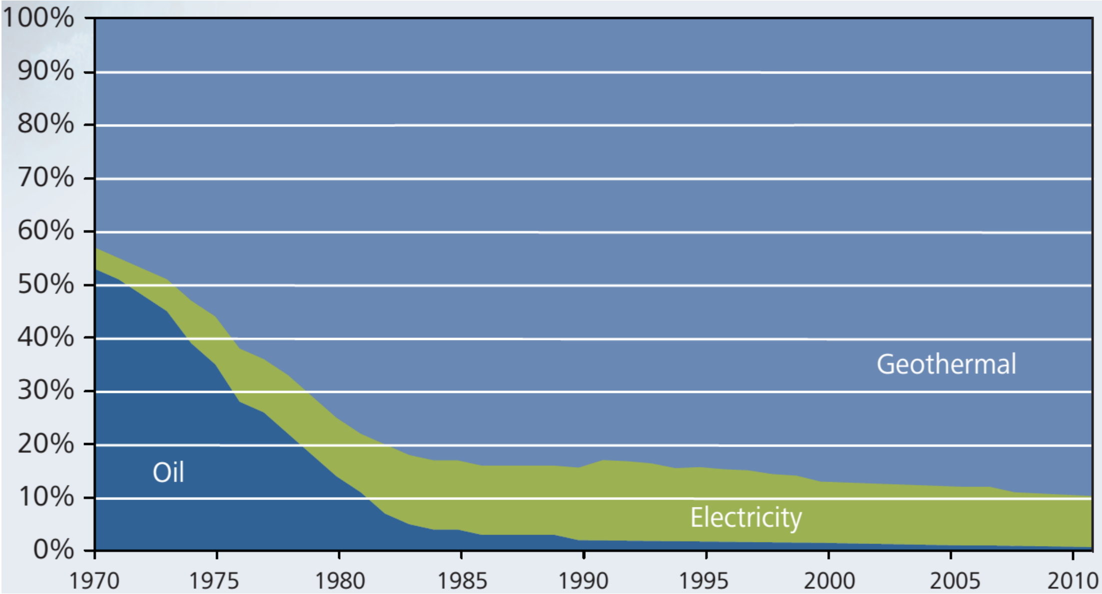

FIGURE 1: Space heating in Iceland by energy source 1970-2011 (Baldvinsdóttir et al., 2013)

1. The cost of heating by oil, as done in previous decades;
2. The cost of electrical heating, as done by close to 9% of the population; and
3. The cost of heating in neighboring countries.

Due to the complex interplay of various factors and the hypothetical nature of reference cases, the outcome of such an undertaking will be suggestive rather than concrete.

2. COMPARISON TO HEATING BY OIL

In 2010, Orkustofnun – the National Energy Authority of Iceland (NEA), published a report on the benefits to the Icelandic national economy of using geothermal resources for space heating in place of oil over the period 1970-2009 (Haraldsson et al., 2010). Figure 2 shows that during this period, the retail price of imported heating oil has at all times been higher than the price of geothermal energy per unit of deliverable heat energy (65% conversion efficiency is assumed for the oil). For some years, the use of oil for heating was "only" 2 times as expensive as heating by geothermal, but in 1979 (Iranian revolution) and 2008 (overheated world economy), it became almost 10 times as expensive. The accumulated savings to Icelandic geothermal district heating customers over this 30 year period amount to 9,510 million USD (adjusted for inflation to February 2014 based on the annual average consumer price index and the average exchange rate (114.1 ISK/USD) for the same month (Central Bank of Iceland, 2014)). By comparison, the total income from employment in 2005 was 7,845 million USD (Iceland Statistics, 2014) (total income is not available for later years from Iceland Statistics; same method of inflation adjustment and conversion to USD as before). Although the consumer group of geothermal district space heating services includes the commercial, industrial and agricultural sectors, the residential sector has a large share in the overall utilization. This suggests that the savings of an average residential customer of a geothermal district heating service in Iceland who subscribed in 1970 amounted to a sizable share of a year's salary over a 30 year period compared to a person who heated their identical home with oil at retail prices. For the year 2005 in particular, when oil was 4 times as expensive as geothermal (which also happens to be the average ratio between the two energy sources over the 30 year period), the total savings of geothermal customers amounted to 341 million USD, which is 4.3% of total income from employment in that year.

In reality, the very small fraction of homes that are still heated by oil in Iceland get a subsidy from the Government that is intended as a measure towards equalizing energy prices. This subsidy is substantial, although it does not suffice to bring oil heating prices down to the level of geothermal district heating (Figure 3). As a result, the largest part of the price difference between geothermal and oil heating is covered by the Government, although the consumer does take part. In this case, geothermal heating is a boon to taxpayers.

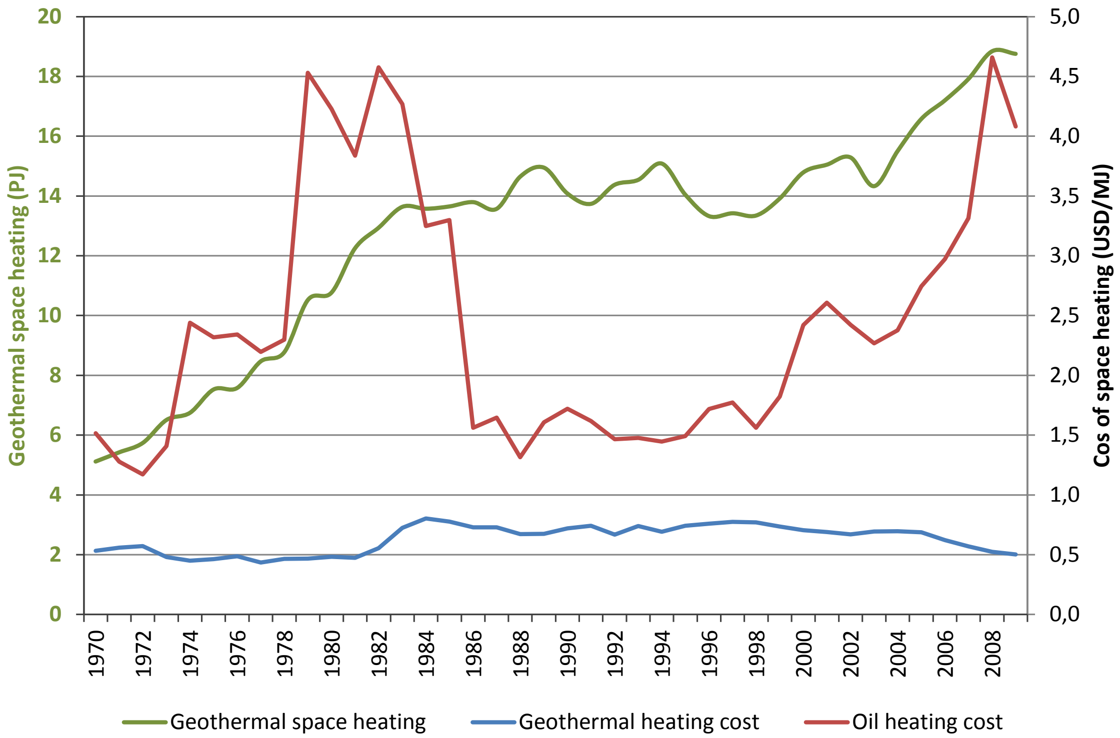

FIGURE 2: Geothermal utilization for space heating and real term energy prices (based on the annual average consumer price index and ISK/USD exchange rate in February 2014) in Iceland over the period 1970-2009 (modified from Haraldsson et al, 2010)

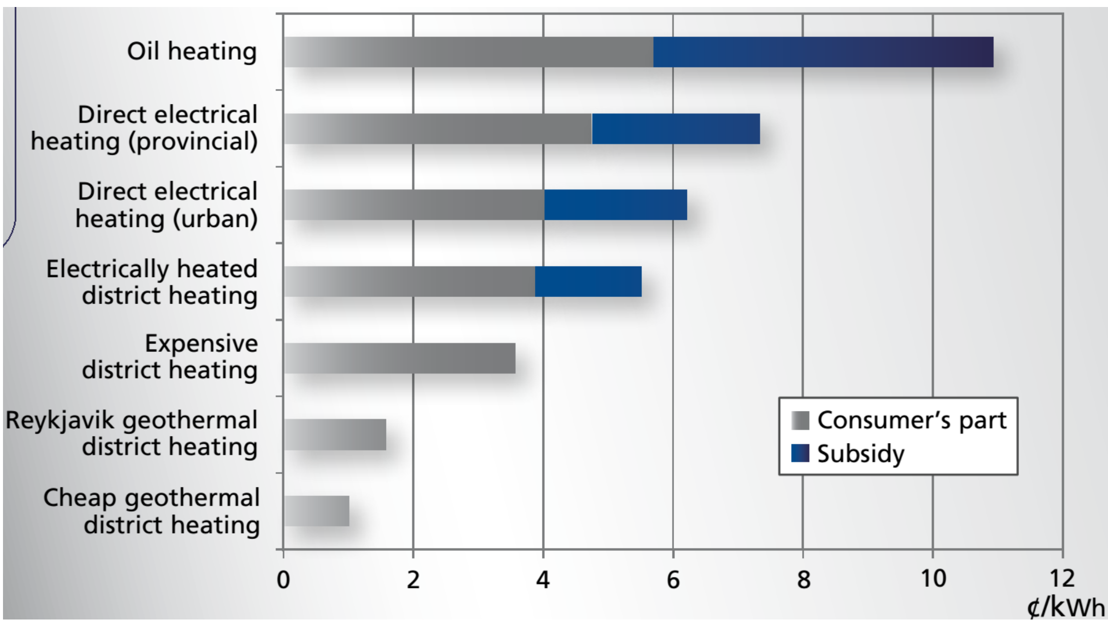

FIGURE 3: Comparison of energy prices for residential heating in Iceland in mid-2009 (Eggertsson et al., 2009)

It is worth noting in this comparison that consumer / State savings translate to foreign currency savings for the national economy at large, and it is sheltered from world market price fluctuations through the use of a stable domestic resource (Figure 2).

3. COMPARISON TO ELECTRICAL HEATING

If geothermal resources were not found in Iceland, but the country and climate would otherwise be the same, it must be seen as a more likely scenario that homes were heated by electricity generated by the country's bountiful hydropower resources than with imported oil. This is supported by Figure 3, which shows average prices for electrical district heating (water heated by electricity in central heating stations), as well as direct electrical heating for urban and rural areas. A conservative approach is taken for this scenario, and it is assumed that urban areas would be serviced with electrical district heating systems, whereas rural dwellers would heat their homes directly.

It is assumed that the heat delivery networks in urban areas would be similar to geothermal district heating networks and that infrastructure requirements would therefore be similar. Two years are selected for the comparison: 2005 is singled out as a year for which data on total income from employment are available and 2009 is selected as the last year reviewed in NEA's report from 2010, mentioned in the previous section. Table 1 summarizes the givens, assumptions and results.

TABLE 1: Comparison between geothermal and electrical heating costs in 2005 and 2009

Year	**2005**	**2009**
Population	293,577 (31 Dec 2005)[1]	317,593 (1 Dec 2009)[2]
Proportion in rural areas	0.061 (1 Jan 2004)[3]	0.055 (1 Jan 2009)[3]
Proportion in urban areas	0.939	0.945
Av. price of electrical district heating	4.6 ISK/kWh[4+]*	8.4 ISK/kWh[5]*
Consumer part	N/A	5.9 ISK/kWh[5]*
Subsidy	N/A	2.5 ISK/kWh[5]*
Av. price of rural direct el. heating	11.4 ISK/kWh[4]*	11.2 ISK/kWh[5]*
Consumer part	6.6 ISK/kWh[4]*	7.3 ISK/kWh[5]*
Subsidy	4.8 ISK/kWh[4]*	3.9 ISK/kWh[5]*
Replaced geothermal heating	16.58 PJ[6]	18.76 PJ[6]
Geothermal heating cost	$13.0 \cdot 10^9$ ISK[6]*	$10.8 \cdot 10^9$ ISK[6]*
Av. price of geothermal heating	2.82 ISK/kWh*	2.06 ISK/kWh*
Av. price of geothermal heating USD¢	2.47 USD¢/kWh*	1.81 USD¢/kWh*
Cost of equivalent electrical heating	$23.1 \cdot 10^9$ ISK*	$44.6 \cdot 10^9$ ISK*
Electrical district heating	$19.9 \cdot 10^9$ ISK*	$41.4 \cdot 10^9$ ISK*
Electrical rural direct	$3.2 \cdot 10^9$ ISK*	$3.2 \cdot 10^9$ ISK*
Total savings	$10.1 \cdot 10^9$ ISK*	$33.8 \cdot 10^9$ ISK*
Total savings USD	**$88.5 \cdot 10^6$ USD**	**$296.2 \cdot 10^6$ USD**

1: (Statistics Iceland, 2006); 2: (Statistics Iceland, 2009a) ;3: (Statistics Iceland, 2009b)
4: (Pálsson and Jónasson, 2005); 5: (Eggertsson et al., 2009); 6: (Haraldsson et al., 2010)
[+]: No distinction made for rural and urban prices
*: Corrected for inflation to Feb 2014

Some of the items in the table warrant discussion:

- *Population*: Although population figures are available for the end of both of the selected years, the division into the urban and rural compartments is not available for 2005. Instead ratios for 2004 are used as an approximation for 2005.
- *Average price of electrical district heating*: The values are obtained from graphs published in the annual publication of NEA, *Energy statistics in Iceland*, as shown in Figure 3. There is a

possibility of a slight visual error in the reading of the numbers. It should be kept in mind that prices vary between heating energy providers, and the published graphs are based on averages. There is a very significant increase in the reported price for electrical district heating between 2005 and 2009 (both values corrected for inflation to February 2014), which is not seen in the price of rural direct electrical heating. The reported price for 2005 is slightly lower than the reported price of "expensive" district heating in the same year, whereas the latter is a considerably better option than electrical district heating in 2009, as displayed in Figure 3. The reason for this change is unclear, but the value for 2005 is assumed to produce a conservative result in the comparison between geothermal and electrical heating.

- *Replaced geothermal heating*: This term refers to the geothermal heating consumption, including space heating and direct water use (bathing etc.), in the two years under examination, as reported by NEA in 2010.
- *Geothermal heating cost*: These costs are obtained from NEA's 2010 report, although values have been adjusted to correct for inflation to February 2014.
- *Cost of equivalent electrical heating*: It is assumed that all geothermal heating is replaced by electrical heating, distributed equally over the population. Consequently, costs are divided between electrical district heating systems and direct electrical heating systems in proportion to urban and rural residents.

The calculated savings in 2005 amount to 88.5 million USD, which is considered a conservative estimate. Although not as big a number as the 341 million USD in savings calculated for the oil scenario, it is still 1.1% of the total income from employment in 2005. The calculated savings for 2009 amount to 296 million USD. Table 2 summarizes these numbers along with savings calculated for Scenario 1.

TABLE 2: Calculated total consumer savings due the use of geothermal resources for space heating compared to heating with oil or electricity

	2005		**2009**
	Savings	Share of total employment income	Savings
S1: Geothermal vs. oil	$341 \cdot 10^6$ USD	4.3%	$671 \cdot 10^6$ USD
S2: Geothermal vs. electricity	$88.5 \cdot 10^6$ USD	1.1%	$296 \cdot 10^6$ USD

These results suggest that out of three energy sources that can be utilized for space heating in Iceland, geothermal is the most cost attractive option and is of high economic significance to consumers.

4. COMPARISON TO NEIGHBORING COUNTRIES

Due to its diffusive nature, there are economic limits to the geographic transport of heat. As a result, the utilization of geothermal resources for direct applications is quite localized, as demonstrated by the fact that the longest geothermal transmission pipeline in the world, found in Iceland, is 64 km in total (Georgsson et al., 2010). In contrast, electricity can be transmitted thousands of kilometers and oil can be shipped around the globe. In Europe, gas is a common source of heat that can be transported in pipelines over thousands of kilometers. Nevertheless, local resources are commonly used where possible, which results in substantial differences in the energy mix between countries. Figure 4 shows this variation for heating in the Nordic countries. It is evident that district heating systems are quite widespread in the region with the exception of Norway, where electricity covers 70-80% of heating demand, with the remainder primarily met by bioenergy (7%), oil (7%) and district heating (4%) (NVE, 2013).

These district heating systems rely on various fuels depending on local conditions and supply. An example is shown for Sweden in Figure 5.

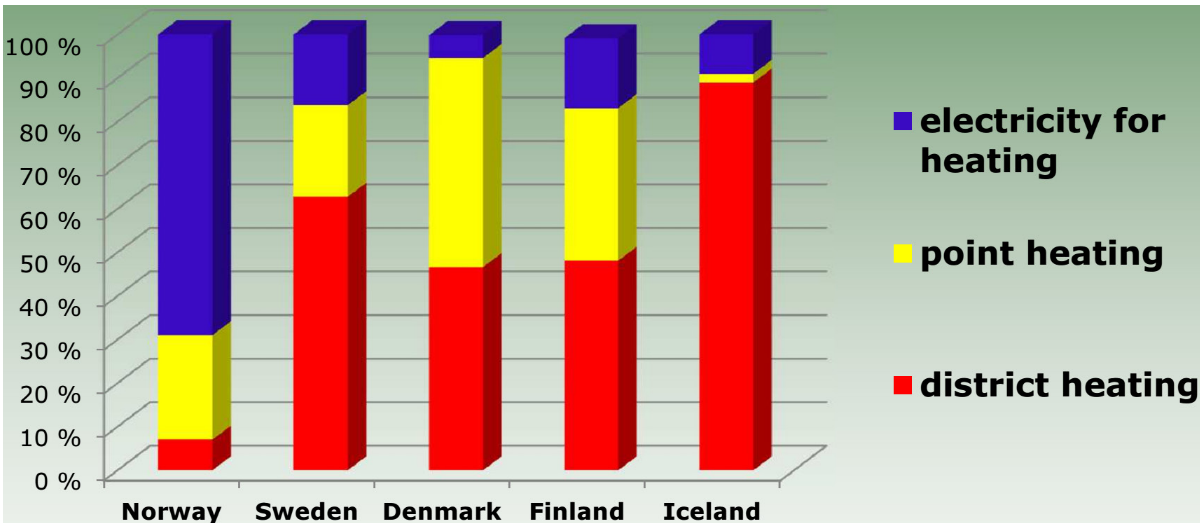

FIGURE 4: Heating in the Nordic countries by energy carrier and energy sources (Hohle, 2011)

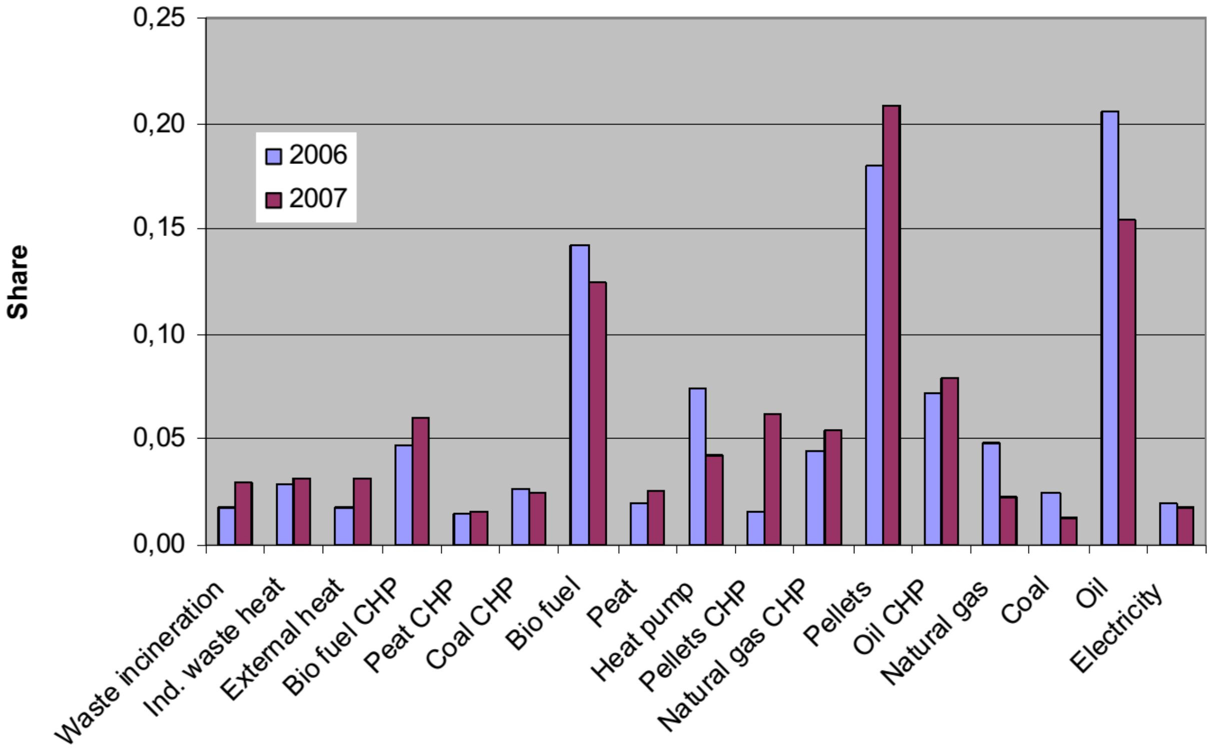

FIGURE 5: Energy source contributions to district heating systems in Sweden in 2006 and 2007 (NEP Research Group, 2009)

Although a considerable fraction of the energy supplied to district heating systems in Sweden derives from fossil fuels, this method of heat distribution offer the possibility of using local wastes, waste heat, biofuels, and environmental heat (including geothermal) along with electricity through the use of heat pumps. It can be assumed that the heat for district heating systems in Denmark, Finland and Norway, as well as other European countries, derives from varied sources also and this, along with policies and tax regulations in each country, affects the district heating price to the consumer. In this context, it is enlightening to compare average district heating prices in different European countries in 2009, based on a survey conducted by Euroheat & Power and shown in Table 3.

TABLE 3: Average district heating prices in Europe, the United States and Korea (Euroheat & Power, 2014)

Region	Country	Price (EUR/GJ)	Price (EUR¢/kWh)	Price (USD¢/kWh)
Nordics	Iceland	2.58	0.93	1.24
	Finland	12.8	4.6	6.2
	Sweden	16.55	5.96	7.97
	Norway	20.8	7.5	10.0
	Denmark	25.03	9.01	12.05
Europe (other)	Russia	4.48	1.61	2.16
	Croatia	8.95	3.22	4.31
	Poland	10.4	3.7	5.0
	Estonia	12.25	4.41	5.90
	Slovenia	12.44	4.48	5.99
	Latvia	13.89	5.00	6.69
	Romania	14.04	5.05	6.76
	Austria	15.96	5.75	7.68
	France	16.61	5.98	7.99
	Czech Republic	17.1	6.2	8.2
	Lithuania	17.6	6.3	8.5
	Slovakia	18.08	6.51	8.70
	Germany	19.55	7.04	9.41
America	United States	8.64	3.11	4.16
Asia	Korea	12.14	4.37	5.84

Although comparable data are available for 2011, 2009 is chosen in line with the previous scenarios. The price of 1.24 USD¢/kWh for Iceland errs only 9.5% from the 1.37 USD¢/kWh obtained from the data published in NEA's 2010 report, which suggests that the values in Table 3 can be accepted with reasonable confidence. It is worth noting that the 1.37 USD¢/kWh value is calculated directly from sales figures from Icelandic geothermal district heating companies and the estimated heat usage for buildings, using the average exchange rate for 2009 from the Central Bank of Iceland to convert the price to US dollars, whereas in Table 2 the price is given in 2014 dollars, arrived at by first correcting for inflation in Iceland to February 2014 and then converting to US dollars using the average exchange rate for that month as reported by the Central Bank.

Out of all countries surveyed by Euroheat & Power, Iceland has the lowest district heating price of 1.24 USD¢/kWh compared with an arithmetic mean value of 6.74 USD¢/kWh, a standard deviation of 2.60 USD¢/kWh, and a maximum value of 12.05 USD¢/kWh. The great variation in prices within the Nordic countries, which all have cold climates and therefore a considerable need for heating, is of particular interest. Out of the 20 surveyed countries, the highest price is encountered in Denmark and the second highest in Norway, whereas Sweden has the 8th highest price and Finland lies slightly below the average. It is probable that the reasons are not only economic, but also political. In general, taxes tend to be high in the Nordic countries and countries with limited domestic energy options, such as Denmark, may want to keep energy prices high in order to promote efficiency and limit consumption. Furthermore, environmental considerations may contribute to high prices. The fortune of Icelandic consumers is therefore the abundance of low-value, environmentally benign geothermal heat that translates to the lowest average district heating price on record in Europe and the wider world.

In the United Kingdom, one of Iceland's neighboring countries, the main source of energy for heating is gas (Association for the Conservation of Energy, 2013). In 2009, the average gas price in the UK was 11.84 EUR/GJ, including all taxes and levies (Eurostat, 2014). Assuming 80% efficiency (Association for the Conservation of Energy, 2013), brings the price up to 14.80 EUR per GJ of usable heat. This translates to 5.33 EUR¢/kWh, or 7.12 USD¢/kWh, which is slightly above the average price for district heating in Europe, and substantially higher than the price in Iceland.

From these comparisons, it is evident that Icelandic geothermal district heating prices are very competitive. However, it is important to be aware of differences in climatic conditions between countries that lead to differences in the length of the heating season. Shorter heating seasons may lead to higher unit prices, as district heating companies must cover incurred costs based on sales over a limited time period each year. Other factors that influence heat demand, and thus consumers' wallets, include:

- *Ambient temperature*: The heat flow through a building wall is directly related to the temperature difference over the wall, indicating that year-to-year fluctuations in ambient temperature affect heat demand as was clearly observed in Norway in 2010 (NVE, 2013).
- *Indoor temperature*, which is influenced by personal comfort choices, habits, prices and other factors, and can therefore vary over the population of a country. It is possible that averages are slightly different between countries.
- *Insulation and airtightness of buildings*, which may vary between countries.
- *Ventilation* preferences of home owners.

5. CONCLUSION

Despite hypothetical arguments, imprecision in data, and a rough methodology, the comparisons presented show that the utilization of geothermal resources for space heating in Iceland is of substantial economic benefit to Icelandic consumers.

REFERENCES

Association for the Conservation of Energy, 2013: *Energy efficiency and excess winter deaths: Comparing the UK and Sweden*, 11 pp. Web: http://www.energybillrevolution.org/wp-content/uploads/2013/12/ACE-Research-Comparing-the-UK-and-Sweden-3.12.13.pdf

Baldvinsdóttir, A.N., Loftsdóttir, Á., Gudmundsson, B., Thorsteinsson, Í., Ketilsson, J., and Georgsdóttir, L., 2013: *Energy statistics in Iceland 2012*. Orkustofnun – National Energy Authority of Iceland, 14 pp. Web: http://www.os.is/gogn/os-onnur-rit/orkutolur_2012-enska.pdf

Central Bank of Iceland, 2014: *Exchange rate*. Website: http://www.cb.is/exchange-rate/

Eggertsson, H., Haraldsson, I.G., Thorsteinsson, Í., and Jónasson, Th., 2009: *Energy statistics in Iceland 2009*. Orkustofnun – National Energy Authority of Iceland, 12 pp. Web: http://www.os.is/media/orkutolur/Energy-Statistics-2009.pdf

Euroheat & Power, 2014: *Statistics overview 2009*. Website: http://www.euroheat.org/Statistics

Eurostat, 2014: *Gas prices for domestic consumers, from 2007 onwards – bi-annual data*. Website: http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database

Georgsson, L.S., Jóhannesson, H., and Bjarnason, Th., 2005: Geothermal activity in Borgarfjordur, W-Iceland, and the exploration, development and utilization of the Varmaland/Laugaland geothermal field. Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 10 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0642.pdf?

Haraldsson, I.G., Thórisdóttir, Th.H., and Ketilsson, J., 2010: *Economic comparison of using geothermal and oil for space heating over the period 1970-2009*. Orkustofnun – National Energy Authority of Iceland, report OS-2010/04 (in Icelandic), 20 pp. Web: http://www.os.is/gogn/ Skyrslur/ OS-2010/OS-2010-04.pdf

Hohle, E.E., 2011: Fuel poverty in an energy rich country. Presented at the IEA Task 29 Conference Renewable energy solutions addressing fuel poverty, Aylesbury, United Kingdom, 18 pp. Website: http://www.task29.net/70.html

NEP Research Group, 2009: *The future of Nordic district heating. A first look at district heat pricing and regulation.* Nordic Energy Perspectives, intermediate report, 52 pp. Web: http://www. nordicenergyperspectives.org/Nordic%20District%20Heat.pdf

NVE, 2013: *Energy consumption 2012. Household energy consumption*. Norwegian water resources and energy directorate, report 16-2013, 38 pp. Web: http://webby.nve.no/publikasjoner/rapport/2013/ rapport2013_16.pdf

Pálsson, Ó., and Jónasson, Th., 2005: *Energy statistics in Iceland 2005*. Orkustofnun – National Energy Authority of Iceland, 12 pp. Web: http://www.os.is/media/orkutolur/Energy-Statistics-2005.pdf

Statistics Iceland, 2006: Population 31 December 2005. *Statistical series, 91-19*, 16 pp. Web: https://hagstofa.is/lisalib/getfile.aspx?ItemID=4060

Statistics Iceland, 2009a: *Population 1 December 2009*. Statistics Iceland, news report 215/2009. Website: http://www.statice.is/Pages/444?NewsID=3784

Statistics Iceland, 2009b: *Statistical yearbook of Iceland 2009*. Statistics Iceland, 394 pp.

Statistics Iceland, 2014: *Total income by economic activity and region 1998-2005*. Website: http://www.statice.is/Statistics/Wages,-income-and-labour-market/Income