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Solar home systems adoption in Sub-Saharan African countries: Household economic and environmental benefits assessment

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A B S T R A C T

Household benefits of adopting solar home system (SHS) kits were investigated. The assessment considered lighting devices for Tier 0 based on scenarios A to E in comparison with kerosene lamps, candles, and torches in 11 Sub-Saharan African (SSA) countries. To assess the impact of mobile money charges on the SHS kit gross price, the SHS kit acquisition by households was examined based on the cash and pay-as-you-go approaches. The study examined the household energy expenditure for each of the Tier 0 scenarios and the respective savings recorded by acquiring a SHS kit on the two payment approaches as well as the greenhouse gases (GHG) emissions avoided by a household. The study results revealed that households across the selected SSA countries would incur an annual energy expenditure in the range of $ 63.28–106.93, with an average of $ 87.31 and record energy expenditure savings of 46.04% and 29.79% for a SHS kit on the cash and pay-as-you-go approaches, respectively. The mobile money charges result in about 0.14–4.69% increment in the kit's gross price. An annual household GHG emissions avoided in the range of 19.51–199.29 kg CO_{2eq} by acquiring a SHS kit was recorded.

1. Introduction

With the continuous fall in solar photovoltaic (PV) module prices over the years coupled with the continent's abundant solar resource, Africa is increasingly turning to solar PV systems to foster energy access and support rapid economic growth in a sustainable manner [1,2]. The falling prices of solar PV systems have attracted the over 600 million Sub-Saharan Africa (SSA) people in rural areas without access to grid connection to solar home system (SHS) kits as an alternative source of energy [2–4]. The sales for plug-and-play SHS kits have grown rapidly in recent years from a small base since 2013–2014 [5]. Currently, the SSA region is the leading market for SHS kits accounting for about 70% of the global total sales [3]. The growth in the SHS kits sales has mainly been evident in countries with strong mobile money ecosystems since mobile money has proved to be the most streamlined mechanism of payment for the pay-as-you-go (PAYGo) operations by the SHS actors [3–6].

Several solar business companies offering the PAYGo payment plan for SHS kits are currently operating in different countries in the SSA region, with the highest concentration reported in the East African countries [3,5,6]. From 2012 to 2017, the PAYGo businesses raised about $ 773 million investment funds, equal to about 85% of all the funds raised by off-grid systems sector, an indication that investors have aggressive expectations in the growth of the PAYGo companies [4,5]. Recent reports indicate that PAYGo payment plan accounted for about 24% of the global sales of off-grid solar PV systems and particularly recorded tremendous increase in sales in SSA countries such as Kenya, Burkina Faso, Cote D'Ivoire, Rwanda, Senegal, Tanzania, and Togo in 2019 [3,6].

SHS kits of less than 200 W capacity have a wide variation in prices, with total installation cost in the range of $ 4.3–14.2 per

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Nomenclature

AC	Alternating current
DC	Direct current
GHG	Greenhouse gases
LED	Light emitting diode
MTF	Multi-tier framework
PAYGo	Pay-as-you-go
PV	Photovoltaic
SE4ALL	Sustainable Energy for All
SHS	solar home systems
SSA	Sub-Saharan Africa
C_{cb}	SHS kit cash price
$C_{pb,mm}$	SHS kit PAYGo gross price including mobile money charges
C_{pb}	SHS kit PAYGo gross price
E_B	Average annual expenditure on Tier 0 energy sources for lighting and phone charging
$E_{F,cb}$	Average annual expenditure on energy post-purchase of SHS kit for cash basis
$E_{F,pb}$	Average annual expenditure on energy post-purchase of SHS kit for PAYGo basis
$GHG_{av,k}$	Total greenhouse gas emissions avoided from kerosene lamps
$GHG_{av,c}$	Total greenhouse gas emissions avoided from candles
$L_{mm,i}$	Mobile money transaction charges incurred
n_L	SHS kit lifespan
P_d	Upfront PAYGo deposit
r	Discount rate
S_{cb}	Total energy expenditure savings for SHS kit cash basis
S_{pb}	Total energy expenditure savings for SHS kit PAYGo basis

watt for 18–136 W SHS kits [2]. These SHS are all direct current (DC) kits that utilize the light emitting diode (LED) lights and provide charging for mobile phones, while the larger capacity SHS kits provide the ability to run small appliances for short periods, representing the largest portion of the SHS market [2]. The alternating current (AC) SHS kits are more expensive than the DC SHS kits because they require an inverter and typically are larger, in the range of 200–750 W. The costs for these AC SHS kits are consistently higher than for the smaller DC SHS kits, falling in the range of $ 14–23 per watt, a level driven in part by the inverter costs and by the costs of the larger, more capable batteries that are installed with them. However, although they are more expensive, AC SHS kits are also more capable systems and can provide a wider range of energy services. The installation costs of SHS kits with more than 1 kW capacity are in the range of $ 3.6–17 per watt [2].

Majority of the SHS kits sold in the SSA region currently are in the range of about 6–100 W capacity [7,8]. It is remarkable that at this scale, manufacturer, distributor and/or retailer margins have a significant impact on the total costs of the SHS kits. Thus, the SHS kits costs vary widely across the SSA region [2,7]. Generally, low income customers are assumed to use 207 kWh per year and a 10–35 W SHS kit, while medium income customers are assumed to use 985 kWh per year and a 200 W SHS kit [4]. Roughly, the SHS kit is estimated to deliver energy for low energy customers in the range of 0.9–1.5 $/kWh [4]. Notably, over the last few years the SHS manufacturing costs have declined by approximately 5–15% and the efficiency of the SHS appliances has also improved [6].

Adoption of SHS kits in SSA region is envisioned as a way of achieving sustainable energy access, especially in the rural places where low-income earners without access to the electricity grid dwell. In SSA countries, about 69% of households use kerosene lamps for their lighting services [9]. The utilization of a single kerosene lamp by a household for lighting services is estimated to emit about 200 kg CO_{2eq} annually [10]. Generally, the African Development Bank predicted the GHG emissions per capita to grow by 1.2% between 2017 and 2025 in Africa [11]. Replacement of a kerosene lamp by a SHS kit is estimated to yield reductions in the GHG emissions of about 36.8 kg CO_{2eq} annually [12]. The combinations of the lighting devices (kerosene lamps, candles, and torches) used in SSA countries vary from one household to another [13–17]. For instance, some households use only kerosene lamps, kerosene lamps & candles, candles & torches, only candles, kerosene lamps & torches, and only torches combinations, which have not been investigated to ascertain the potential GHG emissions avoided in case those lighting devices are replaced with SHS kits in SSA countries.

Furthermore, although improvements in the SHS kits' cost and efficiency were investigated in Ref. [6], and the penetration of SHS kits in the SSA region investigated in Refs. [12,17–23], the household economic and environmental benefits of transitioning from traditional energy sources to a SHS kit for lighting services in the SSA region has not been investigated. Thus, this study examines the household economic and environmental benefits of SHS kits in the SSA region by considering 11 countries for SHS kits of 10–30 W capacity, for lighting and phone charging services. The study investigates the economic benefits of SHS kits by considering the two payment plans, namely, cash basis and PAYGo basis approaches. Also, the study investigates the impact of mobile money transaction charges on a SHS kit gross PAYGo price. For the environmental benefits, the study examines the GHG emissions avoided by a household when it acquires a SHS kit or by changing the combination of the lighting devices used. To undertake these analyses, the household energy expenditure under Tier 0 was assessed based on the set scenarios that comprise of combinations of kerosene lamps, candles, and torches as the lighting devices used.

In undertaking the investigation on the household economic and environmental benefits of acquiring a SHS kit for the case of 11 selected SSA countries, this study made the following contributions to knowledge:

- Presented the impact of mobile money charges on the SHS kits' PAYGo gross price in selected SSA countries.
- Established the household energy expenditure in selected SSA countries by considering different combinations of the lighting devices scenarios.
- Established the household energy expenditure savings by acquiring a SHS kit in selected SSA countries.
- Determined the household lighting GHG emissions avoided by acquiring a SHS kit in selected SSA countries.

The rest of this paper is organised as follows. Section 2 discusses the literature review of the paper. Section 3 discusses the methodology used, while Section 4 presents the case study of the SSA countries considered in this paper. Section 5 gives the results and discussions of this study's findings. Finally, Section 6 gives the conclusions of the paper and the future work to be done.

2. Literature review

2.1. Rural electrification in SSA countries

A multi-tier framework (MTF) for defining and measuring the electricity access level was introduced through the Sustainable Energy for All (SE4ALL) initiative, on a tiered spectrum, from Tier 0 to Tier 5 [6,7]. Tier 0 refers to a household without access to electricity, thus, relies on kerosene, candles, and torches (dry cell battery torches) for lighting services. Tier 1 refers to a household with access to an energy source to light a small lamp, charge a phone and listen to a radio, which is mainly served by a pico-solar PV system (<10 W) for at least 4 h daily. Tier 2 includes the use of general lighting, a TV and fan, which is mainly served by the SHS kits (10–100 W) for at least 4 h daily. Tier 3 includes more appliances than Tier 2 and served by the SHS kits (>200 W) for at least 8 h daily. Tiers 4 and 5 include the use of the full range of modern appliances such as the air conditioners and large refrigerators that are served by isolated micro- or mini-grid systems (800–2000 W) for 16 and 23 h daily, respectively [6,7].

Currently, more than half of the people in SSA region using the off-grid systems have at least Tier 1 (<10 W) access, that is, pico-solar PV kits [6]. SHS kits are often bigger and more powerful kits in comparison to the pico-solar PV kits (<10 W). The SHS kits are composed of a solar panel, a charge controller with a battery inside, a mobile charger, several DC ports for other appliances and a few light points [4]. The recent development in the SHS kits has enabled the possibility of connecting bigger DC appliances, such as refrigerators, fans, TVs, laptops, small-business and agro-processing machines, or even solar pumps [4]. The SHS kits reportedly supply about 90% share of the population served by off-grid systems in the SSA region, yet they represent less than 10% of the total off-grid installed capacity [4]. This achievement is mainly attributed to the innovative business models such as PAYGo, that accounted for about 90% of the SHS kits sold in 2018 [4]. The SSA region had a total newly installed capacity of about 22.77 MW through the PAYGo basis against 2.30 MW through the cash basis, with the East African region accounting for about 15.22 MW installed through the PAYGo basis in 2019 [3].

The PAYGo business model refers to an initiative that allows the customers to pay for the products via technology enabled, embedded consumer financing [5,6]. The PAYGo company typically offers the SHS kit for which the customer makes a down payment (upfront deposit), followed by regular payments for the term in the range of six months to eight years [8]. However, in most cases the repayment period is close to 24 months [8]. These payments are often made via mobile money services, though there are alternative methods such as scratch cards, mobile airtime and cash [4–6]. Under the PAYGo basis approach, the customers make an upfront deposit of about 5–15% of the SHS kit's gross cost and the rest of the payments are made daily, weekly, or monthly based on the availability to pay and the specific characteristics of the target market [4]. The purchase of SHS kits through PAYGo basis approach is reported to result in about 20–40% higher cost compared to the single cash basis approach [4]. Most of the SHS kits sold on the PAYGo basis are typically available to the customers at several classes of prices and system capability as well as payment arrangements [2].

Majority of the PAYGo approaches by the SHS actors rely on mobile money services, however, transactions via mobile money are not free [24]. These transactions are charged by the telecommunication service operators based on the country considered. Generally, these mobile money charges are estimated to add up to as much as 15–20% of the overall gross costs incurred by customers paying for the SHS kits on the PAYGo basis [16,24]. Thus, if these transaction charges were waived or reduced for social goods payments such as the off-grid systems access, it could accelerate and streamline progress by minimizing friction in payments [24]. Therefore, these costs ought to be factored into the SHS kit gross price when assessing the affordability of the households to purchase the SHS kit based on the PAYGo basis approach. Thus, this study examines the impact of the mobile money transaction charges on the PAYGo gross price of SHS kits for each of the selected SSA countries.

2.2. Key SHS actors in SSA countries

The World Bank reported that the global market for SHS kits was worth $ 1 billion in 2016 and is expected to grow to as much as $ 8 billion by 2022, attributed to the rising demand in the SSA region [4,25]. Due to the promising market for SHS kits, big European energy companies have taken the centre place in the SHS business in the SSA region. For instance, Royal Dutch Shell, a British-Dutch oil and gas giant invested funds in 2017 in an Ugandan company known as SolarNow which provides SHS kits to over 25,000 customers in Uganda and Kenya [25]. Also, Electricite de France (EDF), France's biggest power company in partnership with Bboxx, a British solar power company moved into Togo in 2018 with the aim of acquiring about 35% market share for SHS kits in Togo by 2024. In 2018, Engie, a French utility acquired Fenix International, a company that provides SHS kits in Uganda, Zambia, and other countries setting an ambitious target of reaching 20 million off-grid people by 2022 [4,25]. Also, Engie went ahead to acquire Simpa Networks and Mobisol since 2018 [6]. Table 1 shows some of the SHS actors operating in the SSA region using the PAYGo basis approach [4,6,8,16,26]. Ownership types: Rent-to-own means that the customer owns the product after all the payments have been made, while Perpetual leasing means that the customer has to pay a fee as long as he/she wants to use the energy from the kit, but never owns the kit [16].

Other international corporations such as the Japanese conglomerates have recently expressed increased interest in the off-grid sector in the SSA region [6]. For instance, Marubeni corporation took a stake in Wassha in 2018 and in Azuri Technologies in 2019, joining the SHS kits market in the SSA region on the PAYGo basis [25,27]. Marubeni corporation aims to become the largest shareholder in Azuri technologies, a British company that sells solar panels, rechargeable batteries, televisions sets, and other products [25,27]. Likewise, Mitsui & Co. and Sumitomo Corp. have also bought shares in M-Kopa Solar, a Kenyan company that sells solar panels and components, which has SHS contracts with over 800,000 households [4,25]. Also, Mitsubishi Corp. is operating in Cote d'Ivoire in partnership with EDF by renting solar panels and rechargeable batteries to households [25].

2.3. SSA countries' household energy expenditure and GHG emissions

Over 80% of the world's population without electricity access lives in the SSA region, where Nigeria, Democratic Republic of Congo and Ethiopia have the largest population without access of 89, 68 and 61 million, respectively [6]. People without grid access in the SSA region are assumed to spend a huge amount of money on energy services through lighting alternatives, mostly batteries for torch lights, kerosene, and candles [4]. For instance, off-grid households of Mauritania, Chad, Sudan, Rwanda, Kenya, Nigeria, Tanzania, Ghana and Uganda were estimated to spend about $ 150–300 annually just only on lighting and charging mobile phones [2,4]. However, those using the SHS kits are estimated to incur an annualized cost of about $ 60–250 on the same services

Table 1
Some of the companies using the PAYGo approach to sell SHS kits in SSA.

Company	Countries	Ownership Type
Azuri Technologies	Ghana, Kenya, Malawi, Rwanda, South Africa, Tanzania, Uganda, Zimbabwe, Ethiopia, Togo, Sierra Leone, Nigeria	Rent-to-own
Bboxx	Kenya, Rwanda, Uganda, Togo, Democratic Republic of Congo (DRC)	Rent-to-own
Equinox	Rwanda	Rent-to-own
FRES	Mali, South Africa, Burkina Faso, Uganda, Guinea-Bissau	Perpetual leasing
M-Kopa	Kenya, Tanzania, Uganda	Rent-to-own
Mobisol	Rwanda. Tanzania, Kenya, Ghana	Rent-to-own
Zola Electric	Tanzania, Cote d'Ivoire, Ghana, Rwanda, Nigeria	Perpetual leasing
d.light	Uganda, Kenya, Rwanda	Rent-to-own
Vitalite	Zambia	Rent-to-own
SolarNow	Uganda, Kenya	Rent-to-own
SunnyMoney	Zambia, Kenya, Malawi, Senegal, Tanzania, Kenya	Rent-to-own
Greenlight Planet	Nigeria, Kenya	Rent-to-own
PEG Africa	Ghana, Cote d'Ivoire, Senegal, Mali	Rent-to-own
Fenix International	Uganda, Zambia, Mozambique, Cote d'Ivoire, Nigeria	Rent-to-own
Waka Waka	Rwanda	Rent-to-own
ARESS	Benin	Rent-to-own
OOLU	Senegal, Mali, Burkina Faso	Rent-to-own

and estimated to save about $ 750 over the first four years by shifting to the basic SHS kit [4].

Kerosene prices are estimated to be about 46% higher in rural areas of SSA countries compared to urban areas [7,16]. Kerosene lamps, mainly the kerosene lamp with glass cover, followed by the kerosene lamp with simple wick (no cover) are the main lighting devices used in rural SSA, followed by candles [15–17]. Flash light (torches) are only used to light the way to the toilet outside or as a backup light and not as the main device to light the living room [15]. A kerosene lamp with glass cover is estimated to consume about 0.021 l/hr, while a simple wick lamp is estimated to consume about 0.018 l/hr [28]. Likewise, a kerosene lamp is estimated to emit about 2.6 kg CO_{2eq}/l [28]. Rural households are reported to use lighting devices on average 5 h daily, that is, 1 h in the morning and 4–5 h in the evening [15]. Although in the evening it starts getting dark indoors between 6:00 p.m. and 7:30 p.m., most households are reported to switch on the lighting devices around half an hour later and switch them off between 9:30 p.m. and 11:00 p.m. [15]. The monthly expenditure on lighting services varies from one community to another mainly due to the variations in the kerosene prices across the SSA region.

Households in most of the SSA countries are estimated to spend on average about $ 4–4.75 monthly on lighting alone, rising to about $ 6.25 with the inclusion of mobile phone charging costs [16]. In 2011, phone charging for the rural areas in the SSA region was averaged at about $ 0.20 per charging cycle and a customer was assumed to averagely charge their phone thrice a week [29]. Comparison between usage of kerosene lamps and torches for household lighting in SSA revealed that households spend between $ 0.017–0.035 and $ 0.03–0.06 per hour on a torch and kerosene lamp, respectively [13]. Likewise, a packet of eight candles is averagely sold at $ 0.37 in Uganda [30], while a packet of 10 candles is averagely sold at $ 1.05 in South Africa [31]. Thus, based on this background, this study examines the household's expenditure on Tier 0 energy devices taking into consideration the latest fluctuations in the kerosene prices. Also, the study assesses the possible energy expenditure savings of a household in case it acquires a SHS kit for lighting and phone charging services.

Globally, the adoption of SHS kits by households in rural areas and their impacts, mainly the energy expenditure reduction, have been investigated considering a single case study country, unlike in this study that investigates several SSA countries. For instance, in Bangladesh [32–34], India [35,36], Kenya [12,17,18], Uganda [17], Burkina Faso [19,20], Rwanda [21–23], South Africa [37], Zimbabwe [37], Namibia [38], Cote d'Ivoire [39], Benin [40], South Africa [31] and Ethiopia [41,42]. Literature reports that acquisition of the SHS kit comprising of only a basic solar lamp by a household in Kenya would result in a reduction in kerosene consumption of 1.4 L per month and a combined reduction in energy expenditure on kerosene and phone charging of about $ 1.11 per month [18]. Examining a sample of 1048 households in Kenya, study [12] established that use of kerosene for lighting reduces by 1 L per month and about $ 0.68–0.73 monthly cost reduction on kerosene for lighting. A combined reduction in energy expenditure on kerosene and phone charging of about $ 1.79 per month was reported. Likewise, it was asserted that each SHS kit yields a reduction in GHG emissions of about 36.8 kg CO_{2eq} annually [12]. Purchase of solar lantern is estimated to result in 69% elimination of kerosene use altogether and about $ 60 annual saving for the household. The savings differ depending on the previously used lighting source, that is, kerosene lamps account for higher weekly household spending compared to torches [43]. Study [17] reported that about 80% of the respondents stopped using kerosene for lighting once they acquired the SHS kit in Kenya and Uganda.

Household use of kerosene is anticipated to lead to particulate matter levels that substantially exceed the World Health Organisation's (WHO) guidelines for indoor air quality in developing countries' homes that use simple unvented combustion technologies like kerosene lamps. Although epidemiological evidence about morbidity and mortality associated with kerosene lighting is inconclusive, household air pollution is reported to cause an estimated 600,000 preventable deaths a year in Africa alone [43–45]. Laboratory and field measurements revealed that 7–9% of kerosene consumed by simple wick lamps is converted to carbonaceous particulate matter that is nearly pure black carbon emissions [46]. Studies [45,47] assert that indoor usage of kerosene stoves and wick lamps is associated with tuberculosis. Study [39] reported a reduction in the illnesses amongst the household members in Cote d'Ivoire as a result of acquiring a SHS kit. Overall, the WHO guidelines recommend that the household use of kerosene should be discouraged. Generally, a single kerosene lamp is estimated to emit about 200 kg CO_{2eq} annually [10]. Also, most candles used in the developing countries for lighting services are made from paraffin which is a heavy hydrocarbon derived from crude oil. Thus, such candles emit GHG and the burning of a single candle is estimated to release about 10.69 g CO_{2eq}/hr [48,49]. Consideration of the utilization of candles for lighting services revealed that based on the consumer behaviour in relation to various activities in a household, a single candle was reported to result in an average of 2.37 h of burning [50,51]. The burning duration of a candle varies based on the kind of candle used. This study examines the indoor

GHG emissions from the different considered combinations of the lighting devices under Tier 0 and the GH emissions avoided by households in SSA countries by acquiring SHS kits.

3. Methodology

In assessing the economic benefits of an alternative system, attention to the cost reduction in comparison to the existent systems is crucial. Likewise, for environmental benefits, the reduction in the GHG emission due to the adoption of an alternative system is very important [52]. To ascertain the economic and environmental benefits of acquiring a SHS kit by a household, key assessment parameters were selected in this study. For the economic benefits assessment, the capital cost, operation and maintenance cost were considered key parameters in the comparison of SHS kits and traditional lighting sources in the selected SSA countries. Other influential parameters such as mobile money transaction charges, structure and payment durations used by the SHS companies were also considered. For the environmental benefits assessment, the GHG emissions of the lighting source, operation duration, and number of lights were considered as the parameters in the analysis. The method used in this investigation is widely used in the literature to compare technologies, such as in studies [52–54].

A household incurs energy expenditure for both the Tier 0 energy sources and SHS kit options. Thus, the evaluation of the total household energy expenditure savings when it acquires a SHS kit to replace the Tier 0 energy sources was undertaken by using Eqs. (1) and (2), for the cash basis and PAYGo basis, respectively [28].

$$S_{cb} = (E_B - E_{F,cb}) \cdot n_L \quad (1)$$

$$S_{pb} = \left(E_B - E_{F,pb}\right) \cdot n_L \quad (2)$$

where,

$$E_{F,cb} = \frac{r \cdot C_{cb}}{1 - (1+r)^{-n_L}} \quad (3)$$

$$E_{F,pb} = \frac{r \cdot C_{pb}}{1 - (1+r)^{-n_L}} \quad (4)$$

$$C_{pb} = P_d + \sum_{i=1}^{n} (P_{p,i}) \quad (5)$$

where, S_{cb} is the total energy expenditure savings as a result of acquiring a SHS kit on the cash basis; S_{pb} is the total energy expenditure savings as a result of acquiring a SHS kit on the PAYGo basis; E_B is the average annual expenditure on Tier 0 energy sources for lighting and phone charging per household; $E_{F,cb}$ and $E_{F,pb}$ are the average annual expenditure on energy post-purchase of SHS kit for lighting and phone charging per household for cash basis and PAYGo basis approaches, respectively; r is the discount rate (in this study, $r = 3\%$) and n_L is the estimated SHS kit lifespan ($n_L = 1.5*$ warranty). C_{cb} is the cash price of the SHS kit, while C_{pb} is the PAYGo gross cost of the SHS kit. C_{pb} represents the PAYGo gross price of the SHS kit, including upfront deposit payment and all regular daily, weekly, or monthly payments, without applying a financial discount rate to this value [28]. P_d is the upfront (first) deposit; $P_{p,i}$ is the periodic payment; and i is the agreed upon period of paying (that is, $i = 1, 2, 3, \ldots, n$ is days, weeks, or months).

The average annual household energy expenditure on Tier 0 energy sources for lighting and phone charging, E_B was evaluated by using Eq. (6).

$$E_B = E_{d,l} \cdot d_y + E_p \cdot C_{p,y} \quad (6)$$

where, $E_{d,l}$ is the daily expenditure on lighting; d_y is the number of days in a year; E_p is the expenditure on phone charging per cycle; and $C_{p,y}$ is the number of phone charging cycles in a year.

To examine the average household energy expenditure on Tier 0 energy sources for lighting as well as the impact of acquiring a SHS kit on household energy expenditure, scenarios depicting the different possibly used household combinations of energy sources for lighting services under Tier 0 in SSA countries were considered, as shown in Table 2. Based on the World Health Organization, about 49% of households in the SSA region use kerosene as the primary lighting fuel and about 3% use candles, while about 41% use electricity and the rest use biomass, solar and others [14]. Also, for the purpose of normalizing the household energy consumption and expenditure under Tier 0 across the considered SSA countries, the following assumptions were made in this analysis based on the literature data:

- Every household on average uses two kinds of lighting devices daily, based on [12,13].
- Every kerosene lamp consumes on average about 0.021 l/hr, based on [28].
- Each candle at most burns for 2.5 h for every household, based on [50,51].
- Every household on average spends $ 0.026 per hour on each torch used, based on [13].
- Every household on average has one phone which is charged twice a week, thus, 104 cycles per year, based on [29].
- Every household on average uses lighting sources for about 5 h a day, based on [15].

The consideration of torch-based lighting in scenarios D and E is based on literature such as [12,13,55,56] that reported torches as a commonly used source of lighting in SSA region. In this study, torch-based lighting represents all lighting devices that use dry cell batteries as the energy carrier as also used in Ref. [12]. These torch-based lighting devices include among others, single or multiple diode hand-crafted light, LED flashlight, ready-made battery-run LED lamp. Some of these devices are discussed in Ref. [13] at length as well as their usage in some of the SSA countries for lighting purposes.

The daily household energy expenditure incurred under Tier 0 scenarios in Table 2 for lighting was evaluated by using Eq. (7) – (11).

$$E_{d,l,A} = n_{l,k} \cdot F_{l,k} \cdot C_{l,k} \cdot t_{l,d} \quad (7)$$

$$E_{d,l,B} = n_{l,k} \cdot F_{l,k} \cdot C_{l,k} \cdot t_{l,d} + n_{l,c} \cdot t_c \cdot C_{l,c} \quad (8)$$

$$E_{d,l,C} = n_{l,c} \cdot t_c \cdot C_{l,c} \quad (9)$$

$$E_{d,l,D} = n_{l,k} \cdot F_{l,k} \cdot C_{l,k} \cdot t_{l,d} + C_{l,t} \cdot t_{l,d} \quad (10)$$

$$E_{d,l,E} = n_{l,c} \cdot t_c \cdot C_{l,c} + C_{l,t} \cdot t_{l,d} \quad (11)$$

where, $E_{d,l,A}$, $E_{d,l,B}$, $E_{d,l,C}$, $E_{d,l,D}$, and $E_{d,l,E}$ are the daily household energy expenditure incurred under scenarios A, B, C, D, and E, respectively; $F_{l,k}$ is the kerosene fuel consumed by a lamp per hour; $C_{l,k}$ is the cost of kerosene per litre; $n_{l,k}$ and $n_{l,c}$ are the number of kerosene lamps and candles, respectively, for each Tier 0 scenario; t_c is the duration a candle can last ($t_c = 2.5\,hr$); $t_{l,d}$ is the daily duration of running lighting sources ($t_{l,d} = 5$); $C_{l,c}$ is the cost of each

Table 2
Scenarios of Lighting devices used by households under Tier 0 in SSA countries.

Scenarios	Lighting sources	Daily lighting usage description
Scenario A	100% kerosene-based lighting	2 kerosene lamps are used to light the household during the lighting duration
Scenario B	50% kerosene-based lighting 50% candle-based lighting	1 kerosene lamp and 2 candles are used to light the household during the lighting duration
Scenario C	100% candle-based lighting	A total of 4 candles are used to light the household during the lighting duration
Scenario D	50% kerosene-based lighting 50% torch-based lighting	1 kerosene lamp and 1 torch are used to light the household during the lighting duration
Scenario E	50% candle-based lighting 50% torch-based lighting	2 candles and 1 torch are used to light the household during the lighting duration

candle; and $C_{l,t}$ is the cost of using a torch per hour. Thus, to represent the considered scenarios, the daily household energy expenditure on lighting sources in Eq. (6), $E_{d,l} = \{E_{d,l,A}, E_{d,l,B}, E_{d,l,C}, E_{d,l,D}, E_{d,l,E}\}$.

Notably, since most SHS actors use mobile money services for payments of the SHS kits by the households, mobile money charges on the transactions apply. These charges vary from one telecommunication service provider to another as well as from one country to another. Thus, the cost of the SHS kit under the PAYGo basis approach was re-evaluated by taking into consideration the mobile money transaction charges incurred by the household. Eq. (12) was used to evaluate the SHS kit PAYGo gross price with mobile money charges included.

$$C_{pb,mm} = P_d + \sum_{i=1}^{n} \left(P_{p,i} + L_{mm,i}\right) \tag{12}$$

where, $C_{pb,mm}$ is the SHS kit PAYGo gross price by considering the mobile money charges incurred by the household; and $L_{mm,i}$ is the mobile money transaction charges incurred by the household on every PAYGo periodic payment made. To evaluate the household energy expenditure savings by acquiring a SHS kit under the PAYGo basis approach considering the mobile money charges incurred by the household, Eq. (13) was used, which is a modification of Eq. (2).

$$S_{pb,mm} = \left(E_B - E_{F,pb,mm}\right) \cdot n_L \tag{13}$$

where,

$$E_{F,pb,mm} = \frac{r \cdot C_{pb,mm}}{1 - (1 + r)^{-n_L}} \tag{14}$$

From Eqs. (5) and (12), the additional cost incurred by the household, $C_{pb,inc}$ for PAYGo basis approach was evaluated by using Eq. (15).

$$C_{pb,inc} = C_{pb,mm} - C_{pb} \tag{15}$$

When a household shifts from Tier 0 to Tier 1 and above, there is a reduction in the GHG emissions recorded for the lighting services. To evaluate the amount of GHG emissions avoided from kerosene lamps and candles by the household when it acquires a SHS kit, Eqs. (16) and (17) were used, respectively, for each of the Tier 0 scenarios.

$$GHG_{av,k} = n_{l,k} \cdot F_{l,k} \cdot t_{l,d} \cdot G_{f,k} \cdot n_{L,d} \tag{16}$$

$$GHG_{av,c} = t_c \cdot n_{l,c} \cdot G_{f,c} \cdot n_{L,d} \tag{17}$$

where, $GHG_{av,k}$ and $GHG_{av,c}$ are the total household GHG emissions avoided from kerosene lamps and candles by acquiring a SHS kit, respectively, for each of the Tier 0 scenarios; $F_{l,k}$ is the kerosene fuel burning rate (l/hr); $t_{l,d}$ is the duration for which the kerosene lighting device would have been used (hr/day); $n_{L,d}$ is the SHS lifespan in days ($n_{L,d} = 365 * n_L$); $G_{f,k}$ and $G_{f,c}$ are the emission factors for kerosene (kg CO_{2eq}/l) and candle, respectively; $n_{l,k}$ and $n_{l,c}$ are the number of kerosene lamps and candles, respectively, that could have been used daily; and t_c is the burning duration of each candle ($t_c = 2.5hr$). In this analysis, the utilization of kerosene was considered to emit about 2.6 kg CO_{2eq} for every litre used, while the burning of a candle was considered to emit about 10.69 g CO_{2eq}/hr.

The verification of this methodology was done by undertaking a sensitivity analysis. The household energy expenditure savings and GHG emissions avoided were investigated for their sensitivity to the variation in the different input parameters in the range of ±50%.

4. Case study SSA countries

The African continent has an abundance of solar energy potential estimated at about 10,000 GW, of which about 6500 GW is technically exploitable [57,58]. However, due to the different hindrances, this solar energy potential has not been effectively utilized by the African countries. Through the deployment of SHS kits in the SSA region, this solar energy potential is being utilized, especially in areas without access to the national grid network to accelerate the access to clean and affordable energy [3]. Based on the increased penetration of international companies dealing in solar energy technology in the SSA region, further utilization of solar energy in the region is anticipated. Thus, this study considered 11 countries in the SSA region that have implemented SHS kits by using PAYGo and cash payment approaches in their rural and urban areas to examine household economic and environmental benefits of SHS kits. The selected countries represent the different power pools of the SSA region, that is, Eastern Africa: Uganda, Kenya, Tanzania; Southern Africa: Zambia, Mozambique, Zimbabwe; Western Africa: Cote d'Ivoire, Sierra Leone, Nigeria; Central Africa: Cameroon, and Democratic Republic of Congo (DR Congo). Table 3 shows some of the companies and SHS kits sold in the selected SSA countries with the payment plans used by the companies in the region. The local currencies are standardized to the US dollar using the following exchange rates: $ 1 ≡ USh 3559; $ 1 ≡ ZK 22.61; $ 1 ≡ CFAF 549.80; $ 1 ≡ MT 63.26; $ 1 ≡ KSh 107.81; $ 1 ≡ TSh 2319.00; $ 1 ≡ ₦ 411.00; $ 1 ≡ Le 10,263.00; $ 1 ≡ Z$ 361.90.

Table 4 shows the cost of kerosene by litre, each candle and phone charging in rural areas of the selected SSA countries. Also, based on the PAYGo approach periodic deposits that households have to make, Table 4 shows the mobile money transaction charges incurred by the household for every deposit that is made toward the SHS kit procurement in the selected SSA countries.

The assessment of the household's expenditure on lighting and phone charging services under Tier 0 follows the defined scenarios in Table 2 and the respective prices of kerosene in Table 4 for each of the selected SSA countries. Likewise, the assessment of household

Table 3
SHS kits sold in the selected SSA countries and the payment plans used by companies.

Company	Countries	Periodic Instalments	SHS kit details	Total cost, payment duration, warrant	Source
Fenix Int'l	Uganda	Deposit: $ 13.77 Daily: $ 0.22 Monthly: $ 6.74	Fenix Power 3+: 10 W solar panel; 1 control unit; 3 LED lights; 1 phone charging cable; 1 radio; 1 remote	Cash: $ 176.75 PAYGo: $ 216.09 Duration: 30 months Warrant: 3 years	[59]
Fenix Int'l	Zambia	Deposit: $ 13.71 Daily: $ 0.19 Monthly: $ 5.78	Fenix Power 3+: 10 W solar panel; 1 control unit; 3 LED lights; 1 phone charging cable; 1 radio; 1 remote	Cash: $ 115.58 PAYGo: $ 152.48 Duration: 24 months Warrant: 3 years	[59]
Fenix Int'l	Cote d'Ivoire	Deposit: $ 21.83 Daily: $ 0.35 Monthly: $ 10.37	Fenix Power 3+: 10 W solar panel; 1 control unit; 3 LED lights; 1 phone charging cable; 1 radio; 1 remote	Cash: $ 198.26 PAYGo: $ 270.65 Duration: 24 months Warrant: 3 years	[59]
Fenix Int'l	Mozambique	Deposit: $ 18.96 Daily: $ 0.32 Monthly: $ 9.48	Fenix Power 3+: 10 W solar panel; 1 control unit; 3 LED lights; 1 phone charging cable; 1 radio; 1 remote	Cash: $ 179.32 PAYGo: $ 303.35 Duration: 30 months Warrant: 3 years	[59]
Fenix Int'l	Nigeria	Deposit: $ 17.06 Daily: $ 0.34 Monthly: $ 10.23	Fenix Power 3+: 10 W solar panel; 1 control unit; 3 LED lights; 1 phone charging cable; 1 radio; 1 remote	Cash: $ 139.49 PAYGo: $ 221.66 Duration: 20 months Warrant: 3 years	[60]
Azuri	Kenya	Deposit: $ 0 Weekly: $ 3.15 Monthly: $ 12.61	Quad: 10 W solar panel; 1 control unit; 4 LED lights; 1 phone charging cable; 1 radio	Cash: $ 227.25 PAYGo: $ 258.60 Duration: 82 weeks Warrant: 3 years	[61]
Easy Solar	Sierra Leonne	Deposit: $ 24.36 Weekly: $ 2.44	Bundle Plus: 12 W solar panel; 1 battery; 4 LED lights; 1 phone charging cable; 1 radio; 1 torch	Cash: $ 154.94 PAYGo: $ 203.66 Duration: 74 weeks Warrant: 2 years	[62]
Zola Electric	Tanzania	Deposit: $ 13.76 Monthly: $ 10.78	Zola Lights: 12 W solar panel; 1 control unit; 3 LED lights; 1 phone charging cable; 1 radio	Cash: $ 130.62 PAYGo: $ 153.90 Duration: 13 months Warrant: 3 years	[63]
Zonful Energy	Zimbabwe	Deposit: $ 65 Monthly: $ 11	Sun King Home 120: 12 W solar panel; 1 battery; 4 LED lights; 1 phone charging cable	Cash: $ 190 PAYGo: $ 219 Duration: 14 months Warrant: 4 years	[64]
UpOwa	Cameroon	Deposit: $ 23.51 Monthly: $ 11.76	Flash: 12 W solar panel; 1 control unit; 4 LED lights; 1 phone charging cable	Cash: $ 208.01 PAYGo: $ 235.19 Duration: 18 months Warrant: 2 years	[65]
Altech Group	Democratic Republic of Congo	Deposit: $ 20.00 Monthly: $ 10.00	Altech-M600-Omni: 12 W solar panel; 1 control unit; 4 LED lights; 1 phone charging cable; 1 radio; 1 torch	Cash: $ 198.36 PAYGo: $ 260 Duration: 24 months Warrant: 2 years	[66]

Table 4
Cost of kerosene, candles, phone charging and mobile money transaction charges incurred for each PAYGo approach deposit made by the household for the SHS kit.

Country	Kerosene cost ($/litre) [67]	Candle cost ($/candle)	Phone charging cost ($/cycle)	Mobile money transaction			
				Period	PAYGo deposits ($)	Telecommunication service provider	Mobile money charges ($)
Uganda	0.922	0.046	0.112	Monthly	6.74	MTN [68]	0.183
Kenya	0.928	0.049	0.128	Weekly	3.15	Safaricom (M-Pesa) [69]	0.056
Tanzania	0.844	0.051	0.130	Monthly	10.78	Vodacom (M-Pesa) [70]	0.164
Zambia	0.679	0.055	0.108	Monthly	5.78	MTN [68]	0.011
Mozambique	0.683	0.044	0.126	Monthly	9.48	Vodacom (M-Pesa) [71]	0.474
Zimbabwe	1.083	0.038	0.135	Monthly	11.00	Econet Wireless [72]	0.204
Cote d'Ivoire	1.010	0.048	0.124	Monthly	10.37	Orange [73]	0.364
Sierra Leone	0.829	0.051	0.118	Weekly	2.44	Africell [74]	0.078
Nigeria	0.886	0.053	0.105	Monthly	10.23	MTN [75]	0.243
Cameroon	1.202	0.038	0.129	Monthly	11.76	MTN [68]	0.118
Democratic republic of Congo	1.014	0.045	0.132	Monthly	10.00	Airtel [76]	0.273

energy expenditure on lighting and phone charging services under Tier 1 follows the SHS kit costs in Table 3 and the additional mobile money transaction charges incurred in Table 4 for each of the selected SSA countries. The assessment results of the household economic and environmental benefits of acquiring a SHS kit in the selected SSA countries are presented with discussions in Section 5. It is worth noting that the selection of the SHS companies in the selected SSA countries was entirely based on accessibility to the relevant data for this study. Although several companies, both local and international operate in these countries, some of the data relevant to this study was not accessible in the public domain. Inaccessibility of data also limited the pool of SHS kits suppliers considered in the analysis. Furthermore, although the considered terms and conditions for acquiring a SHS kit shown in Table 3 span different time settings of publishing, they are the latest versions available and used by the respective considered SHS companies in the selected SSA countries at the time of undertaking this analysis.

As revealed in Table 3, the warranty period ranges between 2 and 4 years for the SHS kits sold in the selected SSA countries. Disparity in the warranty offered by the SHS kits suppliers could be attributed to the recent improvement in the SHS efficiency and lifespan of solar PV system components [6]. With the durability assurance of the components, several SHS kit supplies have improved their warranty period from 2 years to as high as 4 years as exhibited in Table 3. Offering a longer warranty period is intended to build the clients' confidence in the supplier's SHS kits. However, although the longer warranty period might be intended to attract more clients by the supplier, the opposite could as well happen, particularly in the SSA region. Since the poverty levels in the SSA countries are very high, it is more likely that customers would be attracted by low-priced SHS kits that are not durable over high-priced SHS kits with guaranteed durability.

5. Results and discussion

5.1. Household energy expenditure for Tier 0

Following the set Tier 0 scenarios in Table 2, Eq. (6) – (11) were used to evaluate the daily household energy expenditure on lighting services using the data in Table 4 for kerosene and candles prices of the selected SSA countries as well as the set assumptions. The Daily household energy expenditure on lighting services was applied to Eq. (6) along with the phone charging costs presented in Table 4 to evaluate the annual household energy expenditure on lighting and phone charging services under Tier 0 scenarios. Fig. 1 shows the annual household energy expenditure for selected SSA countries under each Tier 0 scenario.

Fig. 1 reveals that the annual household energy expenditure for the considered Tier 0 scenarios has different patterns in the selected SSA countries. For instance, in Uganda, Zimbabwe, Cote d'Ivoire, Cameroon, and DR Congo, households under scenario D would record the highest annual energy expenditure, while in Kenya, Tanzania, Zambia, Mozambique, Sierra Leone, and Nigeria, households under scenario E would record the highest annual energy expenditure. Generally, in all the selected SSA countries, households under scenarios D and E record the highest annual energy expenditure on Tier 0 energy sources. This is attributed to the fact that these scenarios use torches as one of the main lighting devices, whose hourly operational cost is higher than that of kerosene lamps and candles.

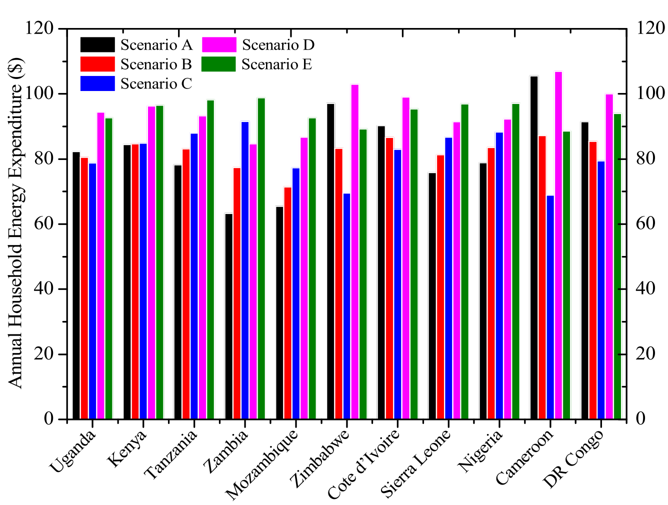

Fig. 1. Annual household energy expenditure for Tier 0 scenarios in the selected SSA countries.

Fig. 1 also reveals that in Kenya, Tanzania, Zambia, Mozambique, Sierra Leone, and Nigeria, households under scenario A would record the least annual energy expenditure, while in Uganda, Zimbabwe, Cote d'Ivoire, Cameroon, and DR Congo, households under scenario C would record the least annual energy expenditure. Furthermore, Fig. 1 also reveals that in all the selected SSA countries, scenario B is the second placed scenario with the least annual energy expenditure incurred by households. The variability in the annual household energy expenditure for each of the scenarios in the selected SSA countries is attributed to the disparities in the prices of the Tier 0 energy sources in these countries. It is worth noting that even within the country, the prices of kerosene, candles, and dry cell batteries for torches vary from one municipality, district, province, or state to another. Generally, the prices fluctuate over time depending on different factors that influence the local economy of the country. This agrees with the assertion that kerosene is more expensive in rural areas of Africa compared to urban areas [7,16].

Fig. 1 also agrees with the assertion in Refs. [14–17] that most SSA households rely on kerosene lamps for lighting services, followed by candles. This could be supported by the fact exhibited in Fig. 1 that scenarios A, B and C that are dominated by kerosene and candles are the least expensive for the households in SSA countries. Also, as asserted in Ref. [15] the torches are mainly used as the backup source of light because they are expensive for the households to rely on as the main source of light as shown Fig. 1 for scenarios D and E. Overall, based on Fig. 1, the household would record an annual energy expenditure in the range of $ 63.28–105.55, $ 71.40–87.22, $ 68.90–91.53, $ 84.70–106.93, and $ 88.61–98.83 for the Tier 0 scenarios A, B, C, D, and E, respectively, across the selected SSA countries. Thus, for all the Tier 0 scenarios, households across the selected SSA countries would incur an annual energy expenditure in the range of $ 63.28–106.93 and an average of $ 87.31 on lighting and phone charging, which is close to the average value of $ 75 reported in 2017 [16]. Thus, it can be deduced that the average annual household energy expenditure on lighting and phone charging services under Tier 0 in SSA countries has increased from about $ 75 in 2017 to about $ 87.31 in 2021.

5.2. Household energy expenditure for Tier 1

The SHS actors in SSA countries offer the kits to the households based on two payment plans as exhibited in Table 3. Although the same SHS kit components are considered, these payment approaches amount to different SHS kit gross prices offered by the SHS actors. From Table 3, the difference in the SHS kit gross price between the cash basis approach and the PAYGo basis approach was evaluated. The percentage difference was evaluated by using cash basis approach as the reference price for the SHS kit for each of the selected SSA countries. Fig. 2 shows the percentage difference in the gross prices of the SHS kits for the selected SSA countries.

Fig. 2 reveals that in all the selected countries, a household would obviously pay more for the SHS kit when they opt to procure it on the PAYGo basis approach other than on the cash basis approach. Across the selected SSA countries, a household would pay about 13.07–69.17% more under the PAYGo basis approach, which closely agrees with the reported range of 20–40% in Ref. [4].

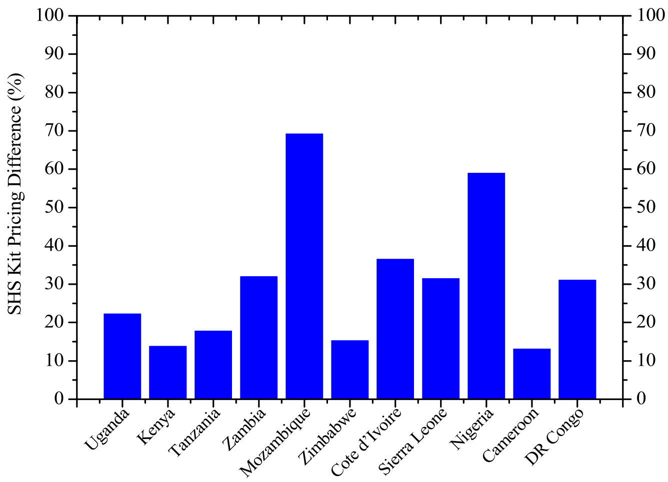

Fig. 2. Percentage difference in the cost of SHS kits in selected SSA countries.

Fig. 2 reveals that a household in Cameroon would pay the least increment in the SHS kit gross price of about 13.07%, followed by Kenya at 13.80%, while a household in Mozambique would pay the highest increment in the SHS kit gross price of about 69.17%, followed by Nigeria at 58.97%. The high difference in SHS kit gross prices exhibited in Fig. 2 for the case of Mozambique and Nigeria could be interpreted as an indirect approach used by the SHS actors to discourage the households from opting for the PAYGo basis approach but rather settle for the cash basis approach, or because of monopoly over the SHS kits market in these countries. This could also be based on the challenges the SHS actors encounter in recovering the SHS kit prices through mobile money services and field agents under the PAYGo basis approach, which they would prefer to avoid in their business operations due to the specific characteristics of the target market [4].

By considering the SHS kits in Table 3 for the selected SSA countries, Eq. (3) was used to evaluate the average annual household energy expenditure on the SHS kit on the cash basis approach, while Eqs. (4) and (5) were used to evaluate the average annual household energy expenditure on the SHS kit on the PAYGo basis approach. Fig. 3 shows the annualized household energy expenditure on the SHS kit for both the cash basis approach and PAYGo basis approach for the selected SSA countries.

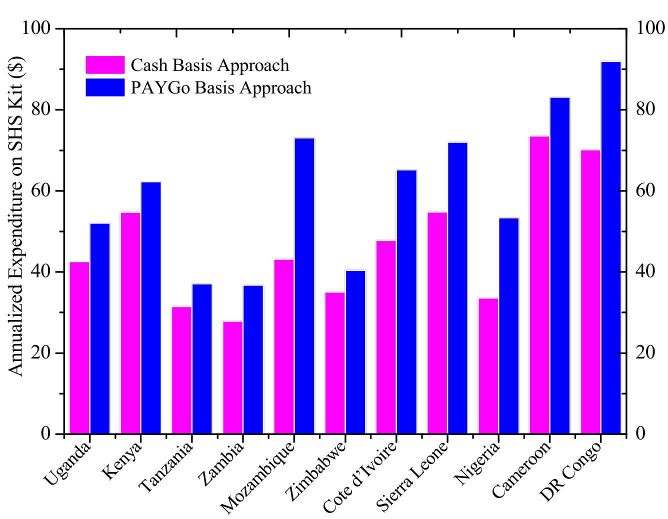

Fig. 3. Annualized household energy expenditure on a SHS kit for selected SSA countries.

Fig. 3 reveal that households in countries such as Mozambique, Cote d'Ivoire, Sierra Leone, Nigeria, and DR Congo record the highest disparity in the annualized energy expenditure on a SHS kit between cash and PAYGo payment approaches. On the other hand, countries such as Uganda, Kenya, Tanzania, Zambia, Zimbabwe, and Cameroon record the least disparity in the annualized energy expenditure on a SHS kit between cash and PAYGo payment approaches. As asserted in Refs. [3,5,6], the PAYGo basis approach is highly developed in the Eastern African countries, followed by the Southern African countries, while still breaking through in the other regions of the continent. Thus, the disparity in the SHS kit payment approaches could be attributed to the level of penetration and adoption of the PAYGo basis approach in some of these countries. As exhibited in Table 1, it is worth noting that there are several other SHS actors in the selected SSA countries which also offer different prices for the SHS kits for the two payment approaches and warranties. Therefore, to conclusively examine the disparities in the SHS kits' prices, it is appropriate to consider all the SHS actors in the country and the factors taken into consideration when setting the prices. This aspect was not investigated in this study because it was beyond the study's scope. Overall, the households in the selected SSA countries would incur an annualized energy expenditure in the range of $ 27.84–73.54 and $ 36.73–91.92 for cash basis and PAYGo basis approaches, respectively. These ranges closely agree with the $ 60–250 range for annualized energy expenditure on the SHS kits reported in Ref. [4], an indication that the prices of the SHS kits in SSA have reduced since 2019 when study [4] was published.

By applying the findings of Tier 0 annual household energy expenditure on lighting and phone charging in Fig. 1 and Tier 1 annualized household energy expenditure on the SHS kit in Fig. 3 to Eqs. (2) and (3), respectively, the household energy expenditure savings were evaluated. Table 5 shows the evaluated household energy expenditure savings on lighting and phone charging over the lifespan of the acquired SHS kit in the selected SSA countries. The values in parentheses in Table 5 indicate cases where the household could instead incur more energy expenditure under Tier 1 than what is spent on lighting and phone charging under Tier 0.

Table 5 reveals that for all scenarios, a household in any of the selected SSA countries would record energy expenditure savings by acquiring a SHS kit through the cash basis approach except in Cameroon under scenario C, which is attributed to the low cost of using candles in Cameroon (shown in Table 4) in comparison to using a SHS kit. For the acquisition of a SHS kit through the PAYGo basis approach, households could record energy expenditure savings in all the selected countries, except for Mozambique, Cameroon, and DR Congo where households could incur more energy expenditure under scenarios A & B, scenario C, and scenarios A, B & C, respectively. The more energy expenditure incurred by households under the PAYGo basis approach could be attributed to the fact that the SHS kits are very expensive in comparison to relying on the Tier 0 energy sources in these countries. Thus, if the agenda for adopting the PAYGo payment plan is to attract households to shift to clean energy systems, then, there is need for a revision in the PAYGo basis approach prices offered to households in some of the SSA countries. This should be done to exhibit the economic benefits of adopting SHS kits by a household through energy expenditure savings.

Using the annual household energy expenditure for Tier 0 in Fig. 1 and the lifespan of the SHS kits in each of the selected SSA countries, the household energy expenditure savings in Table 5 were evaluated as percentages for each of the investigated household energy usage Tier 0 scenarios. Fig. 4 shows the percentages of the household energy expenditure savings when it acquires a SHS kit through cash basis approach and PAYGo basis approach for the selected SSA countries.

Table 5
Annual household energy expenditure savings on lighting and phone charging.

Country	Scenario A ($)		Scenario B ($)		Scenario C ($)		Scenario D ($)		Scenario E ($)	
	Cash Basis	PAYGo Basis	Cash Basis	PAYGo Basis	Cash Basis	PAYGo Basis	Cash Basis	PAYGo Basis	Cash Basis	PAYGo Basis
Uganda	178.85	136.21	170.95	128.31	163.05	120.41	233.37	190.73	225.47	182.83
Kenya	133.67	99.69	134.59	100.61	135.51	101.53	187.15	153.17	188.07	154.09
Tanzania	210.38	185.14	232.35	207.12	254.33	229.09	278.34	253.11	300.32	275.08
Zambia	159.47	119.47	223.04	183.05	286.61	246.62	255.89	215.90	319.46	279.47
Mozambique	100.18	(34.26)	126.93	(7.51)	153.68	19.24	195.92	61.48	222.66	88.23
Zimbabwe	371.87	339.75	289.28	257.16	206.68	174.56	407.54	375.42	324.94	292.82
Cote d'Ivoire	191.51	113.04	175.00	96.54	158.49	80.03	230.85	152.38	214.34	135.87
Sierra Leone	63.12	11.45	79.49	27.82	95.87	44.20	110.15	58.48	126.53	74.86
Nigeria	203.55	114.48	224.85	135.79	246.15	157.09	264.27	175.21	285.57	196.51
Cameroon	96.03	67.21	41.05	12.23	(13.93)	(42.75)	100.18	71.36	45.20	16.38
DR Congo	63.97	(1.40)	45.94	(19.44)	27.91	(37.47)	89.74	24.37	71.71	6.33

Fig. 4 a) reveals that with the exception of Mozambique and DR Congo where a household could incur more energy expenditure of about 11.63% and 0.51%, respectively, for the PAYGo basis approach, households in all the other selected SSA countries would record energy expenditure savings in the range of 23.32–63.86% and 5.03–58.35% for the cash basis and PAYGo Basis approaches, respectively, for scenario A. Fig. 4 a) shows that a household in Zimbabwe records the highest energy expenditure savings of about 63.86% and 58.35% for cash basis and PAYGo basis approaches, respectively, while DR Congo and Sierra Leone record the least energy expenditure savings of about 23.32% for the cash basis approach and 5.03% for the PAYGo basis approach, respectively. The average household energy expenditure savings in selected SSA countries are about 43.91% and 26.37% for the cash basis and PAYGo basis approaches, respectively, for scenario A.

Fig. 4 b) reveals that with the exception of Mozambique and DR Congo where a household could incur more energy expenditure of about 2.34% and 7.58%, respectively, for the PAYGo basis approach, households in all the other selected SSA countries would record energy expenditure savings in the range of 15.69–64.03% and 4.67–55.39% for the cash basis and PAYGo Basis approaches, respectively, for scenario B. Fig. 4 b) shows that a household in Zambia and Tanzania record the highest energy expenditure savings of about 64.03% for cash basis approach and 55.39% for PAYGo basis approach, while Cameroon records the least energy expenditure savings of about 15.69% and 4.67% for cash basis and PAYGo basis approaches, respectively. The average household energy expenditure savings in selected SSA countries are about 43.36% and 26.20% for the cash basis and PAYGo basis approaches, respectively, for scenario B.

Fig. 4 c) reveals that with the exception of Cameroon where a household could incur more energy expenditure of about 6.74% and 20.68%, for the cash basis and PAYGo basis approaches, respectively, and DR Congo where a household could incur more energy expenditure of about 15.72% for the PAYGo basis approach, households in all the other selected SSA countries would record energy expenditure savings in the range of 11.71–69.58% and 5.53–59.87% for the cash basis and PAYGo Basis approaches, respectively, for scenario C. Fig. 4 c) shows that a household in Zambia records the highest energy expenditure savings of about 69.58% and 59.87% for the cash basis and PAYGo basis approaches, respectively, while DR Congo records the least energy expenditure savings of about 11.71% for the cash basis approach and Mozambique records the least energy expenditure savings of about 5.53% for the PAYGo basis approach. The average household energy expenditure savings in selected SSA countries are 41.38% and 24.29% for the cash basis and PAYGo basis approaches, respectively, for scenario C.

Fig. 4 d) reveals that households in all the selected SSA countries would record energy expenditure savings in the range of 29.90–67.13% and 8.12–60.75% for the cash basis and PAYGo basis approaches, respectively, for scenario D. Fig. 4 d) shows that a household in Zambia and Zimbabwe record the highest energy expenditure savings of about 67.13% for the cash basis approach and 60.75% for the PAYGo basis approach, respectively, while DR Congo records the least energy expenditure savings of about 29.90% and 8.12% for the cash basis and PAYGo basis approaches, respectively. The average household energy expenditure savings in selected SSA countries are about 51.30% and 36.51% for the cash basis and PAYGo basis approaches, respectively, for scenario D.

Fig. 4 e) reveals that households in all the selected SSA countries would record energy expenditure savings in the range of 17.01–71.83% and 6.24–62.84% for the cash basis and PAYGo basis approaches, respectively, for scenario E. Fig. 4 e) shows that a household in Zambia records the highest energy expenditure savings of about 71.83% and 62.84% for the cash basis and PAYGo basis approaches, respectively, while Cameroon records the least energy expenditure savings of about 17.01% for the cash basis approach and DR Congo records the least energy expenditure savings of about 2.24% for the PAYGo basis approach. The average household energy expenditure savings in selected SSA countries are about 50.23% and 35.55% for the cash basis and PAYGo basis approaches, respectively, for scenario E.

Overall, considering all the scenarios across the selected SSA countries, the average household energy expenditure savings recorded could be about 46.04% and 29.79% by acquiring a SHS kit on the cash basis and PAYGo basis approaches, respectively. Thus, it can generally be asserted that a household would record significant energy expenditure savings by transitioning from Tier 0 to Tier 1 in the SSA region.

5.3. Mobile money charges analysis

All the considered SHS actors in the selected SSA countries use mobile money services for the households to pay their periodic PAYGo instalments. The mobile money transaction charges along with the upfront deposits in Table 3 were used in Eq. (12) for each of the selected SSA countries to assess the exact energy expenditure incurred by the households on the PAYGo basis approach. Fig. 5 shows the increment in the SHS kit PAYGo gross price due to the incorporation of the mobile money transaction charges incurred by the households evaluated by using Eq. (15). Also, considering that kerosene-based lighting devices are the mainly used sources of light in the SSA region, Tier 0 scenario A was used to evaluate the total household energy expenditure savings by acquiring a SHS kit on PAYGo basis approach, taking into consideration the mobile money transaction charges incurred. Fig. 4 shows the reduction in the household energy expenditure savings when mobile money charges are considered for the PAYGo basis approach.

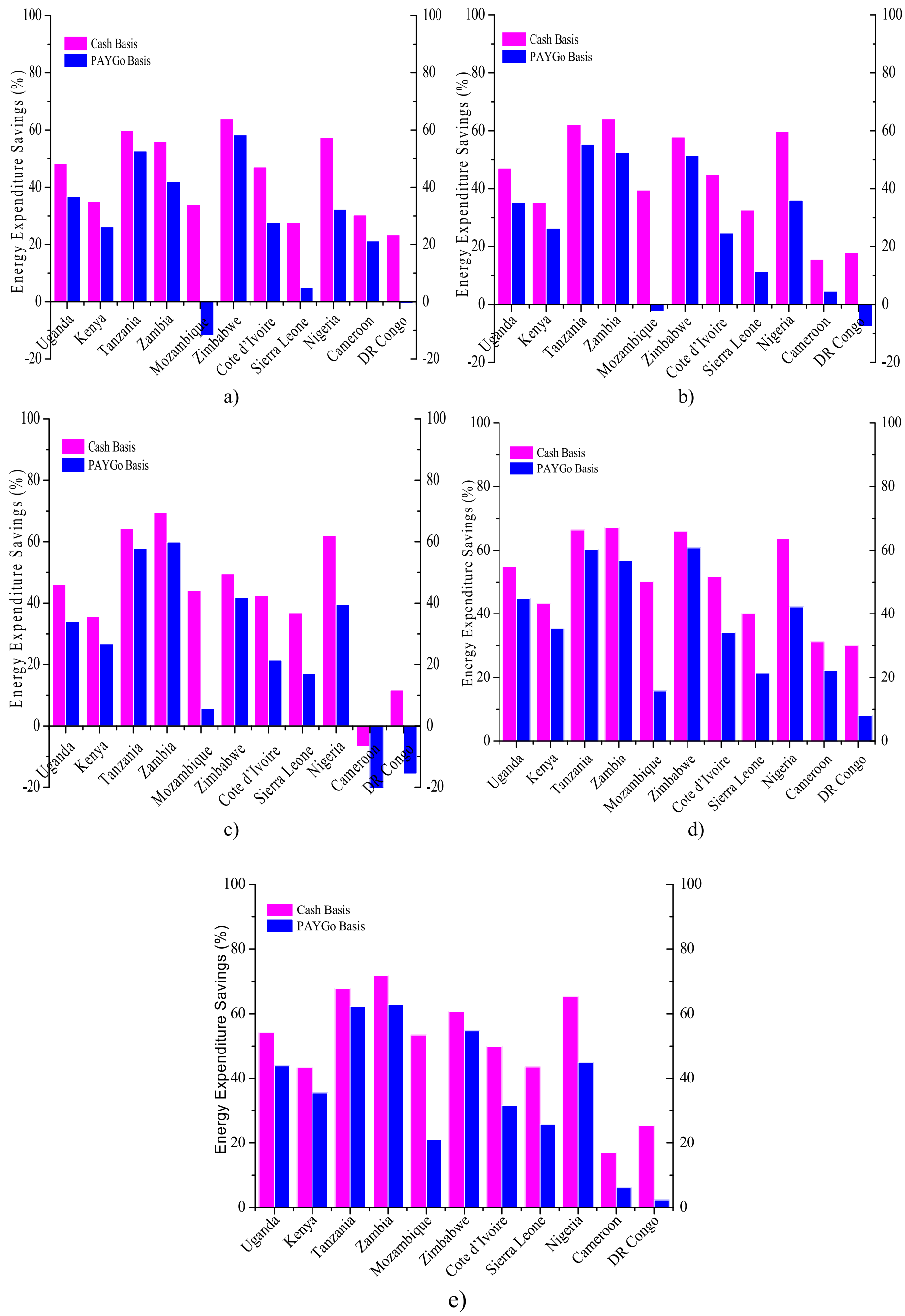

Fig. 4. Household energy expenditure savings by acquiring a SHS kit expressed as a percentage for each of the selected SSA countries: a) Scenario A; b) Scenario B; c) Scenario C; d) Scenario D; and e) Scenario E.

Fig. 5 reveals that the consideration of the mobile money transaction charges incurred by the households on the PAYGo basis approach slightly increases the gross price of the SHS kit. Fig. 5 shows that the SHS kit PAYGo gross price increment is in the range of $ 0.214–14.23 for the considered SSA countries. The households in Mozambique incur the highest gross price increment of about $ 14.230, which could be attributed to the high mobile money charges of $ 0.474 (shown in Table 4) incurred on every transaction made in comparison to the other countries. Likewise, the households in Zambia incur the least increment of about $ 0.214, which could be attributed to the low mobile money charges of $ 0.011 (shown in Table 4) incurred on every transaction made in comparison to the other countries. Therefore, this is an indication that besides the PAYGo periodic payments the household has to pay, the household also has to incur the mobile money transaction charges on every transaction. Notably, unlike the fixed PAYGo periodic deposits that the household has to make over time, the mobile money transaction charges fluctuate based on the telecommunication service provider. The revisions in the mobile money charges by service providers could be in the form of an increment or decrement. Therefore, the households are always exposed to such mobile money charges regardless of the PAYGo payment plan used by the SHS providing companies.

The results in Fig. 5 contradict the reported impact of mobile money charges on the cost of SHS kits in SSA countries in Refs. [16,24]. Studies [16,24] reported that mobile money charges

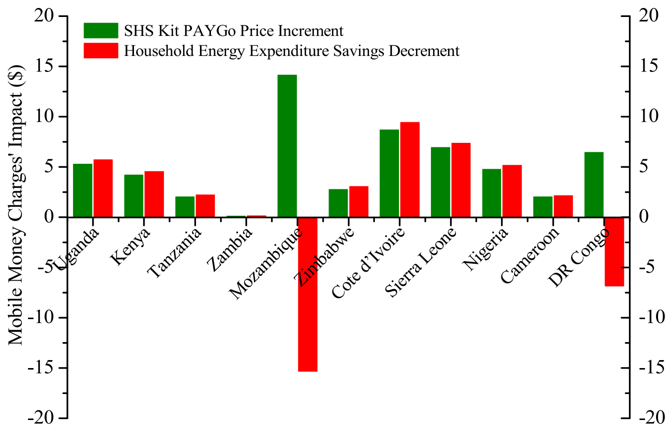

Fig. 5. Impact of considering the mobile money transaction charges on the household energy expenditure for selected SSA countries.

are estimated to add up to as much as 15–20% of the overall gross costs incurred by households paying for the SHS kits on the PAYGo basis. However, based on this study's findings, the increment in the SHS kit gross price due to mobile money charges is in the range of $ 0.214–14.23 (as shown in Fig. 5) across the selected SSA countries, which translates to about 0.14–4.69% increment in the kit's gross price. This low impact of mobile money charges on the PAYGo gross price of the SHS kits could be attributed to the decrement modifications in the mobile money transaction charges in the last four years since studies [16,24] were published.

Furthermore, Fig. 5 shows that consideration of the mobile money transaction charges incurred by the households on the PAYGo basis approach decreases the annual household energy expenditure savings in Table 5. Fig. 5 reveals that mobile money transaction charges reduce the annual household energy expenditure savings in the range of $ 0.232–9.534 for countries such as Uganda, Kenya, Tanzania, Zambia, Zimbabwe, cote d'Ivoire, Sierra Leone, Nigeria, and Cameroon, while for countries such as Mozambique and DR Congo, mobile money transaction charges actually increase the annual household energy expenditure by $ 15.424 and $ 6.949, respectively, in comparison to the scenario A expenditure savings in Table 5.

5.4. Sensitivity analysis of household energy expenditure

To assess the robustness of this study's investigation on the household energy expenditure in SSA countries, a sensitivity analysis was undertaken. In this subsection, the annual household energy expenditure was investigated for sensitivity to the variation in the daily household energy expenditure on lighting services and on each phone charging cycle for scenario A considering the case of Uganda. Also, annualized SHS kit cash price and PAYGo price were investigated for sensitivity to the variation in the SHS kit lifespan, discount rate, cash price and PAYGo price for the case of Uganda. Finally, the annualized PAYGo plus mobile money cost was investigated for sensitivity to the variation in the PAYGo periodic instalment amount, number of PAYGo payment cycles, mobile money transaction charges, SHS kit lifespan, and a case where the PAYGo periodic instalment amount and number of PAYGo payment cycles vary in opposite directions (that is, one increasing while the other decreasing) for the case of Uganda. The sensitivity analysis results of the household energy expenditure are shown in Fig. 6.

Fig. 6 a) reveals that the annual household energy expenditure is very sensitive to the daily household expenditure on lighting services. Thus, in case the household wants to minimize its annual energy expenditures, they could consider using a combination of lighting devices that is cheaper as well as reducing the daily lighting duration if possible. Fig. 6 a) also shows that the annual household energy expenditure has a slight sensitivity to the variation in the phone charging cost per cycle. This could be because the rural households often use low technology phones, mainly for making calls and texting, which do not necessitate daily charging; hence, their phones are mostly charged 2–3 times a week and the cost incurred is relatively lower than that incurred on lighting the household for a week as [16] also reported on these costs.

Fig. 6b) and c), and d) reveal that the annualized SHS kit cost for cash basis, PAYGo basis, and PAYGo & mobile money, respectively, are highly sensitive to the variation in the SHS kit lifespan. The annualized costs inversely change as the SHS kit lifespan varies. This indicates that if the considered SHS kit has a longer lifespan, the household would incur less annual expenditure. Currently, most of the SHS kits in the SSA region have a useful life of about four years [77]. Thus, as the SHS kits lifespan improves, households will be incurring lesser costs on the kits annually than they currently incur on the SHS kits. Fig. 6 b), and c) also show that the annualized SHS kit expenditure increases with the cash price and PAYGo price, respectively, while slightly sensitive to the variation in the discount rate used. Therefore, SHS actors ought to be considerate while setting the SHS kit prices. To ensure minimal annual household expenditure on the SHS kit, expensive kits should as well have a longer lifespan to guarantee that the household energy expenditure of Tier 1 is lesser than that of Tier 0.

Fig. 6 d) reveals that the SHS kit annualized expenditure is very sensitive to the variation in the PAYGo periodic instalment amount and the number of PAYGo payment cycles. Fig. 6 d) also shows that the variation in the PAYGo periodic instalment amount and number of PAYGo payment cycles in the opposite directions would result in a reduction in the annualized expenditure incurred by a household. Therefore, this indicates that other than having high instalments made in a shorter period of time, SHS actors could consider having lower instalments made for a longer period of time to minimize the annual household energy expenditure incurred.

5.5. GHG emissions avoided

The use of kerosene and candles involves GHG emissions to the atmosphere, while the utilization of solar PV systems does not involve emissions [78]. Thus, in this analysis, the Tier 0 scenarios were considered to evaluate the possible GHG emissions avoided by the household when it acquires a SHS kit in the selected SSA countries. Eqs. (16) and (17) were used to evaluate the GHG emissions released from the use of kerosene and candles, respectively, for each of the Tier 0 scenarios. Fig. 7 shows the total household GHG emissions avoided over the lifespan of the acquired SHS kit in the selected SSA countries.

Fig. 7 reveals that the households under Tier 0 scenario A would record the highest amount of GHG emissions avoided, followed by scenarios B and D. This is mainly attributed to the high GHG emission factor of kerosene of 2.6 kg CO_{2eq}/l used, an equivalent of 54.6 g CO_{2eq}/hr, compared to that of candles of 10.69 g CO_{2eq}/hr. Thus, significant GHG emissions avoided could be recorded in households that rely on kerosene lamps for their lighting services. Scenario C records the second least GHG emissions avoided, while scenario E records the least GHG emissions avoided. This is because the torches do not release any emissions during their usage. However, it should be noted that the disposal of the dry cell batteries has negative environmental impacts, such as contaminating the soil and water when the disposed dry cells leach toxic substances like lead metal into the ground [13]. Therefore, although the torches might not emit any GHG during their usage time, the

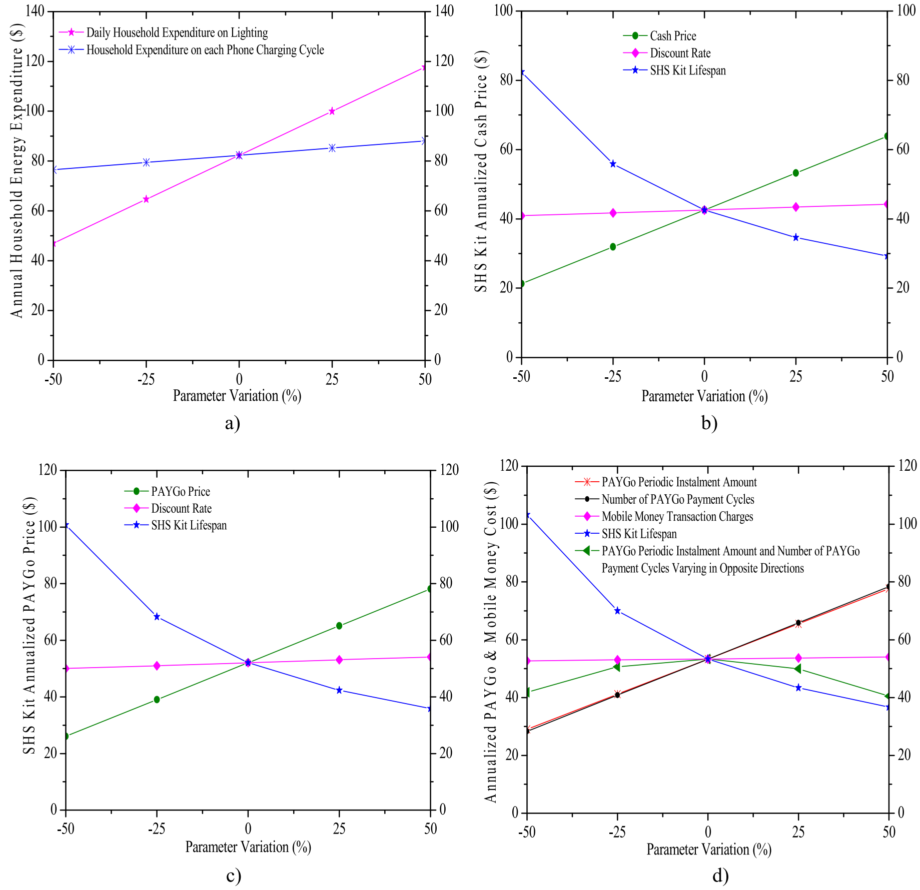

Fig. 6. Sensitivity analysis of household energy expenditure for the case of Uganda: a) Annual household energy expenditure for scenario A; b) Annualized SHS kit Cash basis expenditure; c) Annualized SHS kit PAYGo basis expenditure; d) Annualized SHS kit PAYGo including mobile money charges expenditure.

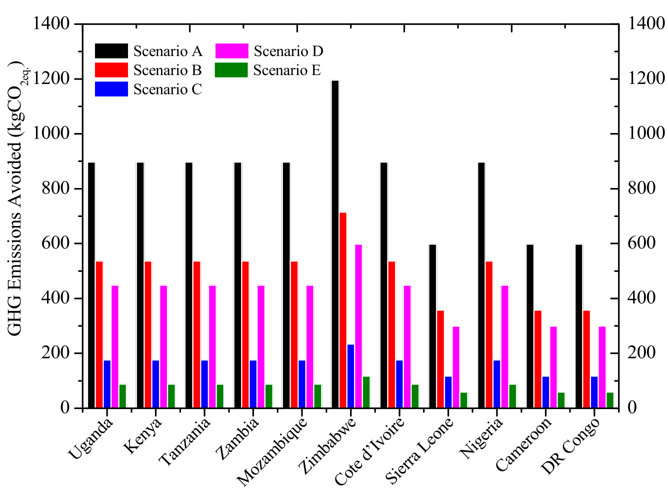

Fig. 7. Household GHG emissions avoided by acquiring a SHS kit over its lifespan in selected SSA countries.

disposal of the dry cell batteries is a point of concern that also needs to be investigated. This aspect is beyond the scope of this study and it was excluded in analysis undertaken.

Fig. 7 also reveals that the amount of household GHG emissions avoided is highly dependent on the lifespan of the acquired SHS kit. For instance, a household in Zimbabwe records the highest GHG emissions avoided because the SHS kit acquired has a 4 years warranty, which by using the lifespan estimate of 1.5 multiplied by warranty period in Ref. [28], is about 6 years. On the other hand, households in countries like Sierra Leone, Cameroon and DR Congo record the least GHG emissions avoided because the SHS kits acquired have a 2-year warranty, hence a lifespan of about 3 years. Thus, to further examine the robustness in accessing the household GHG emissions avoided by acquiring a SHS kit, a sensitivity analysis was undertaken.

Averagely, from Fig. 7, by considering the household GHG emissions avoided by acquiring a SHS kit on an annual basis, the household would record annual GHG emissions avoided of about 199.29 kg CO_{2eq}, 119.15 kg CO_{2eq}, 39.02 kg CO_{2eq}, 99.65 kg CO_{2eq}, and 19.51 kg CO_{2eq} for a transition from scenarios A, B, C, D, and E, respectively, to SHS kit for lighting services. Therefore, for all the Tier 0 scenarios, the households in the selected SSA countries would record an annual GHG emissions avoided in the range of 19.51–199.29 kg CO_{2eq} by acquiring a SHS kit for lighting services.

Furthermore, considering the possibility of a household shifting from one Tier 0 scenario to another, it could as well record some annual GHG emissions avoided. Thus, the annual household GHG emissions avoided by shifting from one Tier 0 scenario to another was evaluated. The annual household GHG emissions avoided were expressed as a percentage of the GHG emissions of the scenario the household is shifting from. Fig. 8 shows the annual household GHG emissions avoided in SSA countries by shifting from one Tier 0 scenario to another.

Fig. 8 a) reveals that a household would record at least about 40.21% annual GHG emissions avoided by shifting from scenario A to scenario B, while the household would record the highest annual GHG emissions avoided of about 90.21% by shifting from scenario A to scenario E. Overall, Fig. 8 a) shows that a household would record annual GHG emissions avoided by shifting from scenario A to any of the other Tier 0 scenarios considered. This is because scenario A comprises of two kerosene lamps, as shown in Table 2, which have more GHG emissions than the combinations of the lighting devices for the other Tier 0 scenarios.

Fig. 8 b) reveals that a household would record more annual GHG emissions of about 67.25% by shifting from scenario B to scenario A, while the household would record the highest annual GHG emissions avoided of about 83.63% by shifting from scenario B to scenario E. Overall, Fig. 8 b) shows that a household would only record annual GHG emissions avoided by shifting from scenario B to only scenarios C, D, and E. This is because scenario B comprises of one kerosene lamp and candles, as shown in Table 2, which have lower GHG emissions than the two kerosene lamps combination for scenario A.

Fig. 8 c) reveals that a household would record more annual GHG emissions by shifting from scenario C to scenarios A, B, and D. The household would record the highest additional annual GHG emissions of about 410.76% by shifting from scenario C to scenario A, while the household would record the highest annual GHG emissions avoided of about 50.00% by shifting from scenario C to scenario E. Overall, Fig. 8 c) shows that a household would only record annual GHG emissions avoided by shifting from scenario C to only scenario E. This is because scenario C comprises of only candles, as shown in Table 2, which have lower GHG emissions than the combinations of the lighting devices for scenarios A, B, and D.

Fig. 8 d) reveals that a household would record more annual GHG emissions by shifting from scenario D to scenarios A, and B. The household would record the highest additional annual GHG emissions of about 100.00% by shifting from scenario D to scenario A, while the household would record the highest annual GHG emissions avoided of about 80.43% by shifting from scenario D to scenario E. Overall, Fig. 8 d) shows that a household would only

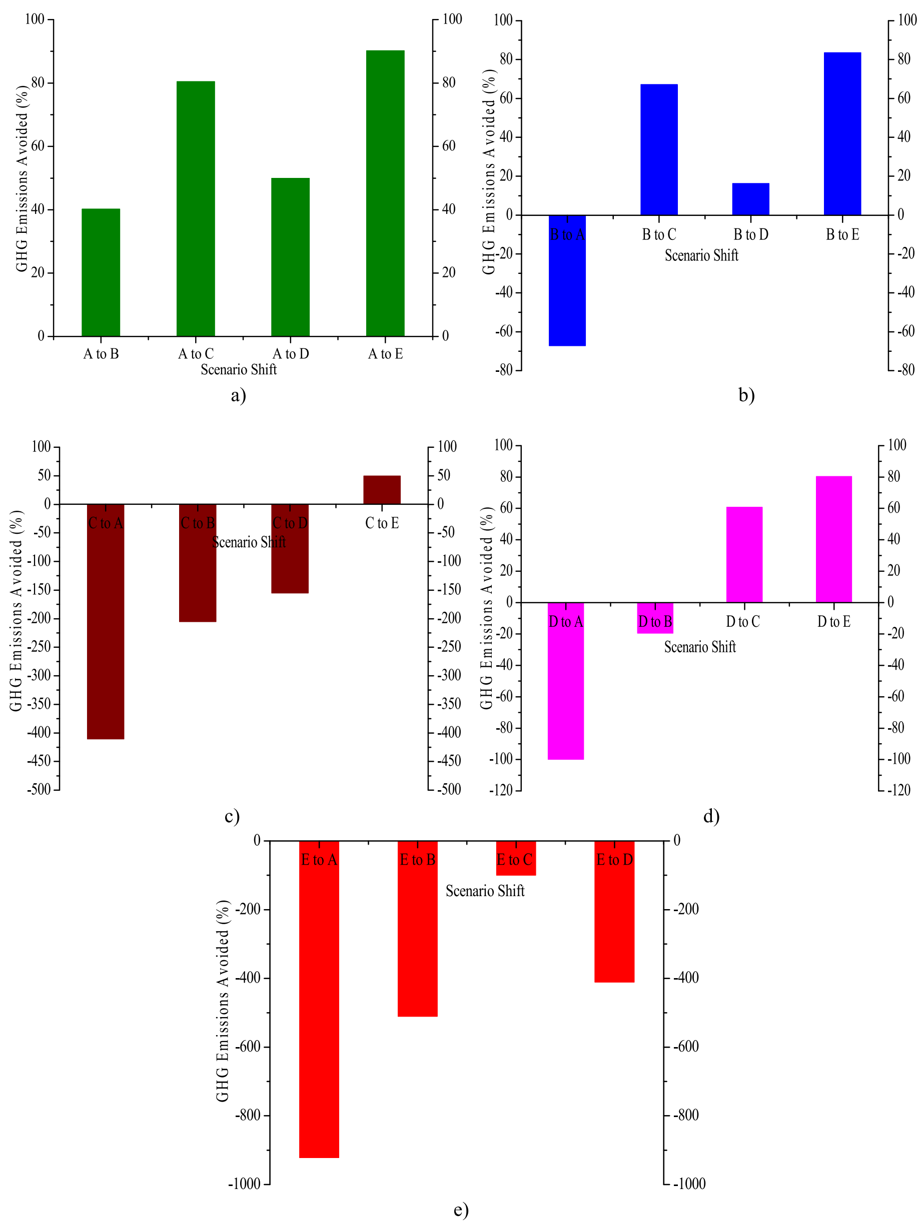

Fig. 8. Annual GHG emissions avoided by a household shifting from one scenario to another under Tier 0: a) shift from scenario A; b) shift from scenario B; c) shift from scenario C; d) shift from scenario D; and e) shift from scenario E.

record annual GHG emissions avoided by shifting from scenario D to only scenarios C and E. This is because scenario D comprises of one kerosene lamp and a torch, as shown in Table 2, which have lower GHG emissions than the combinations of the lighting devices for scenarios A and B.

Fig. 8 e) reveals that a household would record more annual GHG emissions by shifting from scenario E to any of the other scenarios. The household would record the highest additional annual GHG emissions of about 921.52% by shifting from scenario E to scenario A and the least additional annual GHG emissions of about 100.00% by shifting from scenario E to scenario C. This is because scenario E comprise of candles and a torch, as shown in Table 2, which have lower GHG emissions than the combinations of the lighting devices for all the other scenarios.

Generally, Fig. 8 shows that there is a possibility of a household minimizing its annual GHG emissions by shift from one Tier 0 scenario to another. However, this could as well come at an extra energy expenditure incurred. For instance, from Fig. 1, it can be observed that a household shifting from scenario A to any of the other scenarios would incur more annual energy expenditure in most of the selected SSA countries. Thus, the household should consider the annual energy expenditure of the scenarios in addition to the possible GHG emissions avoided prior to undertaking a shift in its combination of the lighting devices.

In the sensitivity analysis, Tier 0 scenario A was considered for the case of Uganda to ascertain the possible GHG emissions avoided by a household in case a SHS kit is acquired. In this assessment, three cases for the variations in the input parameters were considered, that is; (i) either daily lighting duration or SHS kit lifespan varies; (ii) daily lighting duration and SHS kit lifespan vary in opposite directions (one increases while the other decreases); (iii) both daily lighting duration per day and SHS kit lifespan vary in the same direction (both increase or decrease at the same time). These three variations cases in the input parameters were examined in the range ±50%. Fig. 9 shows the sensitivity analysis of the household GHG emissions avoided for Tier 0 scenario A when a SHS kit is acquired for the case of Uganda.

Fig. 9 reveals that the household GHG emissions are highly sensitive to the case when both daily lighting duration and SHS kit lifespan vary in the same direction, followed by either daily lighting duration or SHS kit lifespan varying. By Considering Eq. (16), it is evident that all the input parameters are directly proportion to the output household GHG emissions avoided. Thus, from case (i) it can be asserted that any given variation in one of the input parameters would result in the same amount of GHG emissions avoided by a household as the variation in the other input parameters. Generally, the efficiency and lifespan of solar PV system components are gradually improving with the advancement in technology as reported in Ref. [6]. Thus, it is likely that the lifespan of SHS kits could improve. On the other hand, due to the fluctuations in the fuel prices, households relying on kerosene lamps are likely to shorten their lighting duration to minimize their energy expenditure, as also reported in Ref. [15]. Thus, overall, although case (i) is the commonly occurring variation situation to occur, it can be asserted that case (ii) is the most likely variation situation to happen based on the current economic state in SSA countries and global solar PV technology advancement, while case (iii) is the least likely variation situation to happen. Therefore, cases (i) and (ii) represent the most likely cases of the possible household GHG emissions avoided when it acquires a SHS kit to replace kerosene lamps.

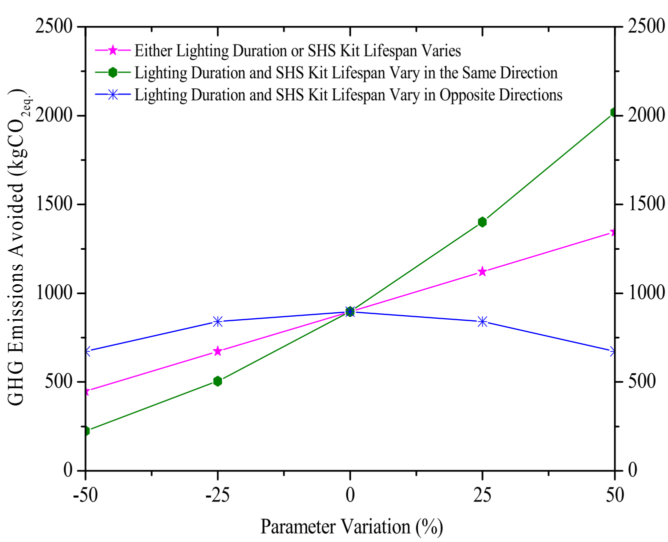

Fig. 9. Sensitivity analysis of household GHG emissions avoided for the case of scenario A in Uganda.

6. Conclusion and future works

This study examined the household energy expenditure and GHG emissions by considering 11 SSA countries. The considered countries were Uganda, Kenya, Tanzania, Zambia, Zimbabwe, Mozambique, Cameroon, DR Congo, Nigeria, Sierra Leone, and Cote d'Ivoire, to represent the different power pools of the SSA region. Tier 0 scenarios were set to depict the possible combinations for the lighting devices commonly used by rural SSA households. Also, the study assessed the economic and environmental benefits of acquiring a SHS kit by a household in SSA countries. The study examined the cash basis and PAYGo basis approaches used by SHS actors to sell the kits to the households to ascertain the possible household energy expenditure savings. Furthermore, the impact of the mobile money charges on the SHS kits PAYGo gross price was also assessed. For the environmental benefits, the study evaluated the household GHG emissions avoided by acquiring a SHS kit for each of the set Tier 0 scenarios. Also, the possible household GHG emissions avoided by shifting from one Tier 0 scenario to any of the other scenarios was assessed. The study also undertook a sensitivity analysis of the household energy expenditure and GHG emissions avoided. The following key conclusions were made from this study:

- The study established that based on the set Tier 0 scenarios, households across the selected SSA countries incur an annual energy expenditure in the range of $ 63.28–106.93 and an average of $ 87.31 on lighting and phone charging services. Households using Tier 0 scenarios D and E record the highest annual energy expenditure, while households using Tier 0 scenarios A and C record the least annual energy expenditure on Tier 0 energy sources. This is mainly due to the reliance on torches as the main lighting device for scenarios D and E is more expensive than the reliance on kerosene lamps and candles by the households. This explains why most of the households in SSA countries use mainly kerosene lamps, followed by candles, and only use torches as a backup lighting device.
- Across the selected SSA countries, a household pays about 13.07–69.17% more on the PAYGo basis approach than on the cash basis approach for the SHS kit. A household in Mozambique pays about 69.17% more by acquiring a SHS kit on the PAYGo basis approach. Such high differences in the offered prices could be that the SHS actors in these countries prefer that all their customers opt for the cash basis other than the PAYGo basis approach.
- For the household energy expenditure savings, most of the selected SSA countries would record savings for both cash basis and PAYGo basis approaches of acquiring a SHS kit based on the

Tier 0 scenario considered. However, households in countries such as Mozambique, Cameroon, and DR Congo would record some additional energy expenditure by acquiring a SHS kit for some of the Tier 0 scenarios. Generally, a household could averagely record energy expenditure savings of about 46.04% and 29.79% by acquiring a SHS kit on the cash basis and PAYGo basis approaches, respectively, across the selected SSA countries.
- The study also established that consideration of mobile money transaction charges in the SHS kit PAYGo gross price could only increase the kit's price in the range of $ 0.214–14.23 for the considered SSA countries. The highest and least increments in the SHS kit PAYGo price would be recorded in Mozambique and Zambia, respectively, which is attributed to the high mobile money charges incurred in these countries by the customers on deposit transactions.
- A household using Tier 0 scenario A, followed by scenarios B and D would record the highest GHG emissions avoided, while a household using Tier 0 scenario E, followed by scenario C would record the least GHG emissions avoided by acquiring a SHS kit in the selected SSA countries. This is attributed to the high emission factor of kerosene of 54.6 g CO_{2eq}/hr in comparison to that of candles of 10.69 g CO_{2eq}/hr. Thus, Tier 0 scenarios (A, B and D) that comprise of kerosene lamps have higher GHG emissions avoided than scenarios (C and E) that mainly comprise of candles.
- A household in the selected SSA countries would record an annual GHG emissions avoided in the range of 19.51–199.29 kg CO_{2eq} by transitioning from Tier 0 scenarios to a SHS kit for lighting services. An assessment of the amount of annual household GHG emissions avoided by shifting from one Tier 0 scenario to another revealed that a shift from scenario A to any of the other scenarios would result in a significant amount of annual household GHG emissions avoided, while a shift from scenario E to any of the other scenarios would result in a significant increase in the amount of annual household GHG emissions released from the lighting devices.

The study considered a single SHS actor from each of the selected SSA countries even though there are several SHS actors in each of these countries as shown in Table 1. Therefore, this study should be extended by considering several SHS actors and mobile money service providers in the individual countries to conclusively ascertain the economic impact of SHS kit on the households. Furthermore, this study considered scenarios for the household combinations of lighting devices to examine the energy expenditure. In the future, field survey data about the household lighting devices and their combinations should be collected and used to ascertain the real-world energy patterns of rural SSA households for the assessment of the GHG emissions and energy expenditure.

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in Renewable Energy Journal.

Authorship contributions

Nicholas Mukisa: Conceptualization, Formal analysis, Methodology, Writing – original draft.

Mele Sikimeti Manitisa: Formal analysis, Methodology, Writing – original draft.

Paul Nduhuura: Writing – original draft, Writing – review & editing.

Erick Tugume: Writing – review & editing.

Chanda Karen Chalwe: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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