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The Industrial Ecology of Renewable Resources

by
Reid Lifset

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The Industrial Ecology of Renewable Resources

Reid Lifset

Associate Director
Industrial Environmental Management Program
School of Forestry & Environmental Studies
Yale University

Introduction

Discussions of renewable resources have historically focused on the threat of exhaustion, exploring whether rates of harvest exceed the rates which the resources replenish themselves. Such analyses are part of larger discussions of resource scarcity in which the prodigious consumption of humankind is compared to available stocks of all kinds of resources with an eye to the opportunities to avoid depletion. Economists and economic historians have raised doubts about this concern, arguing that a focus on depletion of resources is misguided because the price system provides a variety of powerful incentives to address scarcity.[1] As the price of an increasingly scarce resource increases, the incentives for conservation, for improvements in extraction efficiency and for substitution increase. This in turn raises questions about the privileged place that renewable resources occupy in environmental policy discussions: if scarcity is not a major threat, why focus on renewability?

The analysis of the concern with renewable resources, however, is not exhausted by discussions of material scarcity. As Robert Ayres points out, the most important scarcities are soil fertility, clean fresh water, clean fresh air, unspoiled landscapes, climatic stability, biological diversity, biological nutrient cycling and environmental waste assimilative capacity (1993, 189). In this sense, it is not the renewability of the often biologically-based resources that is at issue, but the specific value of the particular resources and the vulnerability of those resources to disruption by human activity. Put another way, the decision to make use of renewable resources needs to be subject to the same searching analysis as any other environmental choice.

It is with respect to these concerns that industrial ecology, by employing a systems perspective, and especially a life-cycle perspective, provides a powerful window on the management of renewable resources. By applying industrial ecological perspectives to questions of energy, forestry, agriculture, biotechnology and the global nitrogen cycle, I hope to illustrate some of the insights that this emerging field can generate.

[1] See Barnett and Morse (1963) and Smith (1979) for the seminal empirical studies of resource scarcity.

Industrial Ecology?

Before examining what industrial ecology can reveal about renewable resources, one needs to understand this curious, even oxymoronic, label. Industrial ecology shares with the zero emissions research initiative (ZERI) a focus on the environmental consequences of production, consumption and waste management. Robert White, as president of the US National Academy of Engineering, one of the institutional proponents of industrial ecology, defined it as

> …the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources (White 1994).

Perhaps the most conspicuous point of intersection between ZERI and industrial ecology is interest in eco-industrial parks.

The name industrial ecology is intended to be metaphorical—and presumably evocative—in several ways. Industrial ecology is *industrial* in that it focuses on product design and manufacturing processes. It views firms as agents for environmental improvement because they are the locus of technological expertise that is critical to the successful execution of green design of products and processes. Industry, as the portion of society that produces goods and services, is an important but not exclusive source of environmental damages.

Industrial ecology is *ecological* in at least two senses. First, the field looks to non-human "natural" ecosystems for models for industrial activity. This is what some have dubbed the "biological analogy" (Wernick and Ausubel 1997). Second, industrial ecology places human technological activity—industry in the widest sense—in the context of the larger ecosystems that support it, examining the sources of resources used in society and the sinks that may assimilate wastes. In this sense, industrial ecology explores questions that are sometimes framed in other fields in terms of carrying capacity.

Many (biological) ecosystems are seen as especially effective at recycling resources and thus are held out as exemplars for loop closing in industry (Graedel 1993, 1996). The most conspicuous example of industrial re-use and cycling of resources is the widely discussed industrial district in Kalundborg, Denmark. The district has a dense web of exchanges that include fuel gas, cooling and waste utility water, steam, waste heat, and scrubber and fermentation sludge. The network of exchanges has been dubbed "industrial symbiosis" as an explicit analogy to the mutually beneficial relationships found in nature (Ehrenfeld and Gertler 1997). Industrial symbiosis in Kalundborg is the archetype for the biological analogy and interest in it as a potential model is one of the more obvious points of overlap with the work of the ZERI community.

Because of the name chosen for industrial ecology, the biological analogy is perhaps industrial ecology's most salient feature, but it is by no means the only notion that drives the field. Industrial ecology makes a self conscious effort to take a comprehensive, systems view of environmental problems, seeking to avoid the kind of partial analyses that lead to mischaracterization of environmental and social phenomena. This effort to avoid the trap of partial analysis inclines the field toward analyses that are global in space and time. It also provides pressure for interdisciplinary approaches.

Typically, the systems-based work in industrial ecology is organized around life cycle-oriented analyses or materials flow accounting (MFA). The life cycle-oriented analyses can take the form of formal life cycle assessments (LCAs), but just as often employ other methodologies which are informed by a life cycle perspective. MFA, the accounting of the flow of materials through economies,[2] provides another basis for efforts at comprehensive analysis. This is why industrial ecology has been described as having a resolute attention to materials flows. The effects of that kind of attention are "subversive" in the words of one leading thinker in industrial ecology, because industrial ecology in focusing on materials flows, brings together concerns that cross regulatory categories, and thus "treats with indifference both what is easy to regulate and what is hard to regulate." (Socolow 1994, 12).

Industrial ecology embraces and builds on many antecedent concepts and tools in the environment field including design for environment (DfE), pollution prevention (P2, also known as cleaner production or CP), LCA, dematerialization and decarbonization, extended producer responsibility (EPR), product-oriented environmental policy and net energy analysis.[3] These elements can be organized by thinking of the field as operating at several scales. At the micro-level, industrial ecology pays attention to unit processes, facility operations and to firm behavior and organization. At the meso level, it examines industrial symbiosis, municipal or regional materials flows and industry sectors. At the macro level, the field focuses on the grand cycles of nutrients (carbon, nitrogen, sulfur and phosphorus), international resource flows, national resource flows and flows within larger regions such as river basins. Figure 1 depicts this set of relationships.

[2] MFA, sometimes called bulk-MFA, is a tool for analysing the flow or mass balance of materials, energy or total mass from environmental sources through economies back to environmental sinks. Substance flow analysis (SFA) is a related tool for analysing the flow of particular *substances* (chemical elements or compounds, or groups of related compounds). The term MFA is also often used to refer to both bulk-MFA and SFA.

[3] For a list of bibliographies on industrial ecology, see <http://www.yale.edu/jie/resources> .

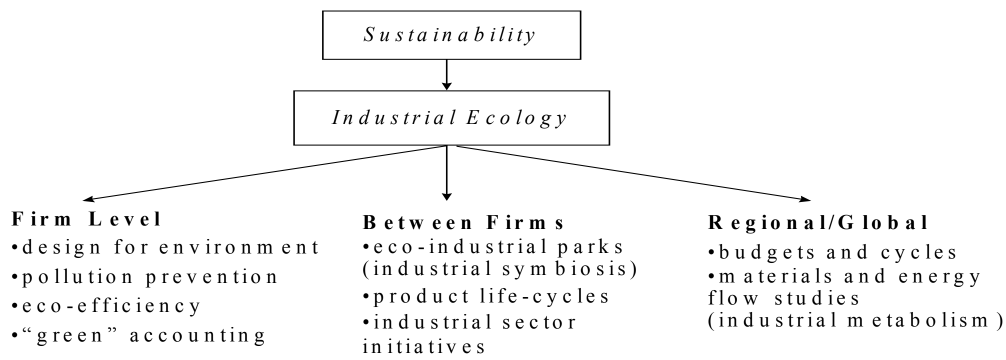

Figure 1

From this capsule summary, it can be seen that industrial ecology emphasizes material and resource fluxes as a means of taking a systems perspective on the environmental consequences of production and consumption. These perspectives highlight important considerations in the management of renewable resources and provide, I hope, additional insight into the nature of the challenges facing society and the possible remedies. I will illustrate this by discussing recent work in industrial ecology as it relates to specific renewable resources.

Viewing Renewable Resources Through the Lens of Industrial Ecology

Several particular perspectives and tools of this emerging field recur in the discussion of renewable resources:

- The de-coupling of economic growth and environmental impacts – industrial ecology pays particular attention to the quantitative study of the degree to which production and consumption can be de-linked from resource throughput. In other words, questions of dematerialization, decarbonization, material or pollution intensity of use, as these issues are variously labeled, examine the rate at which the economy or population can grow without resource use or pollution increasing commensurately (Cleveland and Ruth 1999). The field also examines in more concrete detail the means by which such de-coupling can occur.
- The opportunities for closing materials loops – whether through familiar examples of recycling or through more novel opportunities made possible through co-location (as in Kalundborg).
- The collateral, but important, effects of production and consumption – a systems perspective on environmental problems often reveals that the most troubling environmental effects associated with a particular product or process lie not in the direct releases from its manufacture but elsewhere in the product life cycle.

The definition itself of a renewable resource can become a matter of debate, but for the discussion in this paper, the boundaries of this category are not critical. Here a rather disparate group of topics related to renewable resources are discussed with an eye to how they relate to industrial ecology: energy, forestry, agriculture, biotechnology, and the global nitrogen cycle.

Energy

Clearly, energy is a topic that springs to mind when renewable resources are discussed. Yet, the study of energy and the environment, including renewable energy, is a well established and well developed field. In this sense, industrial ecology simply relies on the substantial body of work in, for example, energy efficiency and net energy analysis. Studies of the global carbon cycle, by attending to anthropogenic effects on grand cycles and the stocks and flows of carbon-based materials, fall clearly with the ambit of industrial ecology (Socolow et al. 1994). Clearly, work on carbon accounting extends well beyond the industrial ecology community, but some analyses, such as the analysis of materials as sources and sinks of carbon (Gielen 1998), make particular of industrial ecology's distinctive focus. In a somewhat different manner, other industrial ecological research on energy has emphasized decarbonization—the reduction in the use of carbon-based fuels per unit of economic activity. Researchers at IIASA have led in the assessment of the degree to which economies are (or are not) decarbonizing and the factors that shape the de-linking (Nakicenovic 1997).

Forestry

Forest products, especially pulp and paper, have long been a focus of life-cycle assessment. The motive behind many of these LCAs has been to identify environmentally preferable paper and solid wood products as a basis for ecolabeling or green procurement initiatives. LCA by its very nature catalogues and emphasizes the resource flows and associated environmental impacts generated by production and consumption of this renewable resource. In this sense, LCA highlights the collateral effects of the use of forest products. That is, LCA is particularly effective at documenting, for example, that the pollution associated with energy generation for pulp and paper manufacture is a significant environmental burden.[4]

LCA is less effective at characterizing the site-specific effects arising from production and consumption in this industry. For example, the ecotoxicological and human health implications of waste water releases from pulp manufacture are one of the key issues in environmental policy toward this industry. To address these concerns effectively, LCA must be augmented by risk assessment or related tools that capture some degree of site-specificity (Owens 1997). The good news is that progress is being made in the integration of these tools (Potting et al. 1998).

[4] Several important, detailed, and provocative studies of the paper industry have taken life-cycle based approaches. These studies are summarized in the special issue of the *Journal of Industrial Ecology* on the industrial ecology of paper and wood (volume 1, number 3).

But industrial ecology includes more than just LCA. Eco-industrial parks are being developed where geographic proximity of paper- and wood-related manufacture is being exploited to minimize environmental impact.[5] In a different vein, land use in forestry has been assessed with an eye toward questions of eco-efficiency, asking "how much land can be spared for nature?" That is, how efficient is the forest products industry in its resource generation and extraction, in its product manufacture and in product use and in end of product life (post-consumer) waste management? And, where might additional efficiency be achieved so that needs can be met while reserving more land for "nature" (Wernick, Waggoner and Ausubel 1997)? This last analysis, a variant of the "de-linking" studies mentioned above, is especially effective at integrating considerations of production and consumption in the assessment of a renewable resource. When coupled with an understanding of ecosystem threats and considerations that can limit resource extraction (Nilsson, Colberg and Hagler 1999, Matthews and Hammond 1999), this type of analysis can provide important insights for policymakers. It can indicate where and how the pressures on renewable resources can be addressed in a systematic manner, that is, by including considerations of global production and consumption along with more familiar, local site-specific analysis of resource extraction issues.

Agriculture

The production of food relies substantially on renewable resources such as solar energy and soils. The environmental impact of agriculture and potential methods for minimizing that impact are increasingly drawing the attention of the industrial ecology community. For example, methodology development for the application of LCA to food production and to the entire food chain (production, distribution, retailing, consumption and waste management) is proceeding under the auspices of European Network for Life Cycle Assessment Research and Development within the food chain (LCANET Food).[6]

Like forestry, the opportunities for environmental improvement through co-location and utilization of by-products are important in agriculture. Here ZERI has been a conspicuous leader in its support for integrated biological systems (IBSs) such as the mushroom-piggery-aquaculture complex at the Montfort Boys Home in Fiji (Bequette 1997). IBSs are important because they show that the benefits of "symbiotic" networks are not limited to exchanges based on wastes from heavy industry. The networks can be smaller, based on less elaborate technology and, especially relevant here, tied to the flows of renewable resources.

Along a different line, as industrial ecology extends its focus from materials flows *per se* to include more detailed assessments of the environmental impact of those flows,

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[5] See, for example the efforts at the Burnside Industrial Park in Nova Scotia, Canada (<http://www.mgmt.dal.ca/sres/eco-burnside/>).

[6] LCANET Food is sponsored by the European Union's Directorate General XII as a "concerted action" in its Food and Agriculture program. Information about LCANET Food can be obtained at the network's web site <http://www.sik.se/sik/affomr/milo/defini.html>

the fate of heavy metals in agriculture has drawn more attention. Put another way, one of the reasons why society worries about the mobilization of heavy metals—and their consequent diffusion through the economy and biophysical environment—is that some of those metals end up in agriculture, tainting the food supply and doing damage to soils. Substance flow analyses (SFA) of the Rhine River Basin in the mid 1990s under the auspices of the International Institute for Applied Systems Analysis (IIASA) shed important light on cadmium flows in northern Europe and their potential impact on human health. Stigliani and his colleagues (1994) found that while cadmium levels in soils (resulting from the contaminants in fertilizer) were not currently threatening human health, the bioavailability of the cadmium could change dramatically if the land were to go out of agricultural production.

The Dutch Program on Metals[7] also sought to identify the fate of metals as they flow into and out of the agricultural sector. Moolenaar and Lexmond (1998) and Moolenaar (1999) use materials balances to articulate the environmental concerns and to propose a framework for heavy metal management in agro-ecosystems.

In an analogous fashion, concerns about both catch fisheries and aquaculture could be illuminated by a systematic assessment of needs for fish protein and resulting production pressures on fisheries. A good start in integrating discussions of consumption and production in this manner has been made by the World Resources Institute (Matthews and Hammond 1999).

Biotechnology

Biotechnology, especially as it relates agriculture and genetically-modified foods, raises complicated technical and ethical issues—as current debates attest. Some controversies in biotechnology are not notably illuminated by industrial ecology because the key issues often do not concern resources flows (e.g., threats to biodiversity, allergenic responses to foreign proteins, etc.). Yet, industrial ecology highlights some important potential advantages and drawbacks of biotechnology.

For example, the role of biotechnology in meeting global food requirements is often argued in terms very familiar to industrial ecologists. Advocates argue that biotechnology can produce more food on the same area of land, thereby reducing pressure to expand into wilderness, rain forest, or marginal lands which support biodiversity and ecosystem services, and that it can displace resource and energy intensive inputs, such as fuel, fertilizers or pesticides, thus reducing unintended impacts on the environment (Beachy 1999, Warnock and Bonner 1999).

At the same time, a recent article in *Nature Biotechnology* reminds us that the systematic analysis of resource consumption is just as important for biologically-based production of materials as it is for more established technologies. Gerngross (1999) examines the production of the biopolymer, polyhydroxyalkanoate (PHA), as an alternative to thermoplastics such as polyethylene or polystyrene. PHA, produced

[7] See <http://www.leidenuniv.nl/interfac/cml/metals/>.

through the fermentation of agricultural feedstocks using genetically engineered bacteria, is thought to be, *prima facie*, environmentally preferable to conventional polymers because it is derived from renewable resources.[8] Gerncross found that a considerable amount of energy is consumed in the process of fermenting glucose from corn: the PHA fermentation process consumes 22% more steam, 19 times more electricity and 7 times more water than a comparable conventional process for producing polystyrene. Further, the growing of corn is energy-intensive because of fuel and fertilizer use and contributing to resource consumption and greenhouse gas generation.

In a different vein, biotechnology may be the means of realizing the loop-closing goals of industrial ecology (and ZERI). Monsanto is working with Heartland Fibers to genetically engineer corn so that the field residues ("corn stover") can be more readily used as a feedstock for paper production (*Pulp and Paper* 1998). This effort to design a waste stream could allow the paper industry to tap the very large and underutilized agricultural waste stream. Biotechnology is also likely to be the source of new approaches to waste recovery technologies.

Nitrogen Cycle

In line with its view of industrial society as embedded in a larger natural system, industrial ecology looks not only at flows of materials and energy, but also the "grand cycles" of elements through the biosphere and the manner and degree to which human activity perturbs those cycles. Systematic examination of the stocks and flows of one such element, nitrogen, reveals that the cycle may be more perturbed by human activity than the widely discussed carbon cycle. Ayres, Schlesinger and Socolow (1994) argue that increased fertilizer production, in the use of nitrogen-fixing crops and in combustion, are increasing the quantity of bioavailable nitrogen with potentially adverse effects. They note that public policies to address the formation of nitric oxides in the combustion of fossil fuels are well developed in many countries, but attention to a larger source of perturbations to the nitrogen cycle—nitrogen fertilizer use—is much less developed. The connection between the disturbances to the nitrogen cycle and issues of carrying capacity are notable. Increased population necessitates increased agricultural production which, in turn, has stimulated greater use of nitrogen fertilizer. The policy implications of perturbation of the nitrogen cycle remain contested (Socolow 1999, Frink et al. 1999).

Conclusion

This short survey of the application of industrial ecology tools and perspectives to topics and concerns in renewable resources has dual goals: to illustrate how industrial ecology can add insight to the analysis of renewable resources and to introduce the work emerging from this field to interested and allied researchers and policymakers around the globe. The brief overview suggests that a systems perspective—whether in the form of a life-cycle assessment, or the analysis of anthropogenic impacts on grand nutrients cycles

[8] PHA is also seen as a preferable because it is biodegradable. That aspect of its environmental character is not discussed here.

or trends in the intensity of materials and energy use can illuminate our understanding of renewable resources.

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Zero Emissions Forum
Environment & Sustainable Development
53-70 Jinguame 5-chome
Shibuya-ku, Tokyo 150-8925
Japan

Tel.: +81-3-3499-2811
Fax: +81-3-3499-2828
Email: unu-zef@hq.unu.edu
http://www.unu.edu/zef

Zero Emissions Forum
Focal Point for Europe
c/o Rüdiger Kühr
Seehofstr.106,14167Berlin
Germany

Tel.: +49-30-42808559
Fax: +49-721-151234313
Email: mbox@zef-germany.de