Industrial Ecology

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GLOSSARY

Design for environment – An engineering perspective in which environmentally related characteristics of a product, process or facility design are optimized.
Eco-efficiency – A business strategy to produce goods with lower use of materials and energy to realize economic benefits of environmental improvements.
Industrial ecology – An approach to the design of industrial products and processes that evaluates such activities through the dual perspectives of product competitiveness and environmental interactions
Industrial metabolism – A concept to emulate flows of material and energy in industrial activities from a biological systems perspective.
Industrial symbiosis – A relationship within which at least two willing industrial facilities exchange materials, energy, or information in a mutually beneficial manner.
Life cycle assessment – A concept and a methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the entire life cycle of a particular material, process, product, technology, service or activity. The life cycle assessment consists of three complementary components: (1) goal and scope definition, (2) inventory analysis, and (3) impact analysis, together with an integrative procedure known as improvement analysis.
Material Flow analysis – An analysis of flow of materials within and across the boundaries of a particular geographical region.
Pollution Prevention – The design or operation of a process or item of equipment so as to minimize environmental impacts.
Recycling – The reclamation and reuse of output or discard material streams for application in products.
Remanufacture – The process of bringing large amounts of similar products together for purposes of disassembly, evaluation, renovation, and reuse.

I. Introduction to Industrial Ecology

Industrial ecology is a nascent and challenging discipline for scientists, engineers and policy makers. Often termed the "science of sustainability" (Graedel, 2000), the contemporary origins of industrial ecology are associated with an article titled 'Strategies for Manufacturing' by Frosch and Gallopoulos (1989) in *Scientific American*. However, historically, indirect references to the concept of industrial ecology date back to the early seventies (Erkman, 2002). The multidisciplinary nature of industrial ecology makes it difficult to provide a consistent and universally accepted definition, but the essence of the topic is captured by the following: – "*Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, economic, cultural, and technological evolution. The concept requires that an industrial ecosystem be viewed not in isolation from its surrounding system, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized are resources, energy and capital"* (Graedel and Allenby, 2002).

In industrial ecology, the approach to understand industry-environment interactions is to move from contemporaneous thinking or thinking about past mistakes to forward thinking. The objective is to minimize or eliminate environmental impacts at the source rather than to rely on traditional end-of pipe measures in a command and control regime. If properly implemented, industrial ecology promotes business competitiveness and product innovation. In addition, industrial ecology looks beyond the action of single firms to those of groups of firms or to society as a whole. Several core elements characterize the discipline (Lifset and Graedel, 2002):

- The biological analogy

- The use of systems perspectives
- Role of technological change
- Role of companies
- Eco-efficiency and dematerialization
- Forward-looking research and practice

Each of the themes offers a plethora of methods and tools for analysis. In following section, we discuss some of the more important aspects and tolls of the core elements, especially those particularly relevant to energy.

II. Methods and Tools of Industrial Ecology

Industrial ecology offers a realm of methods and tools to analyze environmental challenges at various levels – process, product, facility, national, and global and then come up with responses to facilitate better understanding and provide suitable remedies. We discuss some of the important components in the industrial ecology toolbox below.

A. Life cycle assessment

A central tenet of industrial ecology is that of life-cycle assessment (LCA). The essence of LCA is the examination, identification, and evaluation of the relevant environmental implications of a material, process, product, or system across its life span from creation to disposal or, preferably, to recreation in the same or another useful form. The formal structure of LCA, contains three stages: goal and scope definition, inventory analysis and impact analysis, each stage being followed by interpretation of results (SETAC, 1993). The concept is illustrated in Figure 1. First, the goal and scope of the LCA are defined. An inventory analysis and an impact analysis are then performed. The interpretation of results at each stage guides an analysis of potential improvements (which may feed back to influence any of the stages, so that the entire process is iterative). There is perhaps no more critical step in beginning an LCA evaluation than to define as precisely as possible the evaluation's scope: What materials, processes or products are to be considered, and how broadly will alternatives be defined?. To optimize utilization of resources in an LCA exercise, the depth of analysis should be keyed to the degree of freedom available to make meaningful choices among options, and to the importance of the environmental or technological issues leading to the evaluation.

The inventory analysis is by far the best-developed component of LCA. It uses quantitative data to establish levels and types of energy and materials used in an industrial system and the environmental releases that result. The impact analysis involves relating the outputs of the system to the impact on the external world into which outputs flow, or, at least to the burdens being placed on the external world. The interpretation of results phase is where the findings from one or more of the three stages are used to draw conclusions and recommendations. The output from this activity is often the explication of needs and opportunities for reducing environmental impacts as a result of industrial activities being performed or contemplated.

A comprehensive LCA can be expensive and time-consuming. As a consequence, more efficient approaches (streamlined LCAs or SLCAs) have been developed with the intention of retaining the useful broad-scope analysis of the LCA while making the activity more tractable (e.g. Graedel, 1996). In the case of either LCA or SLCA, the effort helps the analyst think beyond the boundaries of a particular facility or process to encompass the full measure of associated environmental implications.

B. Design for Environment

Product design engineers are always faced with the challenge of optimizing the multitude of attributes that determine the success or failure of the product. The paradigm for such design considerations is termed “Design for X” (DfX), where X may be any of a number of attributes such as assembly, compliance, disassembly, environment, manufacturability, reliability, safety and serviceability. Design for Environment (DfE) is the DfX-related focus of industrial ecologists. The core theme of DfE philosophy is that it should improve the environmentally-related attributes of a product while not comprising other design attributes such as performance, reliability, aesthetics, maintainability, cost, and time to market. DfE approaches systematically evaluate environmental concerns during the product life cycle stages of pre-manufacture, manufacture, delivery & packaging, use, and end of life and accordingly set targets for continual improvements. The choice of materials during pre-manufacture and their efficiency of utilization during product manufacture, energy use during manufacturing and product use, environmentally friendly disposal or reincarnation of products at end of life are some of prime considerations in DfE. DfE is also a ‘win-win’ proposition in that it provides a corporation with a competitive edge in an ever-tightening regulatory environment, and promotes ongoing product innovation.

C. Industrial Symbiosis

The industrial ecologist views the economy as a closed system, similar to a natural system, in which the ‘residues’ from one system are the ‘nutrients’ for another. The concept known as industrial symbiosis is a current topic of research for industrial ecologists and environmentalists in identifying strategies to enable businesses to `close the loop'. The objective is to create or encourage the formation of industrial production systems that function similarly similar to biological food chains. In either natural or industrial systems, symbiosis occurs when two or more organisms form an intimate association, either for the benefit of one of them (parasitic symbiosis) or for both or all of them (mutualistic symbiosis) such that there is high degree of synergy between input and output flows of resources. The best-known industrial symbiosis example is the Kalundborg industrial system in Denmark. The qualitative material flows at Kalundborg are shown in Figure 2. The heart of this industrial ecosystem is the 1500MW coal fired Asnaes power plant, which exchanges various residues such as gypsum, steam, fly ash etc., with neighboring entities –Statoil refinery, Nova Nordisk pharmaceutical unit, Gyproc plasterboard facility and the town of Kalundborg.

Industrial symbiosis may occur opportunistically or can be planned. Planned industrial symbiosis appears to offer the promise of developing industrial ecosystems that are far superior environmentally to unplanned ones. Such a system would need to involve a broad sectoral and spatial distribution of participants, and be flexible and innovative.

The formation of ecologically balanced industrial systems result in numerous environmental and economic benefits. Economic benefits, which are shared by participating businesses, governments, and communities, are the primary driving force for setting up such industrial configurations. Entrepreneurs can gain appreciable cost savings from reduced waste management, reduced infrastructure costs, and improved process and product efficiency. There are opportunities for other cooperative ventures such as joint purchasing, combined waste recovery and treatment, employee training, environmental monitoring, and disaster response. The tangible environmental benefits include the reduction of greenhouse gas emissions and toxic air emissions, improving efficiency and conservation in the use of energy, materials and water, improving land use planning and green space development within the industrial complexes, and promotion of pollution prevention and recycling approaches.

D. Eco-efficiency, dematerialization and decarbonization

The human induced activities of production and consumption, both being integral parts of a robust economic world, are considered to be major factors in the sustainability debate. The concept of ‘eco-efficiency’ evolved in the early nineties prior to the Earth Summit. Simply stated, eco-efficiency means doing more with less. The World Business Council for Sustainable Development refer eco-efficiency as “.. *attained by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity*” (WBCSD, 2002). Businesses worldwide have begun to embrace eco-efficiency as a ‘win-win’ strategy. Ideologically, eco-efficiency and dematerialization are synonymous. Dematerialization can be achieved by making the products either smaller or lighter (e.g., personal computers today as compared to a decade ago), by replacing a product with an immaterial substitute (e.g., large scale use of electronic mail over regular postal mail) or by reducing the use of material-intensive systems. Material intensity of use, defined as resource use per gross domestic product, is a commonly used metric to evaluate dematerialization trends. The key determinants that influence intensity of use patterns are changes in material composition of products (material substitution and technological change) and product composition of income (structural changes in the economy and intra-sectoral shifts). The variation of material intensity of use over the last century for some of the materials used extensively in the United States economy is shown in Figure 3. There is an appreciable decline in the use of metals except for aluminum, while the use of paper and plastics continues to grow. These trends also indicate that the composition of materials in the United States economy changed over this period from dense to less dense, i.e., from iron and steel to light metals, plastics, and composites. At the product level similar trends can also be observed, for example, the change in the weight composition of an average automobile in the United States, as shown in Figure 4. Plastics, composites, aluminum, and other specialty materials account for the decline in the use of conventional steel in automobiles over the 1978-2000 period.

In energy systems analysis, dematerialization is analogous to decarbonization, which refers either to moving away from carbon-intensive energy sources to completely carbon-free sources such as hydrogen or solar. While evidence for any comprehensive dematerialization trend remains ambiguous, the situation is clearer with respect to energy. Historically, trends in fuel market share of global primary energy use indicate a transformation from carbon-intensive fossil fuels such as wood and coal to less intensive ones such as oil and natural gas, as shown in Figure 3. The decline in carbon intensity has been very slow, approximately 0.3% per year over the 1850-1994 time period (Grübler and Nakićenović, 1996).

E. Industrial metabolism

The extraction, production and waste treatment of materials cause environmental problems that call for an intervention by all the stakeholders: governments, corporations, and individuals. The approach to link society's management of materials to sustainable development and environmental quality is now well defined and understood. The concept of 'industrial metabolism', first introduced by Robert Ayres (Ayres, 1989a; Ayres et al, 1989b; Ayres and Simonis, 1994), establishes an analogy between economy and environment on a material level. Societies mobilize material from Earth's crust to create 'technomass', in analogy to nature's 'biomass'. The ecosystems in the biosphere try to close the loop by cycling resources and wastes repeatedly. In contrast, modern society tends to use materials once and then discard them. Industrial ecologists (Graedel and Allenby, 2002; Ayres and Ayres, 1996) have begun to assess the physical economy through the lens driven by biosphere guiding principles. The objective of such analytical studies from a systems perspective is to determine the anthropogenic contribution to natural material flows, the causal factors, and the spatial and temporal distribution of environmental problems.

Material balances, based on the universal law of mass conservation, have historically been used as an instrument to describe material flows through the economy (Kneese et al, 1970, Ayres and Ayres, 1996). Within that framework, material flow analysis (MFA) and substance flow analysis (SFA) are two important approaches to assess the current and future state of resource flows and accumulation in the economy and environment. MFA usually tracks material intensities of national economies or sectors thereof, concentrating on bulk flows, while SFA is intended for flows of specific substances to identify specific environmental problems and propose remedial/prevention strategies.

An example of an SFA, a contemporary copper cycle for Germany, is shown in Figure 6. The cycle for Germany represents a highly industrialized country without significant virgin copper resources. Unable to rely on an internal supply, Germany imports copper in different forms at every industrial life stage – production, fabrication and manufacturing, and waste management. Its reuse of discarded and imported scrap is so extensive that non-virgin copper supplies about 45% of all inflows to its industrial facilities. Nonetheless, Germany landfills about 120 Gg Cu/yr, the most of any country in Europe. This substance diagram can be converted to an energy diagram if the flows are multiplied by the energy needed to effect a transfer of ore unit of copper from ore reservoir to another. The results (not shown here) make it obvious that the extraction of copper from its ore is the most energy-intensive step in the entire cycle.

F. IPAT Equation

The environmental impact of materials use has often been conceptually formed by the "IPAT" equation:

$$I = P\ A\ T \qquad (1)$$

in which the overall environmental impact I is expressed as the product of population P, the affluence A (expressed, for example, as Gross Domestic Product (GDP)/person), and technology T (expressed, for example, as environmental impact per unit of per capita GDP). Historically proposed by Commoner, Ehrlich and Holdren, the IPAT equation is now termed as the "master equation" of industrial ecology (Graedel and Allenby, 2002). If the technology factor is expanded somewhat, we can rewrite the equation as

$$I = P\ A\ M\ D\ H \qquad (2)$$

where M is the materials intensity, D the dissipation factor, and H the hazard factor, which depends on the chemical form of the material lost and the susceptibility of the receiving ecosystem. In words, Eq. (2) becomes

Environmental impact = (Population) x (GDP/person) x (units of material/GDP) x (units of pollution/unit of material) x (impact/unit of pollution) (3)

In the energy sector, the equivalent of the IPAT equation is the Kaya's identity (Kaya, 1990), which is a mathematical expression for energy-related carbon emissions and can be written as

$$C = (P)\ (GDP/P)\ (E/GDP)\ (C/E) \qquad (4)$$

Where the total energy-related carbon emissions C is expressed as a product of Population P, GDP per capita, energy intensity E/GDP and carbon intensity of energy use C/E.

Although the master equation and Kaya's identity should be viewed as conceptual rather than mathematically rigorous, they can be used to suggest goals for technology and society. The technology-related terms M, E, and C offer the greatest hope for a transition to sustainable development, especially in the short term, and it is modifying these terms that is among the central tenets of industrial ecology.

III. Industrial Ecology and Energy

Industrial ecology and energy use are inextricably linked as mobilization and utilization of materials in our present technological society is indispensable without the utilization of energy. However, global commons are threatened by environmental emissions from energy use. Simultaneous improvements in material and energy intensities of use is one of the desirable goals to pre-empt ecological damage across different scales and levels. In this section, we discuss energy considerations during different product life cycle stages.

A. Energy considerations in material choice

Embodied energy, or "embedded energy" concept includes the energy required to extract raw materials from nature, plus the energy utilized in the manufacturing activities. Inevitably, all products and goods have inherent embodied energy. More the material is close to its natural state at the time of use, lower is its embodied energy. For e.g. use of sand and gravel has lower embodied energy as compared to copper wire. It is necessary to include both renewable and non-renewable sources of energy in embodied energy analysis. The energy requirements for acquisition in usable form from virgin stocks of a number of common materials are shown in Figure 7. From an industrial ecology perspective, a manufacturing sequence that uses both virgin and consumer recycled material is usually less energy intensive than primary production. The energy requirements for primary and secondary production of various metals are shown in Figure

8. For one of the most commonly used industrial materials, aluminum, the energy requirement for secondary production of aluminum is approximately 90% less than primary production using virgin resource. Therefore, an efficient recycling operation can lead to potential savings in energy consumption and associated environmental damage.

B. Energy considerations in product manufacture

Although the materials extraction and processing sectors have the highest energy intensity, these industries are suppliers to the intermediate processing industries, so one cannot plan to decrease industrial energy use solely by eliminating the extraction industries (which would not be possible in any case). The consumption of energy in selected manufacturing industries is shown in Figure 9. Petroleum and coal production account for the largest energy use. Most of this energy use is attributable to the mining and processing of coal and the refining of petroleum. The trend towards desulfurization of crude oil and the production of high-octane gasoline without the use of metal-containing additives place ever-increasing energy demands on the refining operations. Refinery operations are generally subject to careful supervision and continuing engineering effort to improve efficiencies, but increased attention to cogeneration, heat exchange, and leak prevention are likely to offer opportunities for further improvements. Chemicals and chemical products rank among the industries in Figure 9 as well, although about a third of the amount shown represents petroleum and natural gas as feedstocks for products rather than the fuel that is consumed to produce energy. Of the remaining two-thirds, a substantial amount is used in the generation or removal of process heat as a result of temperature differences between process streams and the heating and cooling streams. The production of compressed gases is another energy-intensive operation in this sector. Primary metals are the third industry listed in Figure 9. Although the extraction of ore from the ground and its shipment are quite energy intensive, the bulk of the energy use is in crushing rock and recovering the target ore, and in generating the large amounts of process heat needed to extract metal from ore and to produce ingots and other purified products.

To maximize the efficiency with which water and energy are used in manufacturing and to minimize overall water and energy loss rates is a major goal of pollution prevention. These actions are seen as complementary to those directed towards routine emissions to air, water, and soil, or to leaks or accidents. Energy audits for the different process operations and for the overall facility are always helpful to indicate opportunities to reduce energy use. A particularly successful energy conservation program to date was initiated by the Louisiana Division of the Dow Chemical Company in 1982. Many of the improvements embodied techniques useful industry-wide, such as installing insulation on pipes carrying hot fluids, cleaning heat exchanger surfaces frequently to improve heat transfer efficiency, and employing point-of-use fluid heaters where storage or long pipelines create the potential for heat loss. The company's energy contest results are summarized in Table 1. It is clear that energy conservation, either through good housekeeping, improved technology, or process change or modification, is always beneficial.

C. Energy considerations during product use

Designing innovative products that provide maximum benefit and service to the customers and are also simultaneously environmentally responsible is a challenge and an opportunity for product designers. DfE guidelines, evolved through feedback from customer expectations and regulatory policies, offer a framework to identify, prioritize, and implement product design improvements.

On a life cycle basis, the 'in-use' phase is often dominant in terms of energy use. For a modern jet engine, for example, an improvement of 0.1% in fuel-burning efficiency is a more important design change than would be difficult material choices, improved manufacturing efficiency, or both end-of life design, so far as the environment is concerned. Energy-efficient designs may sometimes involve new approaches; the result can not only lower cost operation but also improved product positioning (from a sales standpoint), particularly in areas of the world that are energy poor.

C. Energy considerations in remanufacturing and recycling

When products reach end of life, they can revert into input materials if they are recovered and recycled. Recycling operations are usually viable if the quantities recovered are large enough and the discard stream is homogenous and concentrated. Even with extensive recycling, however, a growing economy still has a need for virgin resources and processing of any kind requires energy.

In remanufacturing, products are either refurbished or reconditioned to same quality control as new products, subsequently returned to market. Remanufacturing is more energy-efficient than recycling, as no new materials have to be processed. Remanufacutring also saves on landfill space and costs. From a DfX perspective, design for disassembly is important in remanufacturing, since modular design of products will facilitate disassembly with less of effort and time. In the United States, a remanufacturing tax credit has been included in the Clean Energy Incentives Act to encourage businesses. However, the lack of product take back laws to make producers responsible for their products at end of life and the typical consumer's psychological preference for new rather than refurbished products provide barriers against an extensive and well-integrated remanufacturing industry.

A perspective for product designers, remanufacturers and recyclers is shown in Figure 10 with details provided in Table 2. Different types of products are plotted on the basis of their product lifetime and technology cycle. Masui (2002) identify four product categories, each of which offers a suite of environmental and non-environmental challenges to designers and recyclers. The complexity of the challenge increases in anti-clockwise direction as we move from Type I products to Type IV in Figure 10. Generally speaking, the energy consumption of these products also increases from Type I to Type IV. This characterization focuses on only two attributes and does not include functional and operational efficiency aspects, compatibility, number of parts etc.,. It provides a framework for development of strategies to deal with products at their end of life.

IV. Conclusion

To an extent not generally appreciated, the study of industrial ecology is simultaneously the study of energy – its methods of generation, its employment in driving the engines of industry, and its use by individuals everywhere as they employ the technology of the modern world. Consider the diagram in Figure 11. The driver for all energy use, shown at the left, is the contribution of societal needs and cultural desires related to energy. These define the type and number of energy-using products required to satisfy those needs and desires. The requisite energy is produced by the energy industry, indicated on the right. In the center are the design, use, and recycling of products. It is these steps that are the province of industrial ecology, which aims to satisfy the needs and desires while minimizing

- The use of energy in product design and manufacture
- The use of energy in product operation
- The use of energy-intensive virgin materials
- The magnitude of energy-related environmental impacts

The evolution of our society in the direction of increased sustainability will require not only that energy that is widely available, but that it is used with maximum efficiency, and is such ways that its use produces minimal environmental impact. A close partnership between the energy industry and industrial ecologists will be required to make that vision a reality.

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Table 1 Energy conservation projects at Dow Chemical Company, Louisiana Division

	1982	1984	1986	1988	1990	1992
Number of projects	27	38	60	94	115	109
Average return on investment (%)	173	208	106	182	122	305

Source: Nelson, 1994

Table 2 Guidelines for product designers and recycling technology developers

Product category	End-of-life Scenario	Product Designers	Recycling Technology Developers
Type I	Material recovery	Ease separation of components for recycling high quality material	Develop separation technologies accounting for different physical properties between materials that can not be sorted
Type II	Remanufacturing	Enhance reusability by using common parts and modular components in product family	Develop efficient cleaning and inspection technologies to reduce remanufacturing cost
Type III	Lengthen product life by upgrading	Extend product life by modular design of key devices which define value of product	Develop non-destructive techniques for removal of key components
Type IV	Lengthen product life by maintenance	Enhance disassemblability for facilitating maintenance	Develop diagnostic technologies for maintenance

Figure Captions

Figure 1. Stages in the life cycle assessment of a technological activity. The arrows indicate the basic flow of information. (Source: SETAC, 1993)

Figure 2. Material flows in the Kalundborg industrial ecosystem (Source: Dr. Marian R Chertow, Yale University)

Figure 3. The intensity of use of materials in the United States, 1900-1990. The annual consumption data are divided by GDP in constant 1987 dollars and normalized to unity in the year 1940. (Source: Wernick, 1996.)

Figure 4. The average material composition of a domestic automobile in United States. (Source: DOE, 2001)

Figure 5. Global primary energy substitution, 1860-1980, and projections to 2050 (expressed in fractional market shares, *f*. Note: Smooth lines represent model calculations and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example solar or fusion) (Source: Nakićenović, 1997)

Figure 6. The contemporary copper cycle for Germany (ca.1994). All values are in Gg Cu/yr.

Figure 7. The primary energy consumption required to produce one kilogram of various materials (Source: Schuckert et al., 1997)

Figure 8. Energy requirements for primary and secondary production of metals (Data source: Chapman and Roberts, 1983)

Figure 9. Consumption of energy in selected manufacturing industries (Source: DOE, 1990)

Figure 10. End of life plot for different product categories (Source: Masui, 2002)

Figure 11. Satisfying the energy-related needs and desires of societies and cultures. The principal actors in each column of the diagram are shown at the bottom.

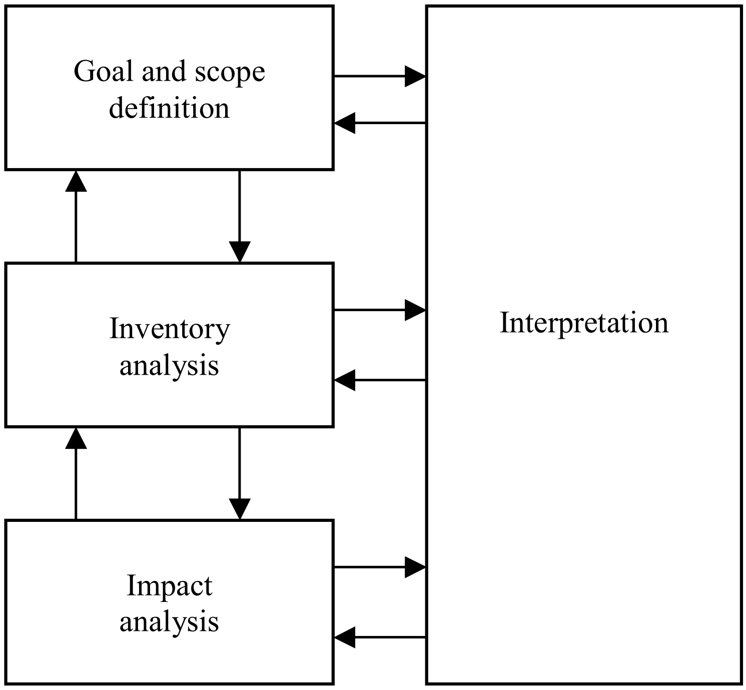

Goal and scope definition
Inventory analysis
Impact analysis
Interpretation

Figure 1.

Industrial Symbiosis at Kalundborg

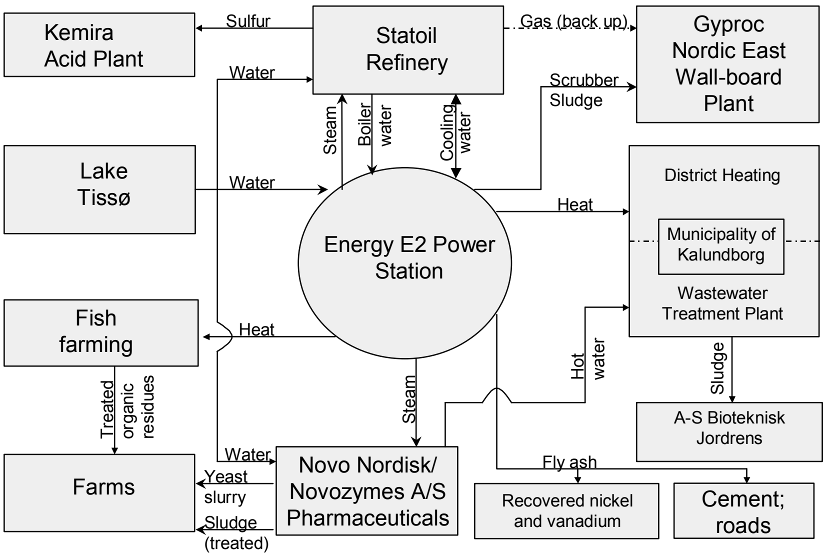


Figure 2.

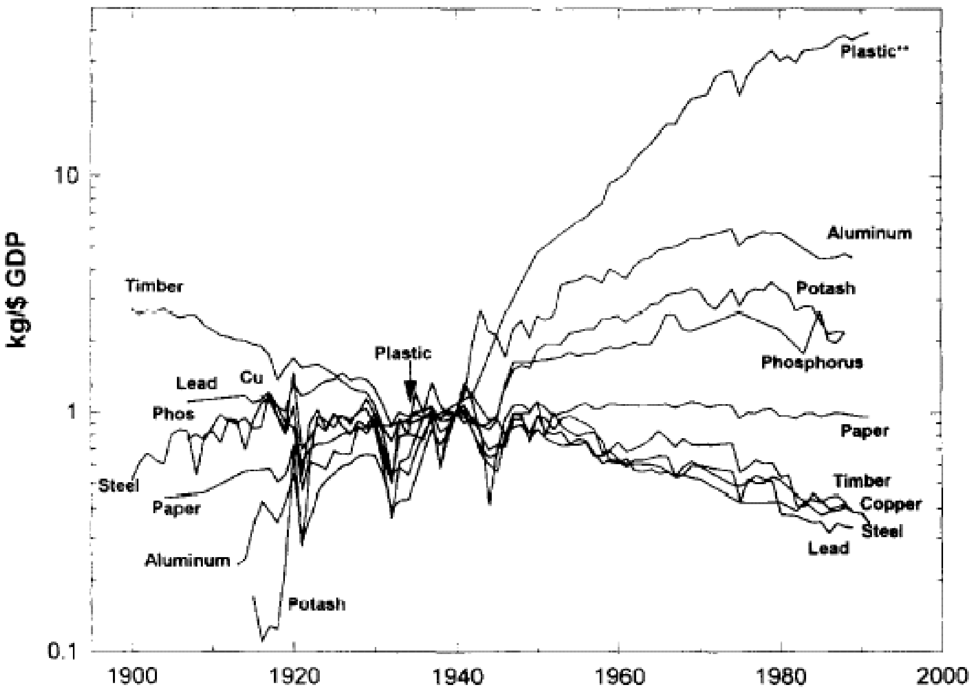
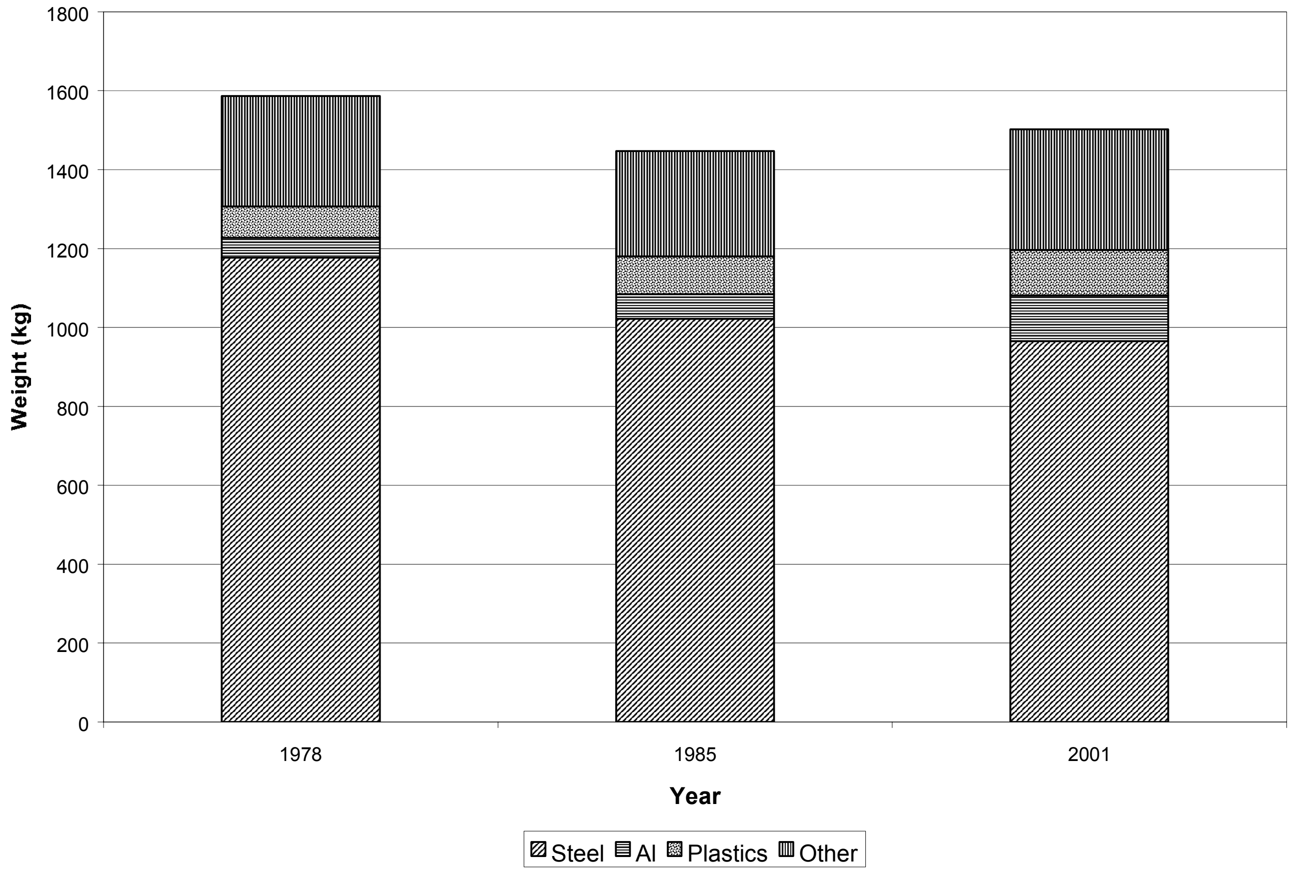
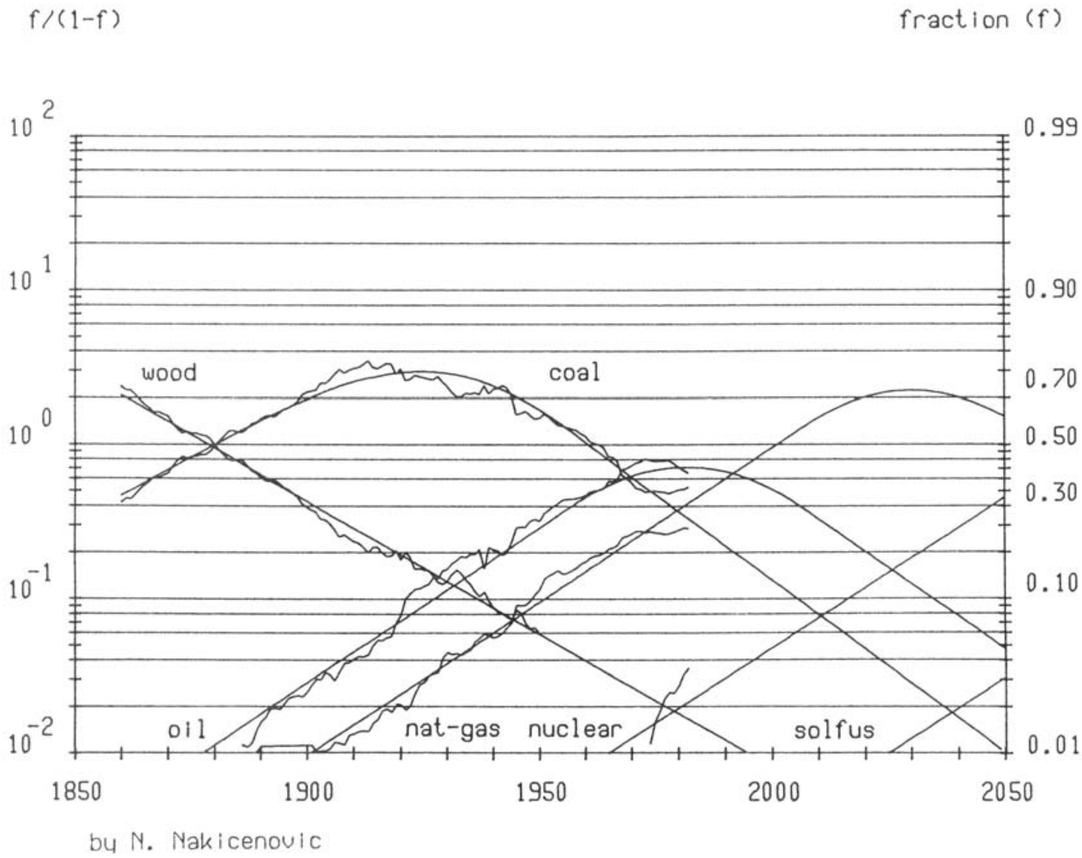

Plastic**
10
Aluminum
kg/$ GDP
Timber
Potash
Plastic
Phosphorus
Lead
Cu
1
Phos
Paper
Steel
Timber
Paper
Copper
Steel
Lead
Aluminum
Potash
0.1
1900
1920
1940
1960
1980
2000

Figure 3.



1800
1600
1400
1200
1000
800
600
400
200
0
Weight (kg)
1978
1985
2001
Year
Steel
Al
Plastics
Other

Figure 4.



f/(1-f)
fraction (f)
10^2
10^1
10^0
10^{-1}
10^{-2}
0.99
0.90
0.70
0.50
0.30
0.10
0.01
wood
coal
oil
nat-gas
nuclear
solfus
1850
1900
1950
2000
2050
by N. Nakicenovic

Figure 5.

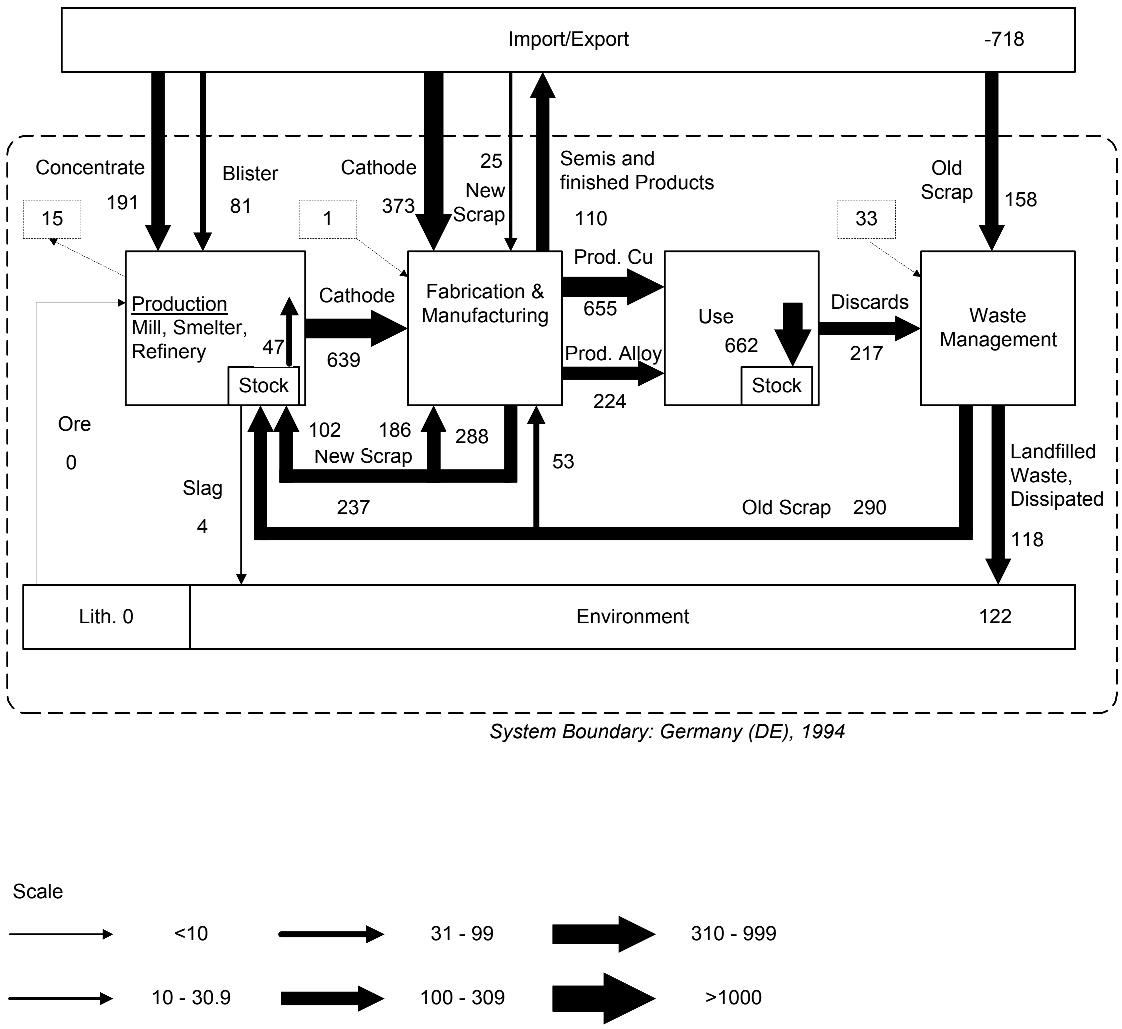
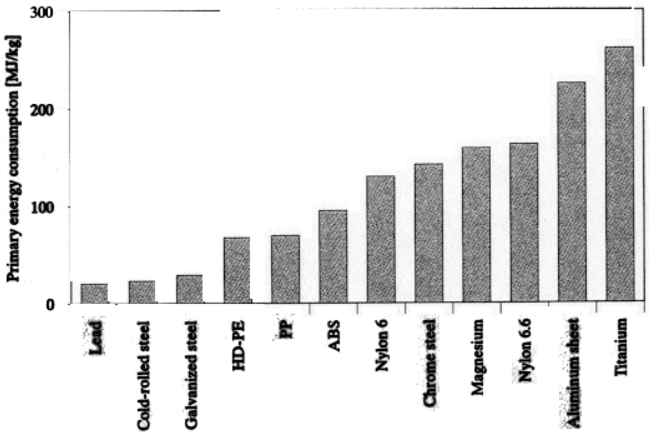
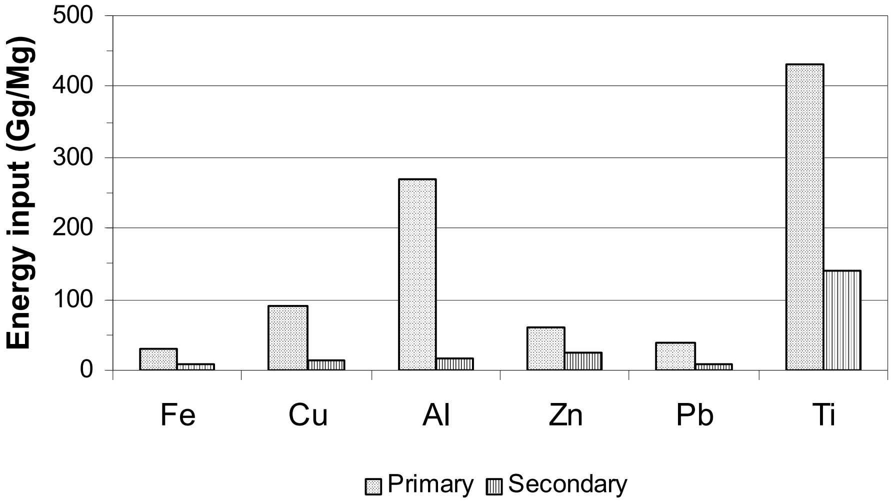

Import/Export -718
Concentrate
191
Blister
81
Cathode
373
25
New
Scrap
Semis and
finished Products
110
Old
Scrap
158
15
1
33
Production
Mill, Smelter,
Refinery
47
Stock
Cathode
639
Fabrication &
Manufacturing
Prod. Cu
655
Prod. Alloy
224
Use
662
Stock
Discards
217
Waste
Management
Ore
0
Slag
4
102
186
New Scrap
288
237
53
Old Scrap 290
Landfilled
Waste,
Dissipated
118
Lith. 0
Environment
122
System Boundary: Germany (DE), 1994
Scale
<10
31 - 99
310 - 999
10 - 30.9
100 - 309
>1000

Figure 6.



Primary energy consumption [MJ/kg]
300
200
100
0
Lead
Cold-rolled steel
Galvanized steel
HD-PE
PP
ABS
Nylon 6
Chrome steel
Magnesium
Nylon 6.6
Aluminum sheet
Titanium

Figure 7.



500
400
300
200
100
0
Energy input (Gg/Mg)
Fe
Cu
Al
Zn
Pb
Ti
Primary
Secondary

Figure 8.

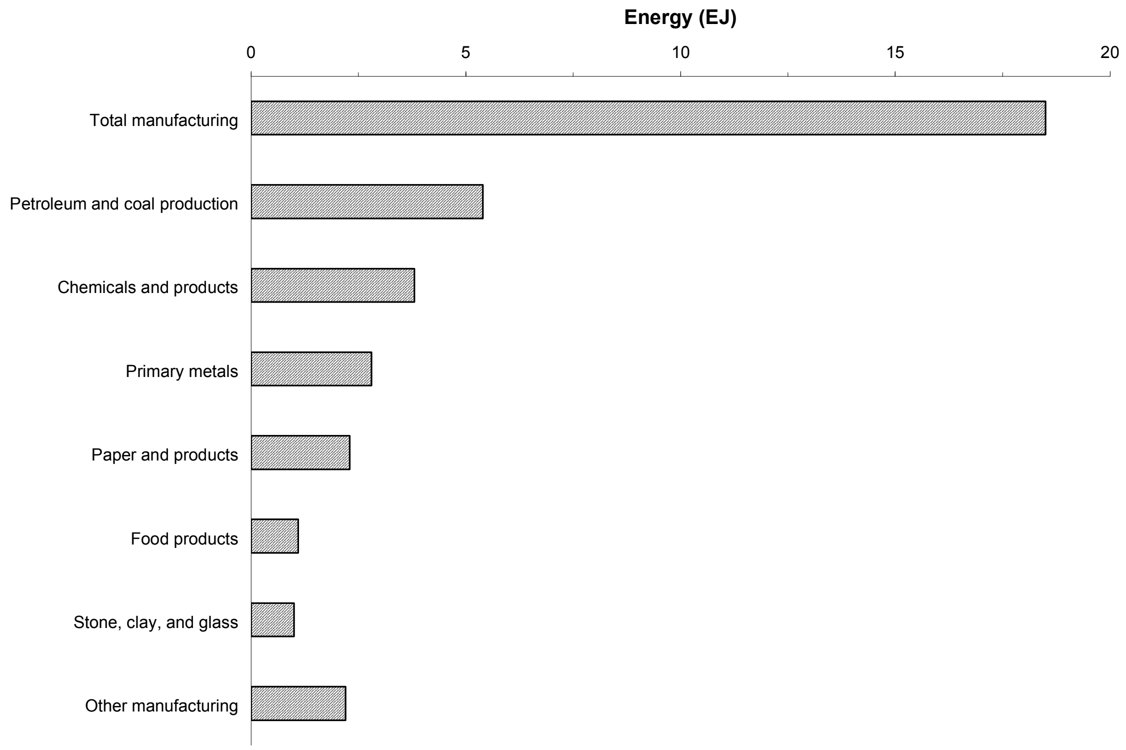

Energy (EJ)
0
5
10
15
20
Total manufacturing
Petroleum and coal production
Chemicals and products
Primary metals
Paper and products
Food products
Stone, clay, and glass
Other manufacturing

Figure 9.

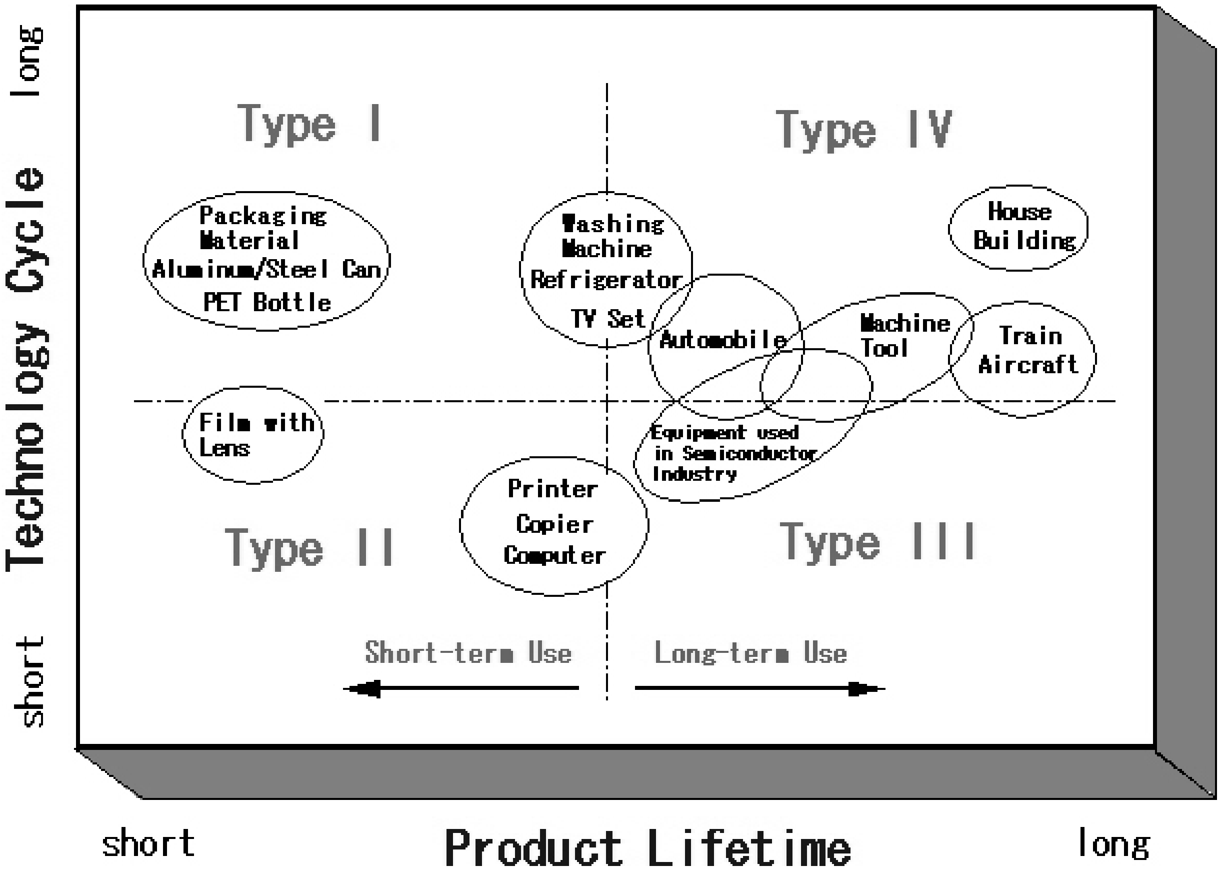

long
Technology Cycle
short
Type I
Type IV
Packaging Material
Aluminum/Steel Can
PET Bottle
Washing Machine
Refrigerator
TV Set
House Building
Automobile
Machine Tool
Train Aircraft
Film with Lens
Equipment used in Semiconductor Industry
Printer
Copier
Computer
Type II
Type III
Short-term Use
Long-term Use
short
Product Lifetime
long

Figure 10.

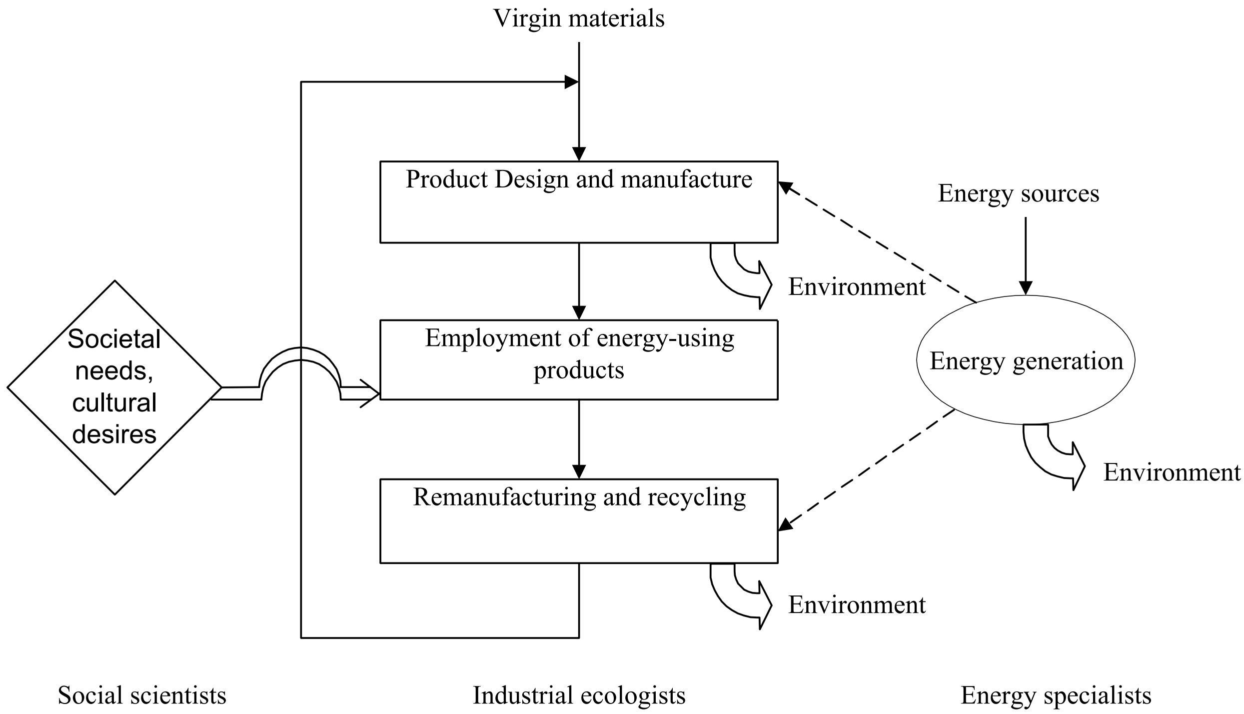

Virgin materials
Product Design and manufacture
Energy sources
Environment
Societal needs, cultural desires
Employment of energy-using products
Energy generation
Environment
Remanufacturing and recycling
Environment
Social scientists
Industrial ecologists
Energy specialists

Figure 11.