1. Industrial Ecology: An Introduction

INDUSTRIAL ECOLOGY? A surprising, intriguing expression that immediately draws our attention. The spontaneous reaction is that "industrial ecology" is a seeming contradiction in terms, the general perception being that industries cause ecological damage.

We are used to considering the industrial system as isolated from the natural ecological system or biosphere, with factories and cities on one side and nature on the other, the problem being perceived as one of minimizing the impact of the industrial system on what is "outside" of it: its surroundings, the "environment". Since long, studies by ecologists have focused on the consequences of the various forms of pollution on nature. As early as the 1950s, strategies were conceived in order to diminish the impact of pollution, which essentially consisted in building filters to ensure that the waste from industries did not "leak" into the environment. This is illustrated in the classical end-of-pipe approach for the treatment of pollution, which has proved to be quite useful, but not entirely adequate in the long run.

Analysis showed that better strategies were required because, the process of building filters was only often just transferring the pollutant from one medium to another (for example, from water to land). Secondly, the process of building filters was not very economical as there was no savings accruing from the process. This approach did not also pay adequate attention to the issue of resources. Considering the increasing population, the rising aspirations of the people and the earth's limited resources, the issue of a more efficient use of resources certainly needed to be addressed.

Cleaner Production, Pollution Prevention and Eco-Efficiency strategies were then evolved, which looked at possible changes in the process or parts of the process, to minimize waste. With this, the economies of production were very often better as lower waste meant better material utilization. By addressing the issues in a preventive way, they represent definitely an important progress. However, today, these strategies remain mainly targeted towards specific manufacturing processes and business strategies within individual companies.

But in all these perspectives, the industrial system was not fully seen as part of the biosphere. A broader view was needed. One needed to think of going even further, and try to apply strategies like Cleaner Production at the level of a cluster of companies, or at the level of an industrial zone, or even for a whole region—in other words, to apply Cleaner Production and similar approaches at the level of a system. This idea stems from the recognition that substantial additional gains, both economical and environmental, can be achieved by addressing issues at the level of a system (a cluster of companies, an industrial zone, a region, etc.), as compared to individual and isolated approaches.

Industrial Ecology explores the assumption that industrial activities should not be considered in isolation from the wider world but rather in terms of an *industrial ecosystem* functioning within the natural ecological system or biosphere. The industrial system, in a similar way to a natural ecosystem, essentially consists of flows of materials, energy and information, and furthermore relies on resources and services provided by the biosphere. It is important to stress at the outset that the word industrial, in the context of Industrial Ecology, refers to all human activities occurring within the modern technological society. Thus tourism, housing, medical services, transportation and agriculture are all a part of the industrial system. And the word ecology, here, refers to the science of ecosystems.

Industrial Ecology can also be seen as a practical approach to sustainability. It is an attempt to address the question: How can the concept of sustainable development be made operational in an economically feasible way?

1.1 Industrial Ecology in a Nutshell

So far, there is no standard definition of Industrial Ecology. Whatever the definitions may be, all authors more or less agree on at least three key elements of the Industrial Ecology perspective:

a. It is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relations with the biosphere.

b. It emphasizes the biophysical substratum of human activities, i.e. the complex patterns of material flows within and outside the industrial system, in contrast with current approaches which mostly consider the economy in terms of abstract monetary units, or energy flows.

c. It considers technological dynamics, i.e. the long term evolution (technological trajectories) of clusters of key technologies as a crucial (but not exclusive) element for the transition from the actual unsustainable industrial system to a viable industrial ecosystem.

Industrial Ecology does not address just issues of pollution and environment, but considers as equally important, technologies, process economics, interrelationships of businesses, financing, overall government policy and the entire spectrum of issues that are involved in a socioeconomic system.

Two terms are often used while talking about Industrial Ecology. These are Industrial Ecology and Industrial Metabolism and it may be useful to clarify what we mean by these expressions.

Industrial Metabolism is the whole of materials and energy flows through an industrial system. It is studied through an essentially analytical and descriptive approach, mainly Material Flow Analysis (MFA), based on the principle of conservation of mass. MFA is aimed at understanding the circulation of the materials linked to human activity, from their initial extraction to their inevitable reintegration, sooner or later, into the overall biogeochemical cycles. The expression metabolism of economic activities (or sometimes socio-industrial metabolism) is also in use and can be considered as synonymous.

Industrial Ecology goes further: the idea is first, on the basis of industrial metabolism, to understand how the industrial system works, how it is regulated, and how it interacts with the biosphere; then, on the basis of our scientific understanding of ecosystems, we try to determine how the industrial system could be restructured to make it compatible with the way natural ecosystems function.

1.2 Industrial Ecology: A Brief History

There is little doubt that the concept of Industrial Ecology existed well before the expression, which began to appear sporadically in the literature of the 1970s. In fact, and not surprisingly, specialists of scientific ecology had all along the intuition of the industrial system as a subsystem of the biosphere. But this line of thought had never been actively investigated. The concepts of Industrial Ecology have been discussed on and off from the 1960s.

The expression re-emerged in the early 1990s, at first, among a number of industrial engineers connected with the National Academy of Engineering in the USA. Every September, the popular scientific monthly *Scientific American* publishes an issue on a single topic. The September 1989 special issue was on Managing Planet Earth. It featured an article, Strategies for Manufacturing, by Robert Frosch and Nicholas Gallopoulos, both then at General Motors [1].

In their article, the two authors offered the idea that it should be possible to develop industrial production methods that would have considerably less impact on the environment. This hypothesis led them to introduce the notion of *industrial ecosystem*. Projections regarding resources and population trends 'lead to the recognition that the traditional model of industrial activity—in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of—should be transformed into a more integrated model: an industrial ecosystem. The industrial ecosystem would function as an analogue of biological ecosystems. (Plants synthesize nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.) An ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialized world is to maintain its standard of living-and the developing nations are to raise theirs to a similar level-without adversely affecting the environment.'

However, as Robert Frosch indicated during his lecture, 'Towards an Industrial Ecology', presented before the United Kingdom Royal Society in 1990: 'The analogy between the industrial ecosystem concept and the biological ecosystem is not perfect, but much could be gained if the industrial system were to mimic the best features of the biological analogue' [2].

In contrast to preceding attempts, Frosch and Gallopoulos's article sparked off strong interest. There are many reasons for this: the prestige and wide audience of the *Scientific American*, Frosch's reputation in governmental, engineering and business circles, the weight carried by the authors because of their affiliation with General Motors, and the general context, which had become favorable to environment issues, with, among other features, discussions around the Brundtland Commission report on sustainable development. The article manifestly played a catalytic role, as if it had crystallized a latent intuition in many people, especially in circles associated with industrial production, who were increasingly seeking new strategies to adopt, to deal with environmental issues.

Although the ideas presented in Frosch and Gallopoulos's article were not, strictly speaking, original, the *Scientific American* article can be seen as the source of the current development of Industrial Ecology. Ideas on Industrial Ecology were also disseminated among business circles on the basis of the *Scientific American* article, but indirectly. Hardin Tibbs, a British consultant who was working in Boston in 1989 for the company Arthur D. Little, says that reading Frosch and Gallopoulos's article inspired him to write a twenty-page brochure called *Industrial Ecology: An Environmental Agenda for Industry*. Arthur D. Little published the text in 1991. It was published again in 1993 by Global Business Network, a consulting company near San Francisco, joined by Hardin Tibbs, which develops prospective scenarios for its member companies [3]. The Hardin Tibbs brochure was quickly sold out, then thousands of xeroxed copies of it were circulated, spreading Frosch and Gallopoulos's ideas throughout the business world. Other authors, also inspired by the Frosch and Gallopoulos article, began to write papers disseminating the idea both in various academic and business circles.

Today, Industrial Ecology is being pursued with unprecedented vigor. It is gaining recognition not only in business communities, but in academic and government circles as well. In 1997, the Journal of Industrial Ecology (MIT Press, http://mitpress.mit.edu/JIE) was launched, and the International Society for Industrial Ecology (ISIE) (http://www.yale.edu/isie) was founded in 2000–01.

1.3 The Industrial Ecology Agenda: Restructuring the Industrial System

The principal objective of Industrial Ecology is to reorganize the industrial system (including all aspects of human activity) so that it evolves towards a mode of operation that is compatible with the biosphere and is sustainable over the long-term. The strategy for implementing the concepts of Industrial Ecology is often referred to as eco-restructuring and can be described in terms of four main elements: (1) Optimizing the use of resources (2) Closing material loops and minimizing emissions (3) Dematerializing activities (4) Reducing and eliminating the dependence on non-renewable sources of energy [4].

1.3.1 Optimizing the Use of Resources

Optimizing the use of materials and energy in any industrial activity starts with an analysis of production processes in order to eliminate unnecessary losses. This is a step that is carried out by individual companies on their own activities and is called Pollution Prevention or Cleaner Production. While there have been considerable efforts in this area during the past 10–15 years, there is still room for further improvement, particularly in the newly-industrializing countries that will represent the principal manufacturing base in the future.

Once we begin to consider the biological analogy underlying Industrial Ecology, we realize that additional aspects of resource optimization are not covered by the approaches mentioned above. In natural ecosystems, certain species feed on the waste of other species and thereby contribute to the creation of a food chain. Industrial Ecology therefore suggests the idea of an industrial food chain in which companies are linked in some form of network in order to exploit unutilized resources or by-products and thereby increase resource utilization.

Thus, the concept of Eco-Industrial Park (EIP) was born in the early 1990s. EIPs are areas in which companies cooperate to optimize resource use, namely, by mutually recovering the waste they generate (the waste produced by one enterprise is used as raw material by another) [5].

The notion of park should not be considered in the sense of a geographically confined area: an eco-industrial park can very well encompass a neighboring city, even a remote enterprise, especially if the latter is the only one around capable of recovering a rare type of waste impossible to process at other factory sites. Hence the new term, eco-industrial networks, where parks represent a particular case, is appropriate. The notion of eco-industrial parks (or networks) is quite different from traditional waste exchange programs. Indeed, it involves a systematic recovery process of overall resources in a given region, within the conceptual framework of scientific ecology. It does not merely recycle waste on an ad hoc basis.

One idea that fits in with the notion of eco-industrial parks is that of industrial biocoenoses. In biology, the concept of biocoenosis refers to the fact that, in ecosystems, various species of organisms always meet according to characteristic patterns of association. Just as in natural ecosystems, there are key species in industrial biocoenoses. Power plants, for instance, are an obvious key species. All kinds of different eco-industrial complexes could develop around thermal power plants (coal, oil, gas, nuclear), given the extent of matter flows involved and the enormous quantity of energy wasted as heat.

Once the best possible associations are determined, including the most appropriate combinations of various industrial activities, the concept can then be extended to industrial complexes. For example, instead of building an isolated sugarcane production unit, one should attempt, from the outset, to plan an integrated complex whose objective is to use all the flows of matter and energy linked to sugarcane processing in the best possible way. In this instance, a number of units could be attached—a paper mill, a distillery, a thermal power station—in order to recover all the different by-products of sugarcane. A variety of possibilities come to mind: pulp–paper complexes, fertilizer–cement ventures, steelworks–fertilizer–concrete partnerships, etc. Granted, there are examples of partial and spontaneous complexes that have been around for a long time. However, the main focus now should be on developing these complexes in a more explicit and systematic way [6].

The Eco-Industrial Park (EIP) is proving to be an important tool within the Industrial Ecology approach and at present there are around 50 EIP projects under way, particularly in North America, Western Europe and Asia [7].

1.3.2 Closing Material Loops and Minimizing Emissions

In natural ecosystems all materials flow cyclically in the form of a quasi-*closed loop*. For example, bacteria, fungi and small invertebrates break down dead matter or waste products from plants into simpler chemical compounds that can once again be used by plants. Companies that carry out this function of recycling wastes in the industrial ecosystem are usually referred to as recyclers. Unfortunately, while natural ecosystems are very effective at closing the material loops, the industrial ecosystem is still far from optimal. Only a small fraction of the waste is returned to the system; the majority is lost from the industrial system (i) through the creation of waste during the manufacturing of products, (ii) as waste that is formed by a product when it is considered to be of no further useful value, and (iii) in the form of products that are designed to be completely or partially dispersed during their use. At present, the losses of materials due to consumption patterns (i.e. types (ii) and (iii) above) greatly exceed those during the manufacturing process.

Closing material loops within the industrial ecosystem, therefore, means addressing the complete life cycle of the product. One way is to make the recycling industry more effective, both with respect to technological solutions as well as logistics. However, energy is required to close the material loop in a natural or an industrial ecosystem. As long as we continue to use fossil fuels as our main source of energy in the industrial ecosystem, recycling will also contribute to the creation of waste from the combustion process. The energy associated with recovery of a material must therefore be considered when deciding on a strategy for closing the loop. In the case of the recovery of aluminum from scrap, for example, the energy requirement for recycling is much lower than that for extraction and purification of aluminum from bauxite. The environmental impact due to recycling is only one-tenth of that to produce virgin aluminum.

Although it is possible to envisage closing material loops for consumption patterns (i) and (ii) above, there are some materials that are designed to be completely or partially dispersed during their use. Some examples are pharmaceuticals, fertilizers, pesticides, detergents, solvents, etc. Such materials clearly cannot be recycled after use and will always represent a loss of resources. Minimizing dissipation of this type of product is a difficult challenge and may be addressed (in some cases) by rethinking about the service demanded.

One area where open material flows can no longer be accepted is when such materials are toxic/hazardous and, in particular, when they are persistent and bio-accumulate (accumulate in living organisms). Whether the material is lost due to inefficient recycling or through dissipative use, sustainability arguments imply that its future use must be seriously questioned and alternative solutions provided.

1.3.3 Dematerializing Activities

An important objective of Industrial Ecology is not only to create cyclic flows of materials but also to minimize the total flow of matter and energy used to provide equivalent services. Technical progress often makes it possible to obtain more service from a smaller amount of matter, such as by producing lighter objects or by replacing one material by another (e.g. a few kilograms of optical fiber allows for more telecommunications throughput than one tonne of copper cable). However, dematerialization is not as simple as it may seem—less massive products may have shorter life spans and will therefore ultimately consume more resources and generate more waste. Furthermore, dematerialization does not apply only to consumer goods, but also to the heavy infrastructure of the industrial system, such as buildings, roads, transportation networks, etc. [8].

At the present time, two strategies are being debated: *relative dematerialization* so as to obtain more services and goods from a given quantity of matter, and *absolute dematerialization*, which strives to reduce the total amount of matter circulating within the industrial system. There has been a recent surge of interest in dematerialization in the context of the so-called new economy, or knowledge-based economy, and there have been many claims that the emerging information technologies will contribute to the dematerialization of the economy. However, this is far from proven, and at this stage we must acknowledge our ignorance about the real impact of new information technologies on resource consumption [9].

Probably one of the best ways to dematerialize the economy is to emphasize the service rendered, or the function, i.e. to market the use of the product rather than the product itself. For many years our economic system has been organized to maximize production. Within the context of Industrial Ecology, the objective is to prioritize use in order to evolve towards a genuine service-oriented society, also referred to as functional economy. This involves strategies such as durability (extending the useful life of a product), renting rather than owning, and selling use rather than the actual product. To illustrate the point, a photocopy machine manufacturer who sells the photocopy service rather than the machine itself, will run a more profitable operation if the photocopy machine, of which he retains ownership, requires as little matter inputs as possible, has the longest possible useful life, is easily recyclable, etc. [10].

1.3.4 Reducing and Eliminating the Dependence on Non-renewable Sources of Energy

Energy is an extremely important factor in the eco-restructuring of the industrial system. All efforts have to be made to increase energy efficiency through developments such as co-generation and energy cascading.

However, fossil fuels (coal, oil or natural gas) are a crucial factor in powering the engines of industrial economies. Combustion of fossil fuels is fundamentally dissipative and lies at the root of many environmental problems, including the enhanced greenhouse effect, smog, oil spills, acid rain, etc. Eco-restructuring, therefore, must involve a change in the way that we obtain energy so as to make it more compatible with the goals of Industrial Ecology. In the first phase we can try to make fossil fuel consumption less harmful—for example, by recovering carbon dioxide gas or by decarbonizing the energy supply via a change from coal and oil to natural gas (and eventually perhaps hydrogen). However, it is clear that this is only a temporary solution and the move from fossil fuels to alternative renewable energies must be made quickly [11].

1.4 The Industrial Symbiosis in Kalundborg

As a matter of fact, Industrial Ecology is already more than a nice theoretical idea: the Industrial Symbiosis, which has evolved during the last three decades in the small city of Kalundborg, in Denmark, offers the best evidence that such an approach can be very practical and economically viable. Kalundborg, located 130 km west of Copenhagen, can be seen as a successful example of an industrial complex minimizing pollution and optimizing the use of various resources. Before addressing the specific issues of developing countries, a short discussion of the Kalundborg Symbiosis would be useful.

The history of Kalundborg really began in 1961, with a project to use surface water from Lake Tissø for a new oil refinery in order to save the limited supplies of groundwater. The city of Kalundborg took the responsibility for building the pipeline while the refinery financed it. Starting from this initial collaboration, a number of other collaborative projects were subsequently introduced and the number of partners gradually increased. By the end of the 1980s, the partners realized that they had effectively self-organized into what is probably the best-known example of a working industrial ecosystem, or to use their term—an *industrial symbiosis* [12].

The Kalundborg Industrial Symbiosis today consists of six main partners:

- Asnæs power station, part of SK Power Company and the largest coal-fired plant producing electricity in Denmark
- Statoil, an oil refinery belonging to the Norwegian Statoil company
- Novo Nordisk, a multinational biotechnology company that is a leading producer of insulin and industrial enzymes
- Gyproc, a Swedish company producing plasterboard for the building industry
- The town of Kalundborg, which receives excess heat from Asnæs for its residential district heating system
- Bioteknisk Jordrens, a soil remediation company that joined the Symbiosis in 1998.

In addition, several other companies participate as recipients of materials or energy. The status of the Industrial Symbiosis in 1999 is shown in Figure 1.1.

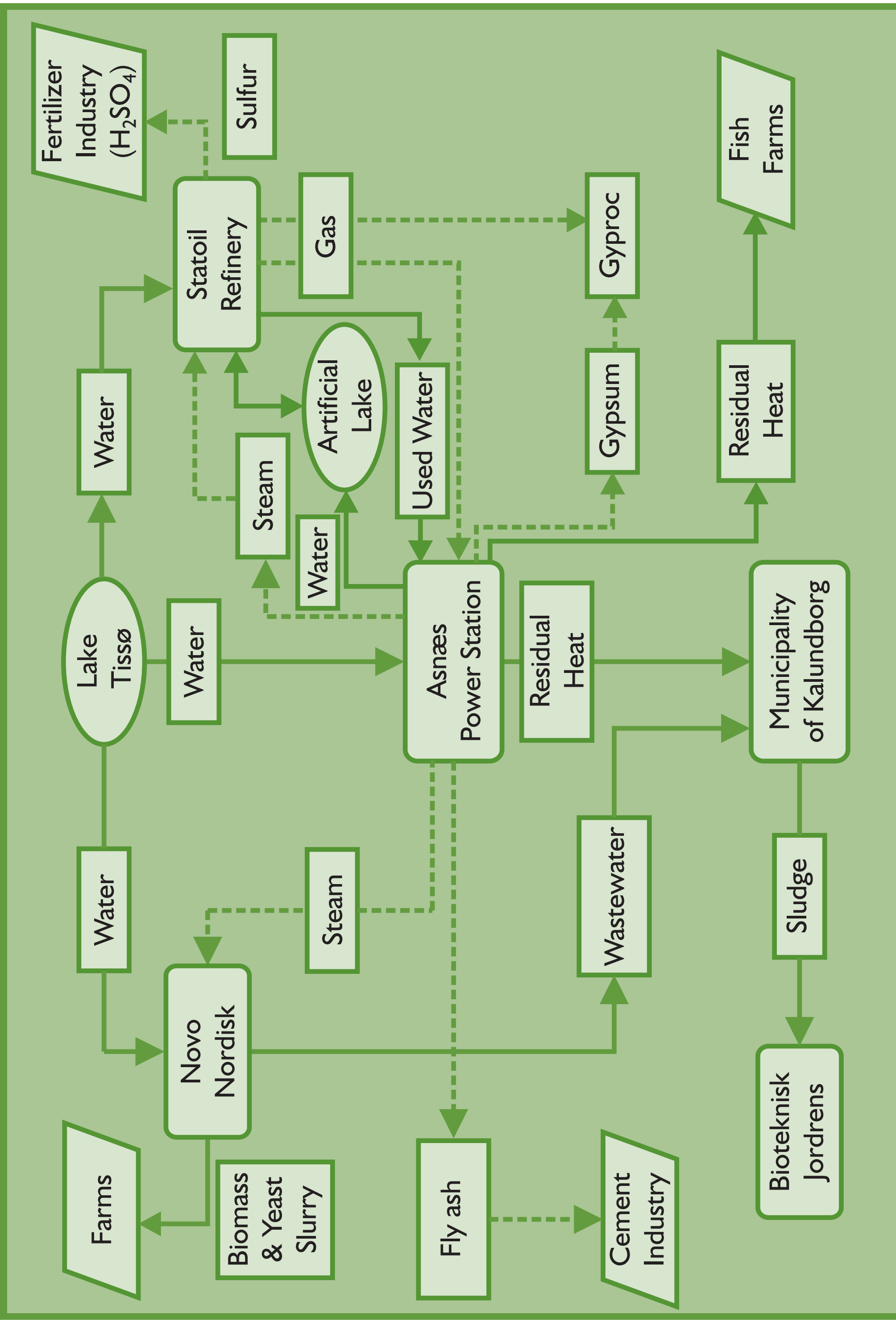
Thanks to the symbiosis, the reduction in the use of groundwater has been estimated at close to 2 million cubic meters per year. However, in order to reduce overall water consumption by the partners, the Statoil refinery supplies its purified wastewater as well as its used cooling water to Asnæs power station, thereby allowing this water to be used twice and saving additionally 1 million cubic meters of water per year.

Asnæs power station supplies steam both to Statoil and Novo Nordisk for heating in their processes and, since it is therefore functioning in a co-generation mode, it is able to increase its efficiency.

Excess gas from the operations at the Statoil refinery is treated to remove sulfur, which is sold as a raw material for the manufacture of sulfuric acid, and the clean gas is then supplied to Asnæs power station and to Gyproc as an energy source.

FIGURE 1.1

Resource Flows in the Kalundborg Industrial Ecosystem (Status 1999)



Source: C. Francis, adapted from Christensen, 1999.

In 1993, Asnæs power station installed a desulfurization unit to remove sulfur from its flue gases, which allows it to produce calcium sulfate (gypsum). This is the main raw material in the manufacture of plasterboard at Gyproc. By purchasing synthetic waste gypsum from Asnæs power station, Gyproc has been able to replace the natural gypsum that it used to buy from Spain. In 1998, approximately 190,000 tonnes per year of synthetic gypsum were available from the power station.

Novo Nordisk creates a large quantity of used bio-mass coming from its synthetic processes and the company realized that this could be used as a fertilizer since it contains nitrogen, phosphorus and potassium. The local farming communities use more than 800,000 cubic meters of this liquid fertilizer each year as well as over 60,000 tonnes of a solid form of the fertilizer.

Finally, residual heat is also provided by Asnæs power station to the district heating system of the town. The system functions via heat exchangers so that the industrial water and the district heating system are kept separate.

The investment made to put the different material and energy exchanges in place has been estimated at $75 million. This is the cost of the 18 projects established up to and including 1998. Keeping in mind that each exchange is based on a separate contract between the two partners involved, revenues can be estimated as coming from selling the waste material and from reduced costs for resources. The partners estimate that they have saved $160 million so far. The average payback time of a project is less than 5 years. Therefore the clear lesson is that a more rational utilisation of resources is not only good for the environment, but also saves money.

In any discussion of Industrial Ecology, the Kalundborg Symbiosis has tended to take center stage as the model to emulate. The importance of the Kalundborg example is not just how a few companies can share their waste for improved profit and societal gain, but more importantly, how local communities and societies can find strategies that can improve their sustainability by using their resources more efficiently. The Kalundborg example is more important from the point of view that it successfully exemplifies a development strategy that is different from the conventional wisdom of the time.

There is no doubt that the Kalundborg model has fruitfully inspired the recent thinking on environmental management of industrial estates and eco-industrial networks. Yet there is also a growing recognition that we need to look beyond

Kalundborg. This is especially true regarding the implementation of Industrial Ecology in developing countries, where the industrial pattern is very unlike Kalundborg.

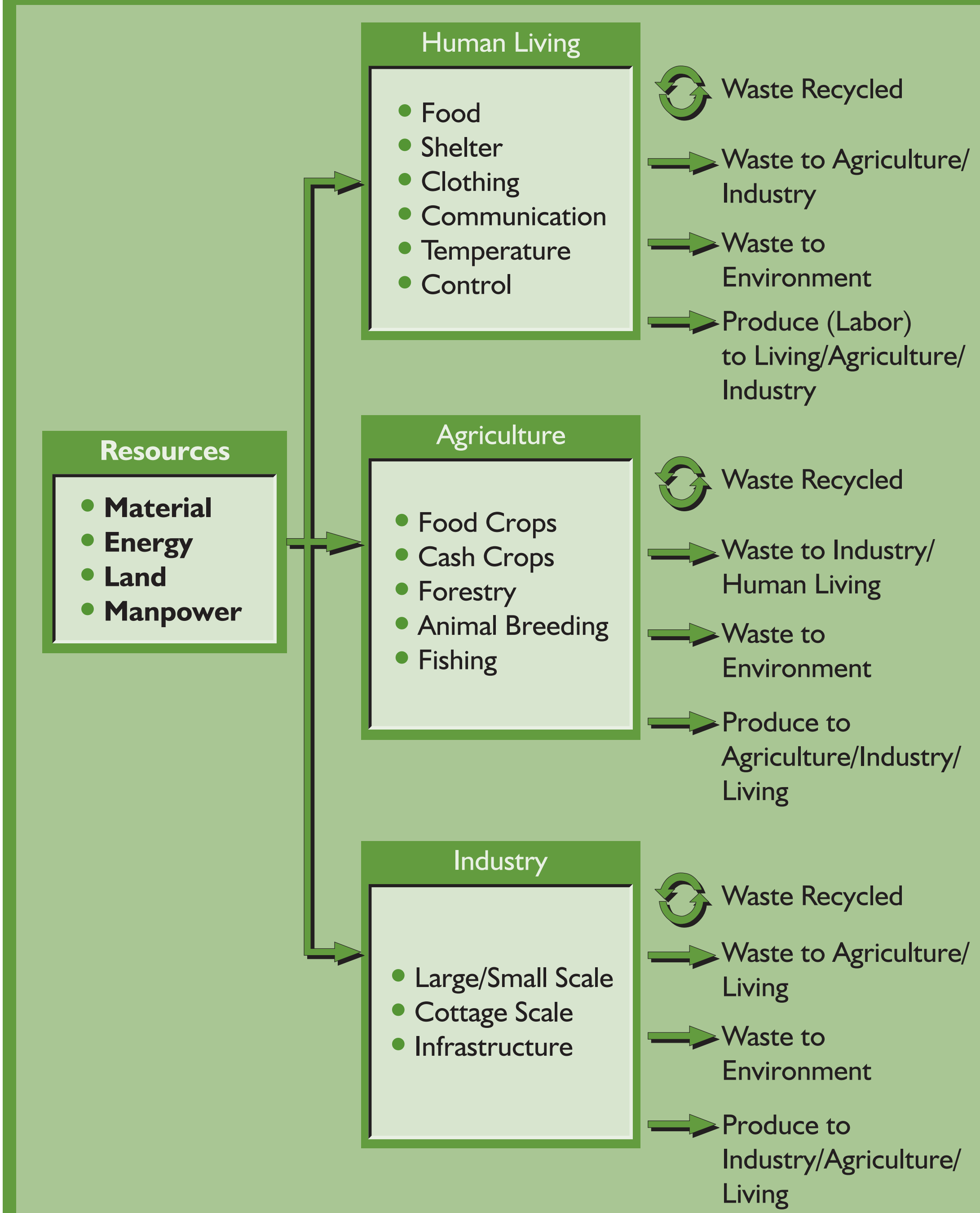
1.5 The Scope of Industrial Ecology

The term Industrial Ecology appears to suggest that it has something to do with just Industry or Ecology. But its scope goes far beyond that. In its very essence, in its broader definition, Industrial Ecology aims to study the flow of all resources (material, energy, land, forest, human resources, or any other) through an entire identified socioeconomic system (a town, region, state) with a view to strategically optimizing their use. The flow refers to the consumption of the resource (both the quantity and method of use) by different entities in the socioeconomic system. By this definition, Industrial Ecology lays emphasis on not just production but on consumption as well, either by individuals or by commercial entities.

The scope of Industrial Ecology at a regional level could be as depicted in Figure 1.2. The utility of such an understanding is obvious. To develop strategies for optimizing the use of resources, it is essential to make a detailed analysis of the quantitative data about their consumption by different entities in society. Such knowledge about the flows and patterns of use of resources, besides contributing to the sustainability of a region in a broad sense, also offers specific advantages. New business and employment opportunities can emerge from creating value from certain resources previously considered as wastes, or from detection of possible innovative linkages between companies. It also allows the anticipation of potential environmental problems, an invaluable asset for planners and public authorities.

FIGURE 1.2

Flow of Resources in an Economic System



Notes

[1] Robert A. Frosch and Nicholas E. Gallopoulos: 'Strategies for Manufacturing', *Scientific American*, Vol. 261, No. 3, September 1989, pp. 94-102. Special Issue on "Managing Planet Earth".

[2] Robert A. Frosch and Nicholas E. Gallopoulos: 'Towards an Industrial Ecology', in A.D. Bradshow et al. (eds), *The Treatment and Handling of Wastes,* Chapman and Hall, London, 1992, pp. 269–292.

[3] Hardin Tibbs: *Industrial Ecology. An Environmental Agenda for Industry,* Global Business Network, Emeryville, CA, 1993. (http://www.gbn.org)

[4] On "eco-restructuring", see Robert U. Ayres and Udo E. Simonis (eds), *Industrial Metabolism. Restructuring for Sustainable Development,* Tokyo, New York, United Nations University Press, 1994, and Suren Erkman, Colin Francis and Ramesh Ramaswamy: *Industrial Ecology: An Agenda for the Long-term Evolution of the Industrial System*, Proposal booklet for the 21st century, prepared for the Fondation Charles Léopold Mayer in contribution to the Alliance for a Responsible, Plural and United World, October 2001 (to be published as a book in 2003; also available at http://www.alliance21.org). Sections 1.3 and 1.4 of this chapter are based on a contribution by Dr. Colin Francis to this last reference.

[5] For an introduction to environmental management of industrial estates, the United Nations Environment Programme, through its Division of Technology, Industry and Economics (UNEP-DTIE), in Paris, has published two reference documents: *The Environmental Management of Industrial Estates*, Technical Report No. 39, compiled by Raymond P. Côté, Paris, UNEP Industry and Environment, 1997 (United Nations Publication: 92-807-1652-2), and *Environmental Management for Industrial Estates. Information and Training Resources,* prepared for UNEP–DTIE by ICAST (Colin Francis and Suren Erkman), Paris, 2001. (United Nations Publication, ISBN: 92-807-2078-3, also available at: http://www.uneptie.org/pc/ind-estates/home.htm)

On eco-industrial parks (EIPs), see for example, Raymond P. Côté and Ed Cohen-Rosenthal: 'Designing eco-industrial parks: A synthesis of some experiences', *Journal of Cleaner Production*, Vol. 6, No. 3/4, 1998, pp. 181–188; Bette Hileman: 'Eco-Industrial Parks Offer Economic And Environmental Advantages', *Chemical & Engineering News*, May 29, 1995, p. 34. See also Ernest A. Lowe: *Eco-Industrial Park Handbook for Asian Developing Countries*, prepared for Asian Development Bank, 2001. (http://www.indigodev.com/ADBHBdownloads.html)

[6] Conceptual examples of such eco-industrial complexes are presented in Nelson Nemerow: *Zero Pollution for Industry. Waste Minimization Through Industrial Complexes*, New York, John Wiley & Sons, 1995.

[7] Anthony Chiu: 'Ecology, Systems and Networking. Walking the Talk in Asia', *Journal of Industrial Ecology*, Vol. 5, No. 2, 2002, pp. 5–8. Additional references on EIPs can be found in the Bibliography at the end of the book.

[8] On the concept of dematerialization, see Robert Herman, Siamak A. Ardekani, and Jesse H. Ausubel: 'Dematerialization', in Jesse H. Ausubel and Hedy E. Sladovich (eds), *Technology and Environment*, Washington, DC, National Academy Press, 1989, pp. 50–69. Examples of increased resource productivity are exposed in: Ernst von Weizsäcker, Amory B. Lovins, and L. Hunter Lovins: *Factor Four. Doubling Wealth, Halving Resource Use*, London, Earthscan Publications Ltd, 1997.

[9] The understanding of the impacts of the knowledge based economy (or information society) on environmental sustainability is only in its infancy. An introduction can be found in: Global e-Sustainability Initiative (GeSI): *Information and Communications Technology*, report released by Global e-Sustainability Initiative and United Nations Environment Programme, Division of Technology, Industry and Economics, 2002 (http://gesi.org). For a preliminary assessment, see Frans Berkhout and Julia Hertin: *Impacts of Information and Communication Technologies on Environmental Sustainability: Speculations and Evidence*, report to the OECD, SPRU-Science and Technology Policy Research Unit, University of Sussex, Brighton, UK, 25 May 2001 (http://www.sussex.ac.uk/spru/). For a discussion in the perspective of the first United Nations World Summit on Information Society (WSIS), to be held in December 2003. See http://www.wsis.ethz.ch

[10] Walter R. Stahel, founder of the Product-Life Institute in Geneva (http://www.product-life.org/) has pioneered the ideas of durability and functionality; Walter R. Stahel: 'The functional society: the service economy', in Dominique Bourg and Suren Erkman (eds), *Perspectives on Industrial Ecology*, Sheffield, UK, Greenleaf Publishing, 2003, pp. 264–282. For recent developments, see Oksana Mont: *Functional Thinking – The Role of Functional Sales and Product Service Systems for a Function-Based Society*, Swedish Environmental Protection Agency, Report 5233, Stockholm, July 2002.

[11] For an introduction to the strategy of decarbonization, see Nebosja Nakicenovic: 'Freeing Energy from Carbon', in Jesse H. Ausubel and H. Dale Langford (eds), *Technological Trajectories and the Human Environment*, Washington, DC, National Academy Press, 1997, pp. 74–88, and also Robert Socolow (ed.), *Fuels Decarbonization and Carbon*

Sequestration: Report of a Workshop, Princeton, NJ, The Center for Energy and Environmental Studies, Princeton University, PU/CEES Report No. 302, September 1997. (available at: http://www.princeton.edu:80/~ceesdoe/)

[12] For an introduction by one of the early practitioners of the Industrial Symbiosis in Kalundborg, see Jørgen Christensen: 'Industrial Symbiosis: A Profitable Potential for Environmental Benefits', in P. Pangotra, S. Erkman and H. Singh (eds), *Proceedings of the Workshop on Industry & Environment*, held at Indian Institute of Management, Ahmedabad, India, February 5–6, 1999, pp. 56–77. For a recent discussion, see John Ehrenfeld and Marian Chertow: 'Industrial Symbiosis: the Legacy of Kalundborg', in Robert U. Ayres, and Leslie W. Ayres (eds), *A Handbook of Industrial Ecology*, Edward Elgar, Cheltenham, UK, 2002, pp. 334–348. The Symbiosis Institute, in Kalundborg, has also a web site: http://www.symbiosis.dk