Sustainable Production, Allocation and Consumption:

Creating Steady-state Economic Structures in Industrial Ecology

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Abstract of the PhD thesis

Industrial Ecology is an application of environmental management transcending the boundary of the individual firm. By comparing industrial systems to natural ecosystems, Industrial Ecology aims to emulate the sustainable state of the latter. Although research is flourishing, there are only very limited examples of Industrial Ecology in practice. Its proposed end state of a sustainable economic system is encapsulated in Thomas Graedel's "type III" system, where all ecosystem components live on their exchange products, and the whole system runs exclusively on solar radiation as its source of energy.

This doctoral thesis is conceived from the recognition that the idea of Industrial Ecology at present is in conflict with the applications of it, and the field thus needs to be grounded in a solid body of theory. Therefore, this thesis examines for the first time the soundness of ideas and current practice of Industrial Ecology in the context of the fields of science concerned:

Ecological economics has the purpose of understanding the relationship between ecological and economic systems. It is the recognition of the biophysical limits to economic activity that is applied to Industrial Ecology in this thesis.
The aim of embedding the economic system into the natural system that ecological economics and Industrial Ecology have in common is examined in the light of research in theoretical ecology, understanding the dynamics of ecosystem development. The consequences for industrial ecological systems lie in the insight that food chains are merely the expression of underlying energetic relationships, and it is the latter that drive an ecosystem in its development towards a mature and stable state.
As Industrial Ecology's method is to compare economic systems to natural systems, the soundness of this method needs to be ascertained. The translation of ideas from one area to another constitutes a use of metaphor, and it is in the valid transfer of ideas that Industrial Ecology has its merit. Consequently, a chapter of the thesis investigates the transfer of ideas in the context of Industrial Ecology.
In a final analytical chapter, the idea of Industrial Ecology is compared to the realities of the current system of international business enterprise. By examining this system and the role of competition within it, both in its ecological and economic consequences, the conclusion is arrived at that Industrial Ecology constitutes a step away from an individualistic perspective in business management, and is therefore not directly and widely applicable in the current system.

Building on these insights, the final chapter proposes a reconceptualisation and reembedding of Industrial Ecology. This is thought to be achieved by incorporating the cyclical ecosystem perspective into industrial ecological development. Further, it is shown that this development can be encouraged by government initiatives such as the implementation of an ecological tax reform.

I, Christoph Hinrich Rochus Bey, declare herewith that the following work is my own work. I have acknowledged the works and ideas of others when making use of them in the text. Permission has been obtained from the publishers of *Business Strategy and the Environment*, ERPEnvironment, for inclusion in this thesis of my journal article published.

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Introduction

1. The core idea of Industrial Ecology

"Learning from nature" is the core philosophy of Industrial Ecology, a still new discipline that is trying to find its place in the canon of sciences. Researchers and practitioners in Industrial Ecology act from a belief that the current form of human development will, in the long term, be leading at least the species *homo sapiens sapiens* into calamity, and probably with it, a vast number of species from the animal and plant kingdoms. The recognition that the current form of economic production and consumption, together with growing numbers of population, is at odds with the surrounding natural system of the biosphere leads industrial ecologists in the endeavour to study nature and how life has developed over the last aeon to develop a firm hold on the earth, with every single niche being explored and occupied. The central idea of Industrial Ecology concerns the adaptation of human socio-economic processes, especially industrial production, to natural constraints, at least on a global level. As such, Industrial Ecology forms part of an important departure from a liberation of human society from natural constraints (which can be seen as underlying all technological development since the Stone Ages). By "learning from nature", Industrial Ecology attempts to reverse this increasing isolation of humankind from its resource base (including waste assimilation capacity).

Industrial ecologists have identified a handful of situations where "nature", mainly understood as natural ecosystems, was taken as a blueprint for different organisation and use of resources. Industrial ecologists have been at work in business enterprises, redesigning production processes. Thus, the discipline showed a slant towards technological solutions, and it is engineers that comprise the biggest part of Industrial Ecology's actors and audience. "Learning from nature", though, is not a trivial enterprise of finding and copying "best practice" situations, very often in an attitude of "pick and mix". When that motto of learning from nature is pondered seriously, the question assumes more than just a technological importance: what image do we have of "nature"? Where does human understanding of nature derive from? What does "learning" constitute, what can be learnt from "nature", and where is behaviour in natural systems misleading as an example for socio-economic behaviour? Consequently, a thorough work in Industrial Ecology needs to take into account more scientific perspectives than just the engineering one. In that, the discipline seems to mirror the general discourse on environmental issues, where either a technological, an economic, a biological/ecological, or a social and philosophical endeavour and understanding is utilised, and more often an integrated perspective of all these fields is called for.

This doctoral project in the field of Industrial Ecology recognises the need for a multidisciplinary perspective. Thus, it became clear to the author that it needed to be a theoretical endeavour: supposedly "interdisciplinary" empirical projects have to place an emphasis on one main discipline that pervades the whole of the research project. As Costanza and King point out in their anniversary editorial to celebrate the first ten years of the scientific journal "Ecological Economics", a survey of the focus of its articles provides an insight towards how most interdisciplinary work is carried out. Contributions can be sorted into the categories of either economics or ecology: once the main perspective has been established, further perspectives are incorporated through a "bolt-on" approach. The aim of this thesis, thus, is not to establish one existing perspective as a foundation, but to build bridges and moderate between a number of different disciplines.

"Learning from nature" comes to be understood in the following as a translation effort between natural and social systems. In the presence of a field with a growing body of research, but, it is felt, lacking proper understanding of the driving forces underneath, this thesis is envisaged to be complementary to the applied research carried out so far. Its main results will be in attempting to validate Industrial Ecology as a coherent scientific field whose applications are an expression of its core ideas and values, and thus, establishing "learning from nature" as a scientific enquiry. This is even more necessary as Industrial Ecology is still in the process of formation and far from being an established field. Scholars from dozens of different academic backgrounds are active, providing, at least in theory, a basis for a lively dialogue. It is interesting, though, to observe that research trying to answer "why?" questions is rare, and that the body of research is taken up by answering "what?" and "how?" questions.

In the same way it must be said that the presence of scholars in Industrial Ecology who come from different fields does not have to lead to a multidisciplinary endeavour: only when inputs from all the different disciplines can be discussed constructively and each and every participant of that discussion is able and willing to abandon the narrow perspective of the specialist field he or she is an expert in can reorganisation of socio-economic systems be undertaken by the sciences in any serious manner. In the absence of this open mind, communication among scientists from many different fields resembles more a "babylonic confusion" than informative work.

What is needed for present attempts to understand and to resolve the conflict between a short term human and a long term ecological welfare is a permeation of the boundaries between the different sciences, especially, the natural and the social sciences (in which we here include the humanities). The rigid separation and definition of scientific disciplines is only a recent phenomenon: from the constitution of the modern sciences in the wake of humanist philosophy at the beginning of the Modern Age in the 16th century until the end of the 19th century (e.g., the impact of Darwin's "Origin of Species" in Britain's Victorian society), scientific discourse was conducted in an ambience of broader education and understanding. The proliferation of knowledge since then, together with a rapid technological development and the specialisation of research that the latter engendered, has made this broader perspective not just very difficult to accomplish, but even difficult to take into consideration. By calling itself "the science of sustainability", Industrial Ecology is as guilty of this tunnel vision as any other monoculture of the mind. The combination of insights from a number of fields of science in a thesis written in a reflecting manner (that owes much to the essays of humanist writers like Montaigne) supposedly supports and contributes to that early modern form of integrative scientific dialogue.

This approach to the research subject enables the researcher to perceive the subject and the work in quite a different way than a more empirical approach would have made possible:

Firstly, Industrial Ecology abounds with case studies and applied research, so much so that this "science" is said to "operationalise" sustainability. This doctoral thesis holds that that claim will need to be examined, by drawing together strands of the sciences that contribute to ecological and economic reasoning and application of it. More applied research in the form of case studies can easily be undertaken by other research projects that are more confined in their scope. Each of these cannot roam far from the immediate subject they are examining: doctoral research, on the other hand, has that licence.

Furthermore, in the course of the doctoral thesis, concepts such as globalisation, sustainable development, economic growth, welfare are discussed; ideas that also have a political nature, not just a economic or technological one. All these terms prove rather difficult to define in a way that is broadly accepted by the majority of participants in scientific and public discourse, as any attempt at definition is met by a discussion on the political motives of the person putting forward the definition. This political stance can be found in the selective approach to data gathering and analysis as well: the data-rich nature of the research subject, the "world system" that surrounds us, demands a research attitude that for most purposes should substitute scope and relevance for focus and rigour. This has become true for life-cycle analyses, for example. For the theme of globalisation it emerged in the course of this research work that the complex nature of the subject under consideration enabled the fitting of selected evidence to a preconceived theory rather than a supposedly independent scientific enquiry.

Lastly, the fact that Industrial Ecology is gaining currency among researchers, business enterprises and government officials means that the discipline needs to be examined critically against what is there to be achieved (a sustainable economic system), in order for it to not become the latest tool for "hijacking environmentalism" (as Welford describes in his book of the same title). For this, not just more case studies are needed (which in Industrial Ecology have considered the "low-hanging fruit" of short term gains), but a systematic examination of all the underlying assumptions to a development path towards sustainable development with the help of Industrial Ecology.

Consequently, what is needed is an investigation not only into the environmental impact of the manufacturing of products and the creation of services, but into the environmental and social consequences of allocating (for example, effects of economies of scale, competition) and consuming them. Thus for this doctoral thesis, the focus of Industrial Ecology lies on whole systems of production and consumption that are embodied in infrastructures rather than on individual products, as is standard practice in the field.

This stance calls for a shift away from the supply-side measures that are preferred by business enterprises - the nature of demand is understood to be an exogenous factor to economic analysis, and changing demand would involve a critical view of growth and consumption. However, given the impossibility to dematerialise completely economic activity, it is precisely there that sustainability and thus Industrial Ecology will have to be anchored. Industrial Ecology, by virtue of its underlying metaphor, is supposed to be a general concept for an entire sustainable economic system, not just a technological solution that is applied in manufacturing. Including analysis of allocation and consumption systems into industrial ecological work reunites the discipline with its conceptual roots, the usefulness of taking nature as an example for reconsidering industrial systems.

A core concept of the thesis that requires the adoption of a multidisciplinary perspective is the action of translating concepts from one realm to another, that is, the activity of "learning" itself in Industrial Ecology's motto. Not only the nature of the source and the target subjects of the translation have to come to the attention of researchers, but also the process of translation itself needs to be understood properly: in the history of science it has been this process that was employed with regularity, and it was there that misperceptions about one subject came to be anchored as dogma in another subject. This translation becomes the mainstay in Industrial Ecology as the "ecological metaphor" that is employed to enable understanding of a social system in terms of the natural one.

This introduction also serves the purpose of making clear the "preanalytic vision" (in the words of the Austrian economist Schumpeter) of the doctoral thesis: this fundamental recognition considers an ecological view of human society, a socio-economic system that is embedded in the totality of all ecosystems that is the earth's biosphere. The preanalytic vision comprises the recognition of biophysical limits to resources and ultimately, resource substitution. More importantly (as chapter 2 argues), the biosphere's finite capacity to assimilate pollution belongs to this category of biophysical limits. This physical perspective, a constraint on an economic system that is growing in absolute physical terms, is the underpinning of the thesis: the second chapter is devoted to a thorough discussion of this perspective that Industrial Ecology is urged to adopt as its scientific basis. The biophysical perspective underlies further the chapters three, five and six.

2. Structure of the argument developed in the thesis

Industrial Ecology has been founded in the confluence of several academic and professional disciplines, the most prominent being engineering. As the field draws upon ideas and concepts of diverse fields, it ought to be evaluated with the help of analytical tools from these fields and to be provided with a coherent grounding. This thesis is concerned with an examination of the validity of Industrial Ecology's contribution to sustainable development. This claim to validity is becoming increasingly important as the theoretical foundations of Industrial Ecology are assumed to have been laid out, and further work will have to focus on actual restructuring and communication of the aims to policy-makers. Furthermore, the field lays claim to being the most important framework for creating structures that adhere to the goal of sustainable development. Industrial Ecology has variously been described as "the science of sustainability" (an editorial statement in Journal of Industrial Ecology) and to be "an operational approach to sustainability" (in the words of Suren Erkman, a science journalist and first historian of Industrial Ecology). This doctoral project takes statements like the above as an invitation for an evaluation of Industrial Ecology in its aim and practice, with respect to a compatibility with what is understood by sustainable development.

Therefore, this work of research proposes that Industrial Ecology be evaluated with respect to its neighbouring disciplines in academic enquiry and practical application. Over the course of history of science the increasing quantity of research endeavours has led to the underlying basis common to all sciences to become fragmented, resulting in only very rudimentary understanding of scientific concepts outside any chosen field. For the subject of Industrial Ecology, which draws heavily on insights from other scientific disciplines, it is of paramount importance to carry out its conceptual translation and application in an informed way, if it is to gain widespread respect in the scientific community and shape governmental and corporate decision-making, rather than becoming a green cloak for a predetermined kind of policy-making that is averse to the prospect of fundamental changes.

For this reason, the thesis is organised in three parts: the first, introduction to the field and the problematic, a second, evaluation of Industrial Ecology within a set of perspectives from the natural and social sciences, and the third, reconceptualising and reforming its applications.
While providing an introduction to the field of Industrial Ecology in research and applications currently pursued, the first chapter serves as a primer to highlight problem areas, most importantly the boundaries of the system under observation. As a conclusion, although Industrial Ecology is seen as a potentially helpful endeavour to bring about a sustainable human society, it cannot be seen as a panacea: the success of the concept in research and in applications depends very much on the recognition of a much broader scope than previously employed.

In the second part, the thesis commences the analysis of Industrial Ecology's scientific foundation by attempting, in the second chapter, to tie Industrial Ecology to an underlying concept of sustainability. The system under investigation by Industrial Ecology will have to be established clearly, as the current confusion of the industrial with the overall economic system results in Industrial Ecology being still a rather vague idea. The chapter considers Industrial Ecology grounded in ecological economic thinking, and most importantly, as a part of a steady-state economic system.

In further chapters of the second part, the thesis examines Industrial Ecology's observed system in an appropriate, that is, a complex systems, context. The following two chapters constitute a focal point of the thesis, as they seek to create a foundation for proper scientific endeavour in Industrial Ecology:

Firstly, in the third chapter the argument will be made that any human-made system should be regarded as a self-organising dissipative system, in the very same way as non-human living or non-living systems. Analysis in this chapter is concentrating on a dissipative system's, and in particular, a human-made system's, underlying energetics and material flows. These insights from work in thermodynamics, particularly the common, energy-dissipating nature of all complex systems, will provide the discipline of Industrial Ecology with the justification and the guidance for the translation between natural and social systems it endeavours.

Having thus established the reason for comparing characteristics of natural ecosystems with industrial systems, the fourth chapter will be an attempt to lay down rules for this translation, which has been done hitherto in a rather haphazard, intuitive way that was carried out on individual and isolated examples rather than in a systematic fashion. In this chapter, the metaphor underlying industrial ecological thinking is discussed and its use evaluated, with respect to the quality of scientific reasoning used in establishing the field. A great number of scientific works in all fields of science is actually governed by the use of metaphors, with varying degrees of success. The validity of one discipline's core concepts is in this case based on assumptions that are derived from translation of ideas from other fields.

In the following and last chapter of the second part, it will be shown what consequences a rebasing of industrial ecological analysis and restructuring will lead to, when the whole of the economic system is contemplated as the system under observation. Industrial Ecology is infused here with a social dimension that is as yet missing: the inclusion of market allocation and consumption patterns in industrial ecological analysis makes it clear that the field cannot be solely grounded on a technological or engineering underpinning. It was questions considered in this chapter that originally gave rise to the whole of the research project: does the process of market allocation contribute to a waste of resources and energy?

The third part, consisting of the sixth chapter and a subsequent conclusion of the research work, will utilise the amendments to the foundation of Industrial Ecology that emerged from the previous part, synthesising them into applications properly informed of the underlying aims and structures of the field. Whereas the second part was mainly taken up by a critique of the present state of scientific enquiry in Industrial Ecology and the founding of a more appropriate scientific basis for industrial ecological research work, the sixth chapter contains an examination of new concepts for research and application that are derived from the foundation laid earlier. As a policy proposal, the implementation of an ecological tax reform in the understanding of gradually rising fossil fuel taxes over a time horizon of two generations is seen to be at the heart of an Industrial Ecology that takes sustainable development seriously.

Part I

A review of Industrial Ecology in theory and application as a basis for the research work

Chapter 1

Industrial Ecology:

Developments in the field and its current standing

1. Chapter introduction

This chapter serves as an overview of the field of Industrial Ecology, pointing out major contributions in research and applications that resulted in the field assuming the position it finds itself in today. The chapter will give an outline of the history of the term and discusses the associated academics and practitioners who helped to bring the field to light as a major contribution towards efforts in environmental protection and management. Industrial Ecology derives considerable strength from diverse origins, and these and the concepts that enriched the field and gave it its appeal need to be analysed. From there on, the discussion sheds light on the individual applications that make up the remit of Industrial Ecology as it is understood today.

The chapter's structure follows the stipulation of research leading to applications that was brought forward in Industrial Ecology independently by two research teams, the team of Wernick and Ausubel at Rockefeller University, and the one led by Vellinga at the Free University of Amsterdam. Both teams agreed on a division into three hierarchical layers: the metaphor (Wernick and Ausubel 1997) or "intuition and beliefs" (Vellinga et al. 1998, p. 323) as the foundation leading to the development of derivate concepts and principles that in turn give rise to applications (Wernick and Ausubel 1997) or research tools (Vellinga et al. 1998, p. 324f).[1] This hierarchical structure is not peculiar to Industrial Ecology, as indeed scientific research in general, and in policy-relevant areas in particular, aims to encompass and franchise these three levels, and more importantly, provide a valid translation from one level to the next, and ultimately, to practical applications.

The last section comprises as a summary salient characteristics of industrial ecological research and applications mentioned before that need to be observed and evaluated further, leading to the introduction of methods to analyse and critique these characteristics constructively in later chapters of the thesis.

2. Landmarks in the establishment of Industrial Ecology as a discipline

An historical approach to developments in Industrial Ecology is appropriate to understand properly the dynamic shaping of the field that is still comprised of participants and ideas coming from many different disciplines, including nearly all fields of the natural sciences and engineering, and several ones of the social sciences. Its historic developments being understood means that the concepts that build the foundation of Industrial Ecology and comprise its remit can be appraised with a view of their validity, which will be done in subsequent chapters. If the field is observed to have undergone a change in its foundations, this will have implications

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[1] It should be noted that in this hierarchical structure of ideas in Industrial Ecology the validity of applications depends on the quality of translation across two layers, arising from the foundation of the metaphor. Research tools and applications are therefore twice removed from the level of understanding the metaphor. This distinction between general concepts and applications is not exclusive to industrial ecology; it applies to any research field that attempts to link theory to practice. It is in the translation of the fundamental level into the layer of applications that a research field is constituted correctly, that is, in the spirit and understanding of those "intuitions and beliefs" or not. Kuhn (1962) called the latter a "paradigm", Schumpeter (1954) used the more precise "preanalytic vision".

for its status as a credible endeavour in research and an appropriate tool for policy-making.

Industrial Ecology as a term came to the attention of a wider audience in 1989, via an article published in the widely read monthly magazine *Scientific American*. The authors, Robert Frosch and Nicholas Gallopoulos (Frosch and Gallopoulos 1989), managed to galvanise the scientific community and to draw attention to the few scattered efforts on the theme with their paper called "Strategies for Manufacturing". It explored the idea that industrial production could be restructured and reorganised to result in a much decreased environmental burden. The resulting industrial system would share a significant amount of characteristics with biological or natural ecosystems. The impact of this article, according to Erkman (Erkman 1997, p. 5), was considerable, as it brought out an intuitive sympathy in many people, especially industrialists who were looking for a new framework to incorporate an increasingly pressing environmental agenda into industrial production.

"Strategies for Manufacturing" centred on the idea that the traditional linear mode of industrial production (input-processing-output), for improving environmental performance of industry, should be supplanted by a cyclical mode, where one producer's output was utilised completely, so that all the wastes that accompany manufacturing would become by-products that could be sold on to other manufacturers, eliminating at one stroke the two problems of increasingly scarce virgin natural resources for input and creation of wastes that created overloaded landfill sites and filled up sinks in the biosphere in the form of pollution that was felt globally. The article suggested the closing of linear streams of resources as an elegant solution that requires technological and organisational changes for the manufacturers (the only actors believed to be involved). Industrial ecosystems are thought to be created to help conserve precious resources, especially metals (examples include cycling of iron and noble metals from the platinum family). These resources are desired to be shifted from landfills back into production processes. Other forms of pollution, such as deposits of various materials in water and air, were not discussed by Frosch and Gallopoulos. The authors refrained from suggestions that go further than the understanding of cyclical networks in industry as a kind of ecosystem.[2]

Since the publication of this article, it has been researchers and practitioners mainly in the United States who by creating research projects and publishing articles and books helped the field to acquire critical mass.

Earlier attempts at creating a new discipline in the confluence of business and ecology had been coming to the surface at least since the year 1970, when a journal called *Industrial Ecology* was launched, but turned out to lead only a very shortlived existence. During that time, efforts to view and assess industrial production from an ecosystem perspective were under way in several places in Europe and in Japan. Erkman (Erkman 1997, p. 3f) emphasises, besides mentioning a project in Austria (at IIASA, Laxenburg) and a conference in Germany (the 1977 annual meeting of the German Geological Association), in particular the work carried out since the late 1960s by the Industrial Structure Council in Japan, a consulting agency to MITI, and the effort in the early 1980s by the Centre de Recherche et d'Information Socio-Politique, an independent research centre in Brussels, Belgium.

The work carried out in Belgium set out to describe the Belgian economy, not in traditional terms of flows of abstract monetary units, but by concentrating on the underlying flows of materials and energy. The study, titled "L'Ecosystème Belgique. Essai d'Ecologie Industrielle" (Billen et al. 1983), can be seen as the first to provide a definition[3] of Industrial Ecology and an application of it, by likening the Belgian economy to an ecosystem. Reception of this study has been reserved at the time, so much so that the authors who worked on it on top of their individual occupations suspended further research efforts.

In Japan, the efforts in the late 1960s seemed to have been built upon and incorporated into successive projects, so that a continuous line emerges over these

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[2] Erkman (1997, p. 5) gives an explanation that might shed some more light on the article's underlying philosophy: The original title of Frosch and Gallopoulos' paper for Scientific American was "Manufacturing - the Industrial Ecosystem View", but this was not accepted by the journal's editor.

[3] This definition will be discussed further below, as it is compared to definitions of Industrial Ecology by a number of other researchers and practitioners.

last 3 decades. The legacy of the project, carried out by the Industry-Ecology Working Group of MITI (it is here that the term "Industrial Ecology" is said to have originated), rather than remaining in an independent position, contributed to and was subsumed in research programmes into development of industrial technology by MITI (Erkman 1997, p. 4).

Published in its first form two years after the article by Frosch and Gallopoulos of 1989, there is one other landmark publication in Industrial Ecology (judging by the amount of quotations of the paper and sustained interest by industrial ecologists in a small town on the island of Sealand, Denmark) that helped to define the field, this time in terms of providing an example of an industrial system exhibiting ecosystem characteristics. Hardin Tibbs' paper "Industrial Ecology: An Environmental Agenda for Industry" was published first in 1991 as a working paper for Arthur D. Little, the strategic business consultants, and subsequent revisions appeared in the two following years with the journal *Whole Earth Review* and the Global Business Network (Tibbs 1992). Tibbs endeavoured to promote Industrial Ecology as the governing conceptual framework that incorporates and strengthens individual applications in corporate environmental management, seeing Industrial Ecology's intent "to create a common cause between industry and environmentalism" (ibid., p. 7). Tibbs uses language that puts a technological emphasis on environmental management solutions, apparently to distance himself and Industrial Ecology from mainstream environmentalism, which is traditionally perceived by industry, he maintains, "as passive, regressive, anti-growth, and anti-technology" (ibid., p. 8).

In his paper, he gives an outline of six areas where application of Industrial Ecology concepts and practices can be useful: creation of industrial ecosystems (discussed below), balancing industrial input and output to natural ecosystem capacity, dematerialisation of industrial output, improving the metabolic pathways of industrial processes and materials use, creating systemic patterns of energy use, and lastly, policy alignment with a long-term perspective of industrial system evolution (ibid., passim). Industrial Ecology, according to Tibbs, can provide a perspective and a yardstick for industrial development in the long run, where industrial and natural systems coexist in harmony, without the former encroaching upon the latter and destroying them.

Tibbs is the first to mention the flagship application of Industrial Ecology, the waste exchange network at Kalundborg, a small town in Denmark, west of Copenhagen. His discussion of the evolving system at Kalundborg popularised it and led to a host of other publications and research (Kalundborg is discussed further below in the section on "industrial symbiosis").

What has to be noted is Tibbs' style throughout the document: in order to get industry to notice the concept of Industrial Ecology and start to develop an interest in environmental management, he has decided to emphasise technical solutions for the description of immediate applications in Industrial Ecology, and to extend his discussion to overall system conditions for an industrial system that achieves a state of sustainable development. Only once, he mentions a moral obligation (which has been a traditionally problematic issue with business enterprises), only to move on quickly. Although Tibbs' writings were based on Frosch and Gallopoulos' article (Frosch and Gallopoulos 1989), his merit lies in introducing the concept of the new field to businesses, and doing so in a more elaborated and comprehensive way than Frosch and Gallopoulos apparently were able to do (cf. note 2).

The collection of seminar papers of a colloquium held by the National Academy of Sciences of the USA in the same year, 1992, can be seen as the first evidence of the field's visibility - among the presenters are a congressman, a lawyer, and several engineers, businesspeople and a high-ranking economist, William Nordhaus (cf. Ausubel, Ayres, Brown, Duchin, Frosch, Henrichs, Hoffman, Jelinski et al., Luzier, Mitchell, Nordhaus, Patel, Piasecki, Ross, Smart, Speth, Stein, Troxell, all 1992). After these publications, the research field could be regarded as established and gathering critical mass in terms of active participants and number of publications appearing in about a dozen journals, mostly in the field of engineering and materials research, but in recent years spilling over into journals of business management. Conceptual papers and books that extended or elaborated the basic framework serving as a scientific foundation, however, have not been published[4] since the founding publications of the early 1990s in the field, which turned its attention increasingly on applications in industry. Below, these applications and individual tools that comprise industrial ecological work in research and practice will be treated, after and in the light of a discussion of the central plank of Industrial Ecology: its observation of economic systems through the lens of ecological systems (natural ecosystems).

Lastly, it is important to point out that the field is indebted, consciously or not, to work carried out by the systems ecologists, brothers Howard T. and Eugene P. Odum, the latter publishing an article in *Science* titled "The Strategy of Ecosystem Development" (E. Odum 1969). This paper not only introduced the scientific community to dynamic ecosystem behaviour in terms of ecological succession from pioneering to mature (climax) ecosystems, but also provided a cue for the field of Industrial Ecology to come, as Odum advised taking these insights further by applying them to the development of human society and its socio-economic system. It will be seen further below how industrial ecologists have reacted to Odum's recommendations.[5]

The following university institutes are currently active in the field, providing research facilities and teaching programmes:
The USA and Canada comprise more than half of the world's research teams at the following universities: Rockefeller, MIT, Harvard, Princeton, Berkeley, Georgia Tech, Yale, Columbia, Cornell, New York, Rutgers (all USA), and Dalhousie (Canada).
The business enterprises AT&T, General Motors and the Lawrence Livermore Laboratory have been focal points in the constitution of industrial ecological research projects.

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[4] There are only three journal publications that offer a critical attitude towards the concept and its implementation: O'Rourke et al. (1996), Commoner (1997), and Connelly and Koshland (1997), and these were related in that the latter two publications reacted to and built on the ideas put forward in the first. Reception of these critiques has been muted in the field: the authors were cited, their ideas, though, not discussed further (e.g., Andrews 2000).

In Europe, research centres are predominantly located in Scandinavia, Austria and the Netherlands, the countries and regions with the highest environmental spending per unit of GDP: NTNU (Norway), Joensuu, Jyväskylä (Finland), Lund, Göteborg (Sweden), Amsterdam, Rotterdam, Leiden (Netherlands), IIASA (Austria), and INSEAD (France).

3. The founding idea of Industrial Ecology

The idea that lies at the heart of Industrial Ecology has been expressed in many ways by a considerable number of participants in the field[6], an idea that can be understood, however, in mainly three different forms that gravitated towards each other and derived strength from association with one another.
Although coming from different perspectives and focusing on different characteristics, these three formulations can be understood to use the very same approach, viewing industrial and economic activity from an ecological and biophysical perspective.

The three instances of the central idea in Industrial Ecology are called the "industrial metabolism" (Ayres and Simonis 1994, title of the book), the "biological ecosystem analogy" (Frosch and Gallopoulos 1989, p. 94, and many others) and "industrial symbiosis" (coined by V. Christensen, production manager of Asnæs of Kalundborg, quoted in Engberg 1993).

These three terms were chosen to represent the core concept of Industrial Ecology, because all of them describe processural activity in material and energy use, albeit on different scales.

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[5] A number of researchers have regularly quoted from publications by one or both of the Odum brothers, among them Frosch and Gallopoulos (Frosch and Gallopoulos 1989).
[6] Raymond Côté (Côté 1995, quoted in Erkman 1997, p. 1) from Dalhousie University provided a compilation of definitions of Industrial Ecology in early literature on the field that emphasised three key elements: the systemic, comprehensive and integrated view of the industrial economy; the focus on material flows rather than monetary flows; and consideration of technological dynamics.

In biology, metabolistic activity refers to the processing of matter and energy at the individual organism level. It is for this reason that metabolistic activity in industrial systems is observed as a cradle-to-grave activity, parallel to biological organisms taking in nutrients and excreting waste. The system boundary for observation of metabolistic activity lies exactly here at the individual level, which might make translation of the concept onto larger entities, eg, whole economies or industrial systems, difficult.

Symbiosis is observed to govern activities of material and energy processing at the inter-organism level, whereas the "ecosystems analogy" describes processing at the highest level, the one of ecosystems that incorporate both relationships between individual actors and processing activities inside an individual actor. The results of ecosystems analysis are translated by industrial ecologists into restructuring of entire industrial systems, or even the whole of the socio-economic system.
Another reason for discussing industrial metabolism and industrial symbiosis as core concepts in Industrial Ecology is the fact that both concepts existed before Industrial Ecology as a field was constituted. The latter, though, incorporated the former two very quickly, and they came to be seen as lying at the heart of the field.

It will be pointed out below how these ideas are used to further not just understanding of Industrial Ecology as a scientific discipline, but also policy-making for industrial restructuring. Industrial Ecology aims to fulfil both a descriptive and prescriptive role. This sets it apart from other concepts, such as pollution prevention or pollution control; Industrial Ecology attempts firstly, to provide a framework for analysis, a language that enables understanding industrial systems, secondly, to establish a desired goal, a sustainable industrial system, and thirdly, to have at its disposal tools that are aimed to assist decision-making towards that goal.

3.1. Industrial metabolism

This term was coined and disseminated by Robert Ayres, an engineer by training become professor of environmental management, at first in a single publication in

1978 (Ayres 1978), followed by a whole string of papers and books that commenced a decade later, chiefly among them the edited volume "Industrial Metabolism" (Ayres and Simonis 1994).

It predates the field of Industrial Ecology, but since the latter's inception as a research field proper in 1989 it has been closely associated and effectively incorporated into Industrial Ecology as a strand of research consistent with the overall aim of the field; documented by a book published by Ayres two years after the edited volume mentioned above: "Industrial Ecology: Towards Closing the Materials Cycle" (Ayres and Ayres 1996).

Ayres defines industrial metabolism as "the whole integrated collection of physical processes that convert raw materials and energy, plus labour, into finished products and wastes" (Ayres 1994, in Ayres and Simonis 1994, p. 3). It should be noted that according to this definition by Ayres, the metabolistic activity of industry and the analysis thereof ceases at the finished product (a cradle-to-grave approach, which will be discussed further below in the context of the ecosystem metaphor).

The concept of the industrial metabolism derives value from the idea of dissipation in systems: Like all complex self-organising systems (cf. Nicholis and Prigogine 1977), both natural and industrial systems, among others, dissipate materials and energy by degrading, dispersing and losing them in the course of usage. The underlying theory of self-organising systems provides the vehicle[7] for translating understanding of the natural systems realm to the one of human-made systems.

Research under the name of Industrial Metabolism as a part of Industrial Ecology is concerned with mapping flows of materials and energy through the whole of the industrial system (mainly through application of materials-balance and input-output analyses).

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[7] This is the immediate meaning of the word "metaphor"; transfer, to carry, to bear (Longman Dictionary of the English Language 1992), discussed further below.

The use of the term indicates an intellectual proximity to the economist Nicholas Georgescu-Roegen, who published extensively on the material basis of monetary flows (in particular, Georgescu-Roegen 1971, passim). Georgescu-Roegen's use of the metabolism metaphor can be well illustrated: Analysing the economic system solely in terms of money flows "... is exactly as if a biology textbook proposed to study an animal only in terms of its circulatory system, without ever mentioning its digestive tract."(cf. Daly 1995, p. 151). Georgescu-Roegen's work was instrumental for providing economic theory with thermodynamic underpinnings, up until the 1990s the only contemporary academic doing so, but himself drawing on earlier work by economists and physicists in the later half of the 19th and the first half of the 20th century (e.g., Jevons 1865, Lotka 1922, Schrödinger 1955).

The idea draws attention to the underlying character of the economic system, that is, processing materials and energy by converting them in production and resulting in circular money flows, chiefly between manufacturers and households. Metabolistic activity is commonly associated with biological organisms which rely on a continuous intake of nutrients, partly assimilating them into body mass, partly using the nutrients' incorporated energy, and finally excreting waste in solid, liquid and gaseous form. Likening the metabolisms of biological organisms to the activities of the industrial system constitutes a use of a metaphor. Anderberg (1998) uses the industrial metabolism concept to describe the material flows in the Rhine Basin from the 1970s to 1988, where a shift in emissions from point-source (extraction) to consumption was diagnosed. Commenting on his own study, Anderberg suggests that industrial metabolism is in need of further development, as the concept neglects the spatial-temporal aspects of material flows as well as linkages to social and human dimensions (Anderberg 1998, p. 317). As yet, Anderberg maintains, the concept of industrial metabolism is unable to provide comprehensive analysis with the aim to reducing overall environmental impact, especially with respect to the impacts involved in consumption and trade. This makes him, to our knowledge, the only researcher who is mindful of the need to transcend the engineering slant that work in Industrial Ecology displays at the moment.

3.2. The natural or biological "ecosystems analogy"[8]

Whereas industrial metabolism, before it became more closely associated with Industrial Ecology, simply advocated that material and energy flows through an industrial system in its entirety should be observed and evaluated, the governing idea of the "ecosystem analogy" includes not only a metaphor, but an aim as well, a desired end state of human development that is conforming to a sustainable development. Thus, the concept has normative qualities, prescribing this end state rather than being descriptive of a present state, as the term industrial metabolism and its usage imply. The assumption of Industrial Ecology, embracing the "analogy", to become a prescriptive tool thus merits and necessitates a more comprehensive analysis, which is carried out in chapters further below.

It is the juxtaposition of human-made systems with natural systems that constitutes Industrial Ecology's attractiveness for as diverse participants as engineers, ecologists, business managers, physicists and related academic researchers and practitioners, prompting Ehrenfeld (1997) to conjure up yet another "paradigm shift".

This comparison serves as a justification to take over whole-scale concepts of ecology, such as biodiversity, and to attempt to translate them into industrial organisation (cf. Côté 2000, p. 11). An earlier and more inclusive attempt at translation can be found in Allenby and Cooper (1994): The two authors' thesis has the purpose to stimulate industrial ecological development by referring to and understanding it in terms of natural ecosystem dynamics. Their translation is based on work carried out by Odum (1969).[9]

The natural or biological "ecosystem analogy" lies at the heart of the field, since it is mentioned by nearly every single publication that is concerned about the term of

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[8] The use of the terms "metaphor" and "analogy" is not consistent by industrial ecologists: As a later chapter shows, much is to be gained for future work in research and application of Industrial Ecology by a proper understanding of what an analogy or a metaphor constitutes, also with the aim to distinguish between metaphors and analogies and indicate proper and also incorrect use. Therefore the term "analogy" is used here in quotation marks to indicate a need for more analysis.

[9] "Exhibit 1" in Allenby and Cooper (1994) has been copied from E. Odum (1969, p. 265), however, without any mention of the latter publication or author.

Industrial Ecology. It is for this reason that the "analogy" merits close attention and evaluation, to what extent it has been informing and shaping applications in Industrial Ecology.

Ayres and Ayres (1996, p. 278f) describe the term Industrial Ecology as

> "... a neologism intended to call attention to a biological analogy: the fact that an ecosystem tends to recycle most essential nutrients, using only energy from the sun to 'drive' the system... In a 'perfect' ecosystem the only input is energy from the sun. All other materials are recycled biologically, in the sense that each specie's waste products are the 'food' of another species."

Extending Frosch and Gallopoulos' mention of biological systems, Graedel (Graedel 1994, in Socolow et al. 1994) discusses three states of an ecological system, "type I" to "type III ecology" (cf. also Jelinski et al. 1992, Allenby and Richards 1994). "Type I" systems are characterised by a mainly linear flow of materials and energy (nutrients, biomass and embodied chemical energy) that uses up local resources and energy and creates wastes as end products.[10] "Type II" systems show more cyclical than linear flows in material and energy exchanges, with the system relying to a considerable extent on incoming solar energy. The system of "type III", lastly, cycles all the material and completely relies on the continuous influx of solar energy. Early on in the course of the evolution of life, Graedel claims, ecosystems moved from a "type I" state to a "type III" state, as the Earth became colonised by living beings that subsequently founded interdependent biological systems. Graedel maintains that "ideal anthropogenic use of the materials and resources available for industrial processes ... would be one that is similar to the ensemble biological model", the latter summarised in the term "type III ecology", in which all resource flows are completely cyclical (p. 24). The description of the economic system and its desired transition towards Graedel's state of a sustainable system warrants close attention. Graedel's concept provides a succinct description of the end state that Industrial Ecology is aiming to help achieve: Attainment of a "type III" state for economic systems.

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[10] It is of interest for this thesis to explore the evolution of biological systems and find evidence for or against Graedel's claim of the gradually closing cycles. Alternative ways of system development (that will encompass ecological development with cyclicity at heart) are discussed in chapter 3.

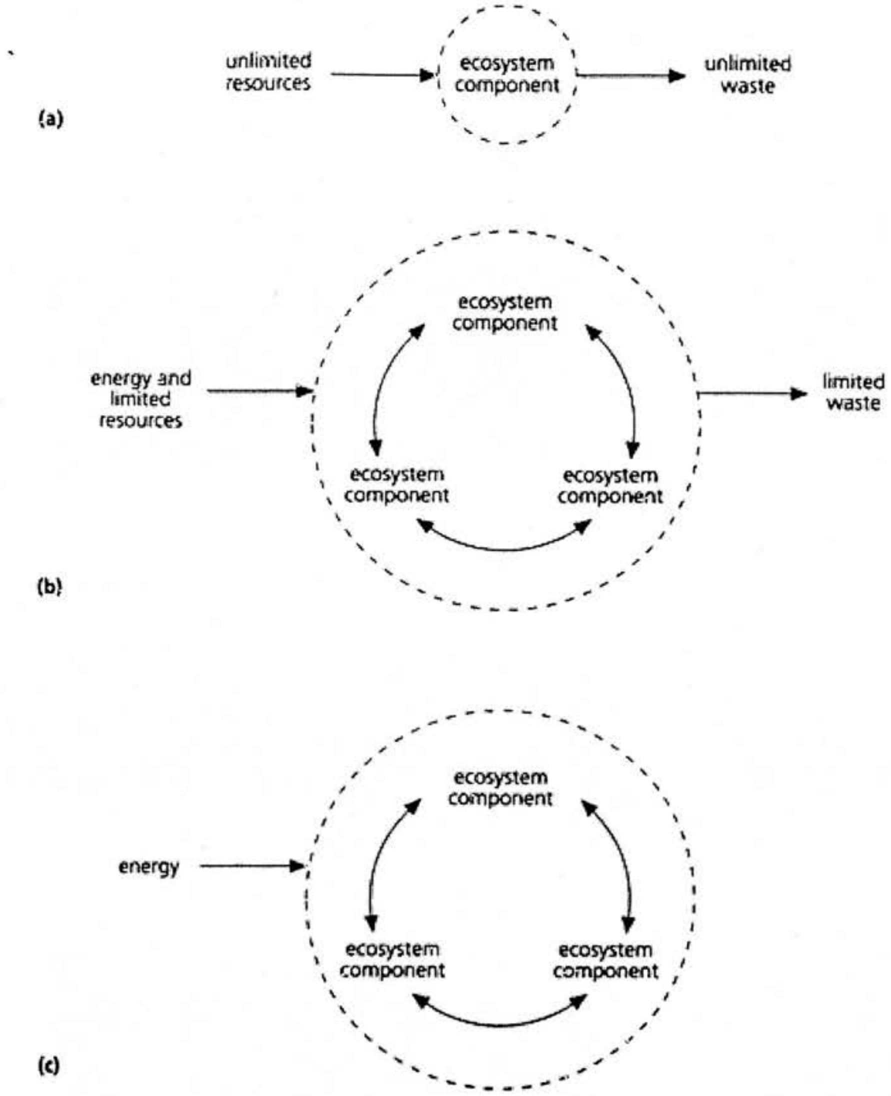

Figure 1.1: The three states of ecological systems; development from "Type I" to "Type III" ecology (Graedel 1994): from linear materials flows in "type I" systems (a) via quasicyclical flows in "type II" systems (b) to truly cyclical flows in "type III" systems.

Allenby and Cooper's article (Allenby and Cooper 1994) builds on this foundation of a sustainable system as conforming to a "type III ecology"; the authors' understanding of the concept of Industrial Ecology is a good example for use of the natural or biological "ecosystems analogy". The authors call for "understanding *human economic and sustenance activity* through the use of an analogy with the science of biological ecology" (Allenby and Cooper 1994, p. 344, emphasis added), and in their use of the "analogy" go as far as suggesting that Industrial Ecology would benefit from insights from the study of biological systems; in particular, that attributes or characteristics of biological ecosystems, such as structure and energetics of biological communities, should be used to describe and reform economic systems. Their suggestions, however, have not yet been taken up by other researchers active in Industrial Ecology, nor taken further by the authors (especially Allenby) themselves. Jelinski et al. (1992), however, provide an idea of how industrial ecologists at present view an industrial ecosystem (cf. Jelinski et al. 1992, figure 2): to the observer, it is rather resembling a "type II" system. However, the authors view such a system as unsustainable, as it is "running down" (Jelinski et al. 1992, p. 793). This conflict between the apparent desired state for the "industrial eco" system and the observed cyclical system in natural ecosystems is important and merits closer attention and further work.

Whereas industrial metabolism has as its remit the flow-through of materials and energy through the industrial system, the natural or biological "ecosystems analogy" takes the entire economic system as the systemic level that should be restructured with the help of Industrial Ecology, as is discussed in Graedel (1994). In this respect, it becomes important to point out the systems under analysis of Industrial Ecology, and distinguish between the industrial system, that is governing extraction of resources, manufacturing until bringing to the market of products and services, and, on the other hand, the economic system as a whole. The industrial system then must be regarded as only a subsystem of the entire economy.

An important part of the analysis in this thesis will discuss the fact that restructuring towards better environmental performance of the industrial system alone, even supposedly in the fashion of Industrial Ecology, does not necessarily lead to attaining an overall "sustainable" economic system, that is, a system conforming to Graedel's "type III ecology".

Writers in the field of Industrial Ecology have been notoriously imprecise when outlining the system under observation: there is no common agreement on whether the economic or the industrial system are to be observed by Industrial Ecology. Frosch and Gallopoulos (1989) started this development, discussing a manufacturing system, with a much reduced environmental impact after it was restructured to exhibit certain ecosystem characteristics. At times the two terms industrial system and economic system, are effectively being used as synonyms (e.g., by Tibbs 1992, passim, and by Socolow 1994, in Socolow et al. 1994), when clearly, they are not. Erkman (1997) solely mentions the industrial system throughout his overview over the field with added bibliography, even when discussing publications that take the economic system as object.[11] Graedel (1994) does so too, but in his definition of the system under observation, the industrial system covers total "anthropogenic use of materials and resources available ... to include agriculture, the urban infrastructure etc." (Graedel 1994, p. 24)

One area where this distinction between the two systems becomes important is the adoption of a cradle-to-grave approach of industrial metabolism, when material flows from extraction to manufacturing output is considered. An economic system that displays the same dynamics as the underlying biophysical system, as advocated by industrial ecologists that base their analyses on the whole of the human system, would have to display cradle-to-cradle characteristics, that is, material flows that are completely cyclical and only powered by solar energy. These would have to transcend merely the industrial system of production and manufacturing.

In this light, a good definition of the remit of Industrial Ecology is provided by the team that researched the "Belgium eco" system (Billen et al. 1983)[12]:

> "To include industrial activity in the field of an ecological analysis, you have to consider the relations of a factory with the factories producing the raw materials that it consumes, with the distribution channels it depends on to sell its products, with the consumers who use them ... In sum, you have to define industrial society as an *ecosystem made up of the whole of its means of production, and distribution and consumption networks*, as well as the reserves of raw material and energy that it uses and the waste it produces ... A description in terms of circulation of materials or energy produces a view of economic activity in its physical reality and shows how *society* manages its natural resources" (emphasis added).

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[11] The confusion of the industrial with the economic system is an example of the *pars pro toto* fallacy, which can be observed in Industrial Ecology. The ramifications of this misuse are profound and are discussed in later chapters.

[12] Quoted in Erkman (1997, p. 3) who seems unaware that the Belgium ecosystem consisting of the whole of the Belgian economy and transcending production systems is at odds with his discussion centring on industrial systems, although this was made explicit.

3.3. Industrial symbiosis

This last defining term for Industrial Ecology has been a contribution not from research into biological systems, but from an application of industrial organisation that became known as the most successful implementation of Industrial Ecology, which saw its inception, however, even before the concept of Industrial Ecology as such was conceived. This is the waste (or rather by-product) exchange system in Kalundborg, Denmark. The term industrial symbiosis was coined by Valdemar Christensen, one of the main architects of the system at Kalundborg and production manager at the local power plant that lies at the heart of the waste exchange programme (quoted by Gertler 1995, ch. 1 passim). It is expedient to define symbiosis first before discussing industrial symbiosis: according to Nultsch (1986),

> "... symbiosis covers the temporary or permanent cohabitation of organisms of different species in close morphological connection and, summarily, mutual benefit. The first characteristic distinguishes symbiosis from a mere coexistence ... the latter from parasitism." (Nultsch 1986, p. 321, translated from the German original)

Symbiosis in industry, according to Christensen, is

> "a cooperation between different industries by which the presence of each ... increases the viability of the other(s), and by which the demands [of] society for resource savings and environmental protection are considered." (quoted in Engberg 1993)

Industrial symbiosis came to describe the individual relationships between the economic actors of the Kalundborg industrial park, exchanges of matter and energy for their mutual benefit, in particular by making use of waste streams and energy resources. The whole of the Kalundborg industrial park that was comprised of individual symbiotic relationships came to be called an "industrial eco" system (see discussion below). Gertler ventures that the proliferation of industrial symbiosis supposedly results in an optimisation of the efficiency of material and energy flows through large-scale industrial processes (Gertler 1995, ch. 1).

4. Developments and applications

Tibbs (1992) provided a first collection of individual applications within Industrial Ecology with his six areas of work that were outlined above - creation of industrial ecosystems, balancing industrial input and output to natural ecosystem capacity, dematerialisation of industrial output, improving the metabolic pathways of industrial processes and materials use, creating systemic patterns of energy use, and policy alignment with a long-term perspective of industrial system evolution.

Tools mentioned by Tibbs and by Wernick and Ausubel (1997) incorporate material flow analysis, life cycle analysis, dematerialisation of industrial processes towards a service or functionality economy, "design for the environment", and, incorporating all the others, designing industrial ecosystems.
Tibbs stresses that work in Industrial Ecology is first and foremost concerned with detailed mapping of patterns inside industrial ecosystems, real and planned.

In line with Erkman (1997)[13], the above work areas could be seen as incorporated into Industrial Ecology's two main trajectories that are in the process of development, dematerialisation of the economy and restructuring into eco-industrial parks.

4.1. Dematerialisation-decarbonisation and the service economy:

The overall system under observation (be it the industrial or the entire economic system) is analysed as to the possibilities of reducing its use of material and energy per unit of output, and in absolute terms, which is known as dematerialisation. Tools for this analysis comprise mostly material flows analysis and life cycle analysis, and mapping tools incorporated in the two (van Berkel et al. 1997, van Berkel and Lafleur 1997). Wernick and Ausubel (1995) discuss a relation of physical data on materials consumption and disposal to monetary measures. Ruth and Dell'Anno (1997) discuss the case of the US glass industry, and Ruth (1998) the case of the US metal industry in terms of material flows accounting. Lowenthal and Kastenberg (1998) take further the criticisms of O'Rourke et al. (1996) with regard to a misplaced focus on materials flows, by introducing energy analysis in industrial

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[13] O'Rourke et al. (1996), in their critical appraisal of Industrial Ecology's theory and applications, would divide work in the field differently, into an area that is concerned with diffusing information of best practice and broader environmental implications of it, and another that aims to supply information by incorporating environmental externalities into market prices.

ecological modelling. Hertwich et al. (1997), and Anastas and Breen (1997) discuss the logical extension of pollution prevention, design for the environment (DFE).

Overall, decarbonisation specialises in a type of dematerialisation that has the specific aim to reduce CO_2 emissions on a systems level, by attempting to delink economic output (probably in value, as measured by GDP) from output of CO_2. The scale of the overall flows of material and energy through the economy is largely based on technological evolution, Erkman (1997, p. 6) surmises, implying that it is the industrial system of production that is the focus of observation in Industrial Ecology (cf. Dobers and Wolff 1999). Ultimately, the achievement of higher degrees of both dematerialisation and decarbonisation would be leading to a restructuring of industrial activity towards a "service economy" (cf. Stahel 1994).

4.2. Eco-industrial parks and "islands of sustainability":

Work in this area is the most prominent in the realm of Industrial Ecology, as the eco-industrial parks are regarded as flagship projects in the field. Research and application focus on industrial zones, retrofitting or designing anew industrial processes that are based on waste or by-product exchanges. These eco-industrial parks are also known as industrial ecosystems, where individual corporate participants' behaviour will resemble the behaviour of individual participants in a natural or biological ecosystem (cf. Côté 2000). Characteristics of industrial ecosystems are explored in Schwarz and Steininger (1997), and Lowe and Evans (1995).

There are around two dozen industrial parks in the process of being studied, mainly in North America (cf. Côté and Hall 1995, Chertow 1999), but a few in Europe as well (cf. Andersen 1997, Baas 1998, and Korhonen 2001), and scattered examples elsewhere (cf. Takeda 1995), for their waste exchange possibilities. The industrial site of Kalundborg provided the model for restructuring other parks. There, businesses since the 1970s have engaged in waste and by-product exchanges, to create a system with a coal-fired power plant at its heart. This system utilises resources and energy with up to doubled efficiency (in the case of coal-extraction efficiency for power generation and district heating, cf. Gertler 1995, ch. 2).

These studies and attempts at implementation of Industrial Ecology can be extended beyond individual industrial parks to incorporate regions, the "islands of sustainability" (Erkman 1997, p. 6, Brand and de Bruijn 1998). By-product exchanges, however, comprise only exchanges of easily usable or highly valuable materials (cf. O'Rourke et al. 1996, Sagar and Frosch 1997). Some studies evaluate the support needed for creation of industrial ecosystems in terms of economic incentives and regulation (Côté and Smolenaars 1997, Lowe 1997, Sinding 2000). Reuter (1998) introduces simulation techniques and evaluates results for industrial ecosystems.

A significant part of industrial ecosystems research concentrates on the morphology of industrial ecosystems, especially the problem of complex cooperative networks, as discussed in Boons (1998), Boons and Baas (1997), Wallner (1999), and Korhonen (2001).

5. Chapter conclusion: Observations and further questions

The introduction to past and ongoing research and practical work in the field of Industrial Ecology has had the primary purpose of identifying areas where more research is required. The overview in this chapter found a focus of Industrial Ecology on the technological side of environmental management and protection, combined with a focus on production systems and industry, where the individual business enterprise was considered one of the pillars towards industrial ecological restructuring.

Industrial Ecology attempts a conceptual leap from the large-scale system behaviour of "type III ecology" to smaller systems and their individual participants: The individual firm and farm as economic agents, Socolow (1994) maintains, should take a central position in industrial ecosystem restructuring.

This position has two consequences: Firstly, concentrating on the individual industrial actor constitutes the systems perspective as a coagulation of individual participants, all independent actors, and thereby negates systems dynamics and characteristics that go beyond the individual actor. The whole is then not more than the sum of its parts. Elevating "firms and farms" to central actors negates the integration of producers, consumers and recyclers, as found in all natural systems. This individualist focus (Socolow 1994, Andrews 2000) is an expression of mainstream economics, a discipline that also holds that market forces alone should coordinate industrial decisions, without a need for particular government regulation in the form of environmental policy (according to O'Rourke et al. 1996, Industrial Ecology is seen to be pandering to accepted thinking).

Furthermore, the perspective of Industrial Ecology gives preference to only one part of the whole economic system, a system that is made up not only of manufacturing and service industries, but also of agricultural production and households (cf. Pietilä 1997): the industrial system of manufacturers and service providers becomes the system under observation. But as the industrial system is only a subset of the entire socio-economic system, this shift in focus, in fact separating the two systems, decouples the latter from achieving "type III" characteristics, at least, it can develop independently and in an unsustainable manner, even when the industrial system is restructured. According to Socolow's postulate, it is material and resource flows in production systems that make up the main body of work in Industrial Ecology. The "eco-industrial parks" that industrial ecology advocates still only comprise manufacturers and service providers.

Industrial ecology at present attempts to marry up the individualist maximising *laisser faire* perspective of mainstream economics with an ecosystem perspective - an inconsistency that when followed through, will make the concept fail in aiding to bring about sustainable development, becoming the latest victim to turn "from green to grey". In that vein, Welford (1997) argues that this has happened to a number of disciplines, including sustainable development and corporate environmental management, that are policy-relevant and provide a bridge between theory and application.

The question to be investigated is: how to integrate the individual firm into an ecosystem-like network, in which there is no centrality of the individual actor?

Dematerialisation is a major characteristic of industrial ecological restructuring, but it is not quite clear what exactly is endeavoured to be dematerialised. Again, dematerialisation of products will address only one side of the economic system. Furthermore, the creation of a service economy can be seen as naïve or even escapist: Is the service economy planned to become reality world-wide, or only in local and national subsets? The population in a service economy would still have the basic requirements of material and energy that need to be satisfied by production in one way or another. Would pollution and resource extraction associated with production be relocated even to a higher extent to developing countries? Cantlon and Koenig (1999) provide a glimpse into the problematic of the global economic system, trade and industrial ecology.

Vague understanding of ecological and biological science underlying the metaphor of Industrial Ecology currently hampers serious scientific advances in the field and facilitates trivialisation of ecological concepts, such as "waste as food", cf. Tibbs (1992), Côté (2000), and "recycling networks", cf. Lowe and Evans (1995).
This weakness at the heart of Industrial Ecology has been noticed by participants in the field: there is a conflict between proponents of the metaphor that advocate a stricter application of it (understanding underlying parallels in energy and material flows, as all systems, whether human-made or not, conform to the same constraints of dissipative systems) and opponents who maintain that the ecosystem metaphor should not be taken literally, and serve rather as an inspiration than a guideline (Frosch and Gallopoulos 1989, Boons, oral communication June 2000).

Commoner (1997) admonishes evaluation of an optimum scale of industrial production locally (in line with understanding of natural ecosystems and their local assimilation capacity, and also with respect to production of toxins). His suggestion of incorporating a social, political and economic perspective into Industrial Ecology, is flanked by requiring assessment into the real-world impact of industrial systems. Taking on the challenge, this work will endeavour to ground Industrial Ecology in the appropriate framework, which feed into applications of Industrial Ecology and against which industrial restructuring towards achieving ecosystems behaviour can be assessed. Thus, the next part of this work illustrates how Industrial Ecology will fit into a number of broader frameworks, namely ecological economics and theoretical ecology, the study of ecosystem behaviour in nature.

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Part II

Providing Industrial Ecology with a foundation of appropriate theory

Industrial Ecology concerns itself with the restructuring of economic activity, especially industrial processes, to conform to natural system constraints. It uses imagery borrowed from understanding natural systems to describe and shape economic system structures. To overcome the limitations of Industrial Ecology that were pointed out in the previous part, Industrial Ecology's merely technological perspective needs to be expanded. This part's purpose is to delineate essential areas that Industrial Ecology ought to include in its work, so that it becomes a successful tool for the achievement of its stated aim, sustainable development.

Chapters 2 and 3 emphasise the physical view of sustainability in two different ways: the former will ground Industrial Ecology in ecological economic theory that recognises a biophysical dimension to economic processes, the latter will provide Industrial Ecology with a solid foundation in theoretical and systems ecology, especially by discussing the role of resource and energy use in biological evolution.

Industrial Ecology makes use of language from other scientific disciplines. This constitutes part of its attraction as a concerted effort from many corners, a potential rallying point for a very often disjointed group of researchers and practitioners. Its value, though, depends on the accuracy of translation between different fields, to be specific, on its use of the biological metaphor. Thus, chapter 4 is taken up with an analysis of metaphor use and representation of knowledge in general and will provide recommendations for Industrial Ecology to improve its work.
Both chapters 3 and 4 are very closely related, despite the seemingly different nature of their subjects: Although in the analysis of metaphor a set of rules is introduced to translate between the natural and the social systems more correctly, this does not legitimate the understanding of industrial systems in terms of natural systems

dynamics. What is needed is a justification for doing so, and this justification will be found in the course of the third chapter. Natural and social systems are understood to adhere to the same dynamic behaviour that characterises all dissipative systems. This is the level of the context of justification, as opposed to the context of recognition. The vehicle for recognition of the similarities between the natural and the social, for example the "natural systems analogy", cannot explain why the similarities occur. This explanation is the purpose of the third chapter.

As the last chapter in this part, chapter 5 will provide a discussion of whether and how Industrial Ecology can fit into the current economic climate and system of business management. Industrial Ecology at present focuses on the production side, the industrial system. An Industrial Ecology that seeks to make economic activity compatible with ecological system constraints needs to include not only the supply side, but the demand side and in between, allocation on the market as well in the analysis of ecological impacts.
The issues of competition, market allocation and ownership need to be addressed to find out how economic actors could engage successfully in industrial ecological activity today. Furthermore, the viewpoint of competition as the mainspring of economic success in the long-term will be contended, and the ecological impact of market allocation discussed.

At the end of this second part, the underlying systems that Industrial Ecology relies on - whether it does so consciously, or, as is found to be the case, mostly unconscious of the ramifications of doing so - will have become clear, together with the processes of translating from one to the other. The third part builds on the insights gained from that embedding and suggests modifications to the way Industrial Ecology operates.

Chapter 2

Ecological economics: a framework for reshaping industrial infrastructure towards creating industrial ecosystems

Hypothesis: Industrial Ecology and ecological economics share with one another the viewpoint recognising a biophysical dimension to economic processes. An Industrial Ecology that explores strategies for restructuring economic activity toward sustainable development, with the help of insights from understanding natural systems, has a need for an economic theory that places at its core the recognition of limits to available resources and sink capacity, and advocates economic policy-making that is mindful of these limits.

1. Chapter introduction

In the previous chapter it was established that Industrial Ecology, despite its claims for being the "science of sustainability" or "operationalising sustainable development", has a rather strong technological slant to its theory and applications, and due to this limitation might be in danger of not achieving its objective, namely, of helping to bring about a sustainable economic system.

The role of technology in economic development, and therefore, industrial ecological policy, is by no means value-free, a fact which can be observed in the way our society is organised in terms of its infrastructure that makes possible a specific economic system. The economic system's technological dimension was put in place by exercise of preferences of individuals (cf. Norton et al. 1998), and over the course of roughly 50 years - from the end of the 19th century to the end of WWII - took the shape it still largely has at present. Industrial Ecology, with its largely technological perspective today, is part of this economic-social-technological development - these values are embodied in its chosen perspective. Thus, for rendering Industrial Ecology a useful application of sustainable development policy-making, it needs to founded on the values that are conducive to that development.

This chapter proposes a conceptual framework that Industrial Ecology should be built around, so that Industrial Ecology in turn can serve within this framework as an application. The framework suggested will have to be consistent with objectives towards creating a sustainable economic system. These are not merely of a technical or economic nature, but take into account the preservation of natural "capital" and recognise the role of social justice in allocating costs and benefits of environmental protection.

Grounding Industrial Ecology in ecological economics provides the framework that broadens the field's remit from a merely technological approach towards becoming an application of sustainable development in its economic, ecological and social dimension. The most important characteristic of this grounding is the recognition that the economic system is seen as embedded in the natural system in its use of resources and sink capacity, and thus, it is dependent on the biosphere's carrying capacity. As ecological economics recognises this relationship, it can serve as a litmus test for evaluating projects in Industrial Ecology.
We should note this embeddedness as the preanalytic vision (in Schumpeter's understanding, cf. Schumpeter 1954) of ecological economics, and indeed, Industrial Ecology. As will be discussed in detail later, this preanalytic vision rather separates ecological economics from other forms and traditions of economics.

An economic system (especially, a production system, cf. Pietilä 1997) that is restructured in what can in effect be called a cosmetic industrial ecological fashion, as indicated in the previous chapter, cannot conform to the type III system specification – for all its refashioned interior workings towards seemingly 'cyclical' processes it would nevertheless remain a linear system in the form of Boulding's (1980) 'cowboy economy'. It would still have a system boundary where resources and wastes cross from the larger system (the biosphere) into the economy, the subsystem of the larger system, and are returned back as wastes and pollution. Once matter leaves the (sub)system boundary, it traditionally is of no concern to the participants in that system. This thinking is embodied in much of the writing about the 'environment', implying an inside and an outside to the human system (cf. Allen 1996, and also further below in chapter 4). The work in this chapter is concerned with collapsing this boundary, and thereby embedding the human economy into the natural system.

In the course of the analysis, it will be confirmed that Industrial Ecology thus cannot be a value-free exercise, independent from an economic, social and political context (this independence is implied by calling Industrial Ecology the "science of sustainability"), it is a tool that is employed against a background of a specific economic theory and system. By itself Industrial Ecology does not guarantee bringing about sustainable development. It needs to be rooted in an appropriate economic theory that takes the limits of resources and energy on Earth as its starting point. An Industrial Ecology that contributes to an ecologically sustainable use of resources and energy would seek to abolish in its analysis the system boundary between the natural and the human system and consequently arrive to see the latter as embedded in the former.

There have been a number of efforts to characterise an economic system that is built on ecological economic theory with respect to and in comparison with the current economic system (e.g., cf. Daly 1992). This latter system is described by an economic theory that is very often called 'neoclassical'. Neoclassical and ecological economic theories are sometimes seen as different in their extremes, but sharing a fairly extensive common ground (cf. Crane 1997). Characterisations like those will necessarily be somewhat crude, as they emphasise specific points of an economic theory. Depending on the choice of those points of reference, the two explanatory systems can then be seen as either sharing a common ground or being antithetical to one another.

In this chapter, the focus of analysis lies on the boundary of the economic system, the two 'ends' of a linear relationship: the one end where resources enter the production and consumption system (from extraction from the natural system), and the other, where wastes are released into the surrounding environment. The distinction between an economic theory that is built on a predominantly closed or inclusive system (with respect to resources, cf. the "type III" system discussed above) and, on the other hand, one built like an open linear system that places much emphasis on resource extraction from a production perspective then becomes a rather pronounced one. From this point of view, the two different models of an economic system, similar to Boulding's 'cowboy economy' and 'spaceship economy', have not much in common with one another.

The chapter commences with an example for environmental policy-making that, although taken up with the aim to reduce environmental burden, might have the opposite to the intended results, as this policy is viewed in isolation, and not in context. In this example, as a *caveat* for industrial ecologists, it will be shown that market forces will not by themselves aid development towards sustainability. There is a need for governments to set an appropriate regulatory framework. Following that, the main points in this chapter discuss, in the form of a review and discussion of existing literature, an economic theory that can support Industrial Ecology as a strategic tool to help attain a sustainable economic system. Two sections are devoted to the unique characteristics of ecological economic theory, and the contrasts between the latter and neoclassical economics, whereas the third denotes areas of possible overlap between ecological economics and Industrial Ecology, resting on the similarity between the former's concept of a steady-state economy and the latter's "type III" ecosystem that was introduced in the previous chapter.
The last part, in the form of a conclusion, contains some original ideas for embedding Industrial Ecology in ecological economic theory.

2. A point in case: The delusion of solely market and technology-led approaches to sustainability

As an introduction into the problematic, the following section will provide an example for an environmental policy proposal that is not yet recognisant of the system boundary between the economic and the natural system, in that it does not concern itself with its overall effects in terms of environmental impact on the latter. Similar to the industrial ecological research and applications detailed above, the pursuit of technical efficiency for environmental protection is a technological tool, and not integrated with other efforts of economic theory and policy-making.

The idea of increasing resource efficiency, under the catch phrase "more from less", is seen as a means for improving the environmental performance of industrial production without having to change its overall direction and focus. The analysis below will serve as a point in case for integrating policies for pursuing sustainable development into a proper context that is created between overall aims and a multitude of applications that are orchestrated to work towards those aims and that between each other create synergy effects rather than cancel each other out[14].

2.1. The fallacy of leaving increasing technical efficiency to market forces

The promotion during recent years of increasing technical, and in particular, energy, efficiency as the solution to environmental problems has become one of the cornerstones of practising sustainability in industrial production and household consumption. The rationale behind that is of course very simple: If a given output in production or level of consumption can be achieved by using less resources and energy, the thus increased output/input ratio leads to a smaller ecological impact of that particular process of production/consumption.

A number of writers in the field have devoted their efforts to promoting increasing technical efficiency for solving or helping to solve the environmental predicament that is looming. Technical efficiency and its role for achieving sustainable development came to the fore with the publication of Schmidheiny (1992). One of its most prominent advocates is Ernst von Weizsäcker, who in his book "Faktor Vier" makes the claim that overall technical efficiency can at least rise quadruply with today's technology. A halved ecological impact would be the result of that

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[14] This could be seen as the achievement of a different aim to sustainable development, namely, undisturbed and increasing industrial production under a system of a hegemony of business interests.

endeavour, he maintains, taking into account world population expanding to double the numbers today.

This proposal sounds attractive, in that it promises to deliver environmental quality without great sacrifices in consumption, an indicator for material well-being. Moreover, it spurs innovation and technological development, traditionally a strong motor for economic growth. The following points, however, cast doubt on the effectiveness of the pursuit of (technical) efficiency, if it remains a strategy merely being pursued on its own:

Firstly, underlying this proposal is the assumption that, all other things being equal, by employing technology with increased technical efficiency, one unit of input from the resource end of the economic system will lead to a higher output, or conversely, it will be possible to achieve the same output with less input – the two instances of an economic relationship. Is this so called *ceteris paribus* condition (all other things being equal) a justifiable assumption?
The second question concerns the scale of technically efficient production and the direction of the economic relationship in the first objection: Would increasing technical efficiency really lead to an absolute reduction of ecological impact, or, regarding market forces, to greatly increased demand and consequently, increased production with either the same or even increased ecological impact?

For attending to the first question, there is a need for a brief detour into the roots of economic thinking. For economic analysis that is often leading to political decision-making, it seems to be expedient to look first and foremost at the technical implications (also often regarded as the main factors for calculating financial expenditure) of production/consumption processes, and to disregard their socio-economic context. Seemingly, if only the technical side is being regarded, with all other factors being equal, a smaller ecological impact would be the result of achieving the same output in quantity with less resources and/or energy.

However, it is exactly the above *ceteris paribus* assumption which does not hold in social, real-world situations. As Myrdal (1978) very forcefully argues, the economic system, being a part of the entire social system, is subjected to "*circular causation*, implying that, if there is change in one condition, others will change in response. These secondary changes in their turn will cause new changes all around, even reaching back to the initial condition, the change in which we assumed began the process, and so on in further rounds." (p. 11)

Hence, a phenomenon investigated with the *ceteris paribus* assumption for ease of analysis might lead to very different insights and recommendations than the same phenomenon investigated without all other factors being considered equal.[15] The assumption of *ceteris paribus* conditions is a good example for traditional economic analysis being in need of systemic analysis, as alluded to by Myrdal's statement above, a type of analysis where a whole network of factors is being considered and where complex models would try to find out how changes in one or few factors would lead to changes in the whole system and its structure. A realm where *ceteris paribus* can be observed to hold in many instances is the field of engineering and technology[16]. The insight of circular causation and systemic change, on the other hand is related to Hardin's "first law of human ecology", namely, that it is impossible to "do merely one thing" (Hardin 1991), as every action that takes place in social as well as in natural systems results in side effects, whether they are intended, desired or not. Again, it is only within systems conforming to the axioms of classical mechanics where it is possible to separate parts and actions from one another, so that one cause can have exactly one effect.

One result of this shift in analytic focus towards whole systems behaviour surely is that there is a trade-off in terms of analytical accuracy, for reduction of complexity for handling data more easily is the very reason of *ceteris paribus*. The question of where to reduce complexity without invalidating the whole analytical framework is a profound one: the decision to do without the *ceteris paribus* assumption would

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[15] This insight has appeared in economic writings over the last century: "Unmathematical economists are culprits of the characteristic vice of treating variables as constants." Edgeworth, quoted by Georgescu-Roegen (1971).

[16] It is classical mechanics where economic theory looked to for its metaphors to enhance its standing as an analytically rigorous scientific discipline. Mirowski (1989) provides a detailed account of the development of economic theory in the wake of the Newtonian revolution.

probably ask for different simplifications with possibly different detrimental effects on analytical rigour and applicability of recommendations.

The second point of objection to the concept of technical efficiency bringing about sustainable development by itself follows from the first, by concerning the expected result of decreasing ecological impact on the basis of increasing technical efficiency. One has to distinguish between two different levels of aggregation in an economic system to shed more light on this question: the first is the micro-level of, for example, individual technical appliances that use energy more efficiently, so that more output can be generated with the same input, or the same output generated by reduced input. The second level is the macro-level of overall economic activity, and especially, overall energy consumption. If energy efficient technical appliances still use about the same input for creating higher output (an example would be the fivefold increase of office lighting levels from the 1940s to the 1970s, cf. Herring 1999), there would not be an overall reduction in energy consumption. Moreover, this statement still assumes a static economy. Annual growth rates of GDP of around 2%, as is customary in the industrialised world, are the strongest trend offsetting any gains in energy efficiency, again illustrating the need for regarding the micro-level in context with the macro-level.

Wackernagel and Rees (1996) point out that by increasing energy efficiency, the associated reduction in the costs of energy entices consumers to consume more (the socalled 'take-back effect', cf. also Herring 1999). The discussion is by no means a recent one: since the 1860s, economists, starting with Jevons (on consumption of coal in Scotland), have debated the seemingly counterintuitive finding that increasing energy efficiency does not lead to reduced consumption.

Following from the above, promoting higher technical efficiency could be an ineffective or even counterproductive environmental strategy, as it might lead to an even faster depletion of resources, build-up of waste in the atmosphere, the oceans and the soil, and the destruction of vital complex and sensitive life-preserving processes. The use of efficient technology then needs to be managed by government regulation, rather than leaving its effectiveness to market forces alone. Money that is being saved by more efficient handling of resources and energy has to be directed into appropriate spending channels, so as to not create additional environmental impacts by production and consumption of the products on which this money is being spent. Ideally the money saved by reduced energy consumption has to be diverted away from the stream of transformation of resources and energy for the purposes of consumption.

The pursuit of technical efficiency by itself concentrates on the supply side, but does not at all consider the wider effects on demand. This argument points towards the importance of government regulation in environmental policy to guide market forces, which, if left to themselves, would not automatically bring about sustainable development. The idea of leaving sustainable development to market forces alone is still believed, mostly among academics and policy-makers in the market liberalist tradition (cf. Nelson 1997).

Increasing technical efficiency as a tool transcending the supply side then must be in the service of increasing environmental effectiveness, that is, reducing absolute, not just relative (per unit of output), demand for energy and resources.

There are parallel situations which corroborate the points made above:

one example is the problem of the carbon cycle and global climate change, and the political struggle towards an agreement on remedies to it. Trees fix carbon only when they grow. Hence, it is not sufficient to just plant new trees at a rate equal to the felling of others or the marginal rate of CO_2 emission (e.g., as in the policy of the WTO to make its conferences "carbon-neutral"). To really achieve that, the life-cycle of the wood that binds CO_2 has to be extended well into the use of the dead timber and its post-consumption disposal, for once wood decays, the previously fixed carbon is released again into the atmosphere. So the best method of fixing carbon seems to be to plant new trees continuously in increasing quantity in line with economic growth[17]. The fully grown trees are cut and the timber used for building and similar purposes. Thus the wood is not burned or left to rot with the carbon dioxide being released, but it remains intact, thus becoming and remaining a carbon sink. As this is not very practicable (trees will have to compete with other projects

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[17] As at present there is a strong correlation between economic growth and CO_2 emissions.

for land use and wood decays in any use and has to be replaced), removal of carbon from the atmosphere must be achieved chiefly by other means. Ultimately, planting of trees distracts from the real issue - only a decarbonisation of economic flows and reduction of the scale of the carbon cycle can achieve the target of stabilising the world climate in the face of economic production and consumption.

The last point to be borne in mind, and thus returning to the *ceteris paribus* simplification, is the recognition of the complex systemic nature of the world, be it in the ecological system or in our own society. The energy efficiency theorem holds only when one assumes a static point of observation: in the production and consumption system at one specific point in time, increasing technical or energy efficiency will certainly have the effect of decreasing use of resources per unit of output. A dynamic system, however, will not conform to this simple mathematical relationship. An evolutionary perspective will be a better platform of explanation for the increased consumption of resources under increased technical efficiency.

Furthermore, simple measures which only have specified and desired effects and also can be used on their own do not exist, as the "first law of human ecology" mentioned above stipulates. The examples given show that the employment of a single tool for remedying a complex problem will not necessarily achieve the goal stated. However well-intended its design might have been, its effects would very easily be either negligible or even harmful. Thus, it is not the single instruments that bring about change, but a whole reshaped system, where the individual tools complement each other in objective and effect.

For this endeavour of creating a strategic environment for policy measures, there is a need for distinguishing between macro-level effectiveness (reduction of the overall ecological impact of economic production and consumption) and micro-level efficiency. *Ceteris paribus*, a remainder of an economic theory that took its cue from classical mechanics, neglects these differences in scale.

3. Ecological economic theory

3.1. The core assumption of ecological economics:
Embedding the human economy in the natural system

Ecological economics as a discipline proper came into being only 13 years ago, with the launch of the scientific journal "Ecological Economics" and the inauguration of the International Society of Ecological Economics (ISEE) in 1988. However, work in line with the remit of ecological economics has been carried out for most of the 20th century, predominantly in the form of a critique of classical and neoclassical economic theory. This work was undertaken by specialists in their respective fields of economics, several disciplines of the natural sciences, and philosophy. The scientific writers were very often outsiders in their own fields (e.g., the chemist Frederick Soddy or the economist Nicholas Georgescu-Roegen, cf. Martinez-Alier 1994), a situation that the discipline of ecological economics by its inauguration has endeavoured to overcome. Ecological economics now is an umbrella for highly diverse work coming originally from a whole host of fields of science. Despite, or perhaps because of, that diversity, participants in ecological economics have clustered around some core propositions that provide the springboard for research work carried out in the field.

The mainstay of ecological economic activity in research and applications has been the recognition that the circular flow of money in the human economy is not self-sustaining and independent; on the contrary, it does depend on an underlying linear flow of natural resources and energy. Ecological economics therefore tries to understand the relationships between two realms these different flows adhere to: the human economy, and the biosphere of the Earth with its biogeochemical flows.

This relationship is expressed in the definitions of ecological economics' remit. A good decade after its formulation, Costanza's definition, "ecological economics addresses the relationship between ecosystems and economic systems" (Costanza 1989, 1991) has become an important orientation point for all following research in the field, echoed by many other writers (e.g., Faber et al. 1996, Edwards-Jones et al. 2000).

Hussen, quoting Costanza, elaborates on this standard definition of ecological economics and emphasises the complex systems perspective that needs to be employed:

> "Ecological economics deals with a comprehensive and systematic study of the linkages between ecological and economic systems. Its basic organizing principles include the idea that ecological and economic systems are complex, adaptive, living systems that need to be studied as integrated, co-evolving systems in order to be adequately understood (Costanza et al. 1993)." (Hussen 2000, p. 153)

Indirectly from these definitions, and directly from those authors' works, the core proposition of ecological economics emerges as viewing the human economy as a subsystem of the biosphere. Thus, attempting to embed the workings of the economic system in the natural system becomes ecological economics' policy proposal. Ecological economics is therefore the field of science that proposes combining the remit of economics - solely understanding the human system of exchange of goods and services - and the remits of natural sciences, chiefly among them ecology - understanding of the biosphere, with *homo sapiens sapiens* the only species excluded from analysis - a combination that, although felt to be long overdue, had not been realised before.[18]

This viewpoint has several important consequences for ecological economic theory and applications:

First in importance is the recognition of limits to resources and sinks: economic activity is seen to lead to a depletion of natural resources and to an accumulation of pollutants, thereby signifying the linear nature of the economic system that has material inputs and outputs, rather than being composed solely of the circular flows of money. This position is particular to ecological economics; in other fields like

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[18] In that respect, ecological economics becomes a reinvigorated and enhanced human ecology: The latter field of science is expressly concerned with humankind as the missing link in ecology, stating that only the inclusion of *homo sapiens sapiens* would complete ecology's picture, as worldwide there are no ecosystems anymore that are not in some way shaped by human behaviour.

neoclassical economics the existence of limits, especially to resources, is disputed. Scientists who reject the notion of absolute scarcity cite the seemingly averted resources crisis[19] for proof that there will be found a way to overcome the resource shortage "Neo-Malthusians" are predicting.

Related to the above first point is the question of valuation for sustainable development: market prices as of now reflect economic considerations, that is, scarcity in the marketplace, not absolute (biophysical) scarcity. If individual resources are not critical for ecosystem functioning and also substitutable, this reasoning might be accepted. However, there is an absolute limit to the totality of resources which is not included when trying to establish individual resource scarcity. The bigger issue behind this lies in exposing the biophysical reality behind monetary values and economic choices: how much is the depletion of resources and sink capacity represented in the price of any one consumer good? What kind of environmental degradation does the consumption of such a good cause?

Rees ("How should a parasite value its host?", 1998) thus comes to the following conclusion:

> "Ecological economics sees the material economy as an inextricably integrated, completely contained and wholly dependent growing subsystem of a non-growing biosphere. From this perspective, there are no externalities and we are more humble about prospects to substitution. Most important, there are real limits to material growth and the issue of optimal economic scale is a critical concern (Daly 1996).
> "Ecological economics also recognizes the economy as a complex, far-from-equilibrium, self-organizing system subject to the second law of thermodynamics. This is a critical distinction given that the economy is embedded in the ecosphere." (Rees 1998, p. 50)

The arising question of the contribution of economic growth to human welfare will be discussed further below.

The third point following from the perspective of the human economy as a subsystem of the biosphere is the recognition of the need of scientific endeavour to

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[19] They arrive at this conclusion by way of looking at economic indicators such as prices for raw materials: these have considerably relaxed over the last three decades, indicating a reduction in scarcity. In Norgaard's view (Norgaard 1990), however, this procedure is "logically flawed".

lead to policy-making, both for private enterprise and government legislation. In particular, the call for government regulation with sustainable development at its heart is an ecological economic speciality. Ecological economists, aided by institutional and evolutionary economists, reason that because equilibrium theory does not play a dominant role anymore for the understanding and management of complex systems, market forces alone cannot lead to either efficient or to effective and equitable allocation, and therefore have to be backed up by an appropriate framework of government policy.

The last point concerns ecological economics' epistemology: As humanity cannot claim exemption any more from the constraints of nature (the lack of awareness or even rejection of which showed the limitations of some traditional fields of science), ecological economics has devoted itself to becoming more aware of its own limitations as a science. Above all, research into complex systems where the observer is part of the system under observation collapses the traditional boundary between the object of study and the "disinterested", that is neutral, personally uninvolved, objective, researcher. Ecological economics, in the view of Funtowicz and Ravetz (1990), is a post-normal science, characterised both by high decision stakes (possibly the survival of human civilisation) and high systems uncertainty. Bearing in mind, as ecological economics strives to do, these inherent limits to knowledge, brings to mind the mathematician Kurt Gödel's (1931) work on axiomatic systems. He proved mathematically that even logically closed axiomatic systems must contain at least one theorem that cannot be either proved or disproved. In other words, to describe successfully a system in its entirety, analytical tools are needed that are of a higher logical order than the system itself - a method that has been instrumental for the success of laboratory science, where the boundary established between researcher and contained object serves as Gödel's tool outside the system under observation. In the case of biosphere-economy interaction, though, Gödel's theorem gives the researcher no hope of fully understanding and controlling.

3.1.1. Areas of concern for ecological economics that arise from embedding the human economy in the biosphere

As became apparent in the statement quoted from Rees (1998), the recognition of a finite resource base in the biosphere, being the constraint that the human economic system has to exist on, has strong implications for the nature and meaning of economic growth, and related to that, the nature and direction of sustainable development. If economic growth *per se* for ecological economists begins to look like a questionable means for achieving a sustainable (that is, of long-term stability) coexistence of the human system (Rees 1998: "parasite") within the larger system of the biosphere, the question becomes of interest for a large and powerful part of society, in particular, private enterprise. Work in ecological economics does reflect this difficult situation, with a number of authors attempting to find a compromise between advocating a healthy natural environment and a thriving business environment. What is undisputed is the existence of theoretically limitless solar energy (limitless for all human purposes, if it can be utilised to that degree, cf. chapter 3), the continuous source of energy very nearly all of Earth's living systems depend on[20].

As Earth is a closed system with respect to physical resources, economic growth cannot continue as it has in the past, relying on the extraction of virgin resources and a plentiful sink capacity to accommodate and assimilate the waste output of the human system.

The following treatment is not meant to be exhaustive, but can be seen as merely a listing of the salient issues; there are other writers and researchers who have devoted their attention solely to that question (e.g., Daly 1992, 1996; Ayres 1995, 1996, 1998; Douthwaite 1992, among many others).

Economic growth, as it has happened throughout the industrial period, involves growth of a physical nature. Every "creation" of goods and services in reality can only be a transformation of resources and energy (in line with the first law of thermodynamics, see chapter 3). At least the production of goods is impinging on

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[20] The term "solar energy" comprises some sources of continuous, rather than renewable, energy other than direct insolation as well, such as wind, wave or tidal power, as the Earth's climate is driven by the sun's radiation.

absolute scarcities for extraction and sink capacity, and the production of services doing so if the energy used comes from other than renewable sources (and more stringently, those renewables that do not use up sink capacity, either).

Growth could in theory occur within sustainable development if it is solely in solar energy use, but Ayres (1995) maintains that this assumption of basing the economy on solar energy is, for the time being and for a medium-term socio-political perspective, not a realistic one. Thus, although in principle economic growth need not be antithetical to environmental protection, this new relationship "... will require something like a revolution in trade policy, technology policy, industrial policy, labor policy, fiscal policy and tax policy" (Ayres 1995).

Only in the aftermath of WWII, since the fifth decade of the 20th century, has economic growth become a key element of economic policy, as it had begun to be researched by economists around 20 years earlier. Ayres (1996) ventures to say that it served as a convenient means for satisfying the majority of economic actors: the pursuit of economic growth is built on the expectation of a future with improved material welfare for all. The hope that growth will ameliorate the poors' conditions sustains present income differentials. Thus the difference between one part of economic growth to serve the improvement of basic living standards and another part to sustain "conspicuous consumption" (Veblen 1994) became neglected. (cf. Douthwaite 1992 for a comprehensive treatment on the possible illusion of benefits from economic growth.)

If most writers on the ecological impact of economic growth stress the relationship between the above and manufacturing output, it has to be pointed out that economic activity is actually inherently service-oriented: as it aims to lead to the creation of welfare through satisfaction of needs, it is the benefits arising from the consumption of products and services that are demanded, not necessarily the products themselves (which are merely "carriers of benefits"). An increase in economic activity is most likely to result, but does not have to, in an increase in materials throughput and fossil fuel use. There are, however, no services without any material input at all. Even the growth of a highly dematerialised "service economy" (Stahel 1994) will confront a ceiling of scarcity and therefore, will have to be addressed at one time. For the time being, dematerialisation efforts serve the purpose of giving the economy and the natural system some "breathing space", given that gains from higher efficiency and dematerialisation are not spent in an environmentally harmful way at all.

Rees is mindful of the problems economic growth poses for the life-support functions of the biosphere when offering his understanding of the nature of sustainability:

> "From this perspective, the fundamental question for ecological sustainability is whether remaining natural capital stocks (including other species populations and ecosystems) are adequate to provide the resources consumed, and assimilate the wastes produced by the anticipated human population into the next century, while simultaneously maintaining the general life support functions of the ecosphere." (Rees 1996)[21]

The second important implication for research and policy-making, related to the study of whether economic growth can be rendered compatible with a sustainable position of the human system within the biosphere, concerns the question of valuation in decision-making:
Accordingly, ecological economics places more of a focus on the biophysical attributes of economic processes, not only on their monetary value. A basket of different and incommensurable values is regarded as a more appropriate basis for decision-making. The composition of this basket needs to be made explicit in order to avoid inappropriate comparisons and substitutions between incommensurable indicators. Embracing nonlinearity as a dominant characteristic of complex ecological and economic systems is a further obstacle in the valuation of ecosystem services, as two different "units" in resource and more importantly, sink capacity, can have very different values (even two of the same resource in two different

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[21] The above quote has only the purpose to show that the economy is facing constraints - it is not intended here to delve into the issue of regarding nature as capital and the problems associated with that. Suffice to say that the idea of maintaining natural capital as a condition for sustainable development is not universally accepted: building on the critique of the idea of regarding nature as capital, Hinterberger proposes a different approach of tracking material inputs into the economic system as a proxy for measuring environmental impact, with the aim of delinking employment, GDP and material flows (cf. Hinterberger et al. 1997, Hinterberger and Luks 1998).

spatio-temporal situations). Price signals need to be predictable (within certain limits) in order to act as indicators and steering mechanisms of behaviour. In non-linear systems, as resource and sink capacity changes in an unpredictable way, prices for ecosystem services would change accordingly and would thus not be of informative value for economic decision-making (on the concept of nonlinearity in the economics of sustainable development, e.g. cf. Rao 2000, p. 73f.).

As mentioned in the previous section, ecological economics can be regarded as a unique field in the canon of the social sciences, in that it strives to become self-aware, that is, mindful of its limitations as a science. In this self-criticism ecological economics embodies a critique of scientific activity in general and its own activity in particular: The recognition that most of its scientific endeavour is spent in situations of non-linearity (increasing returns, no equilibrium, enabling thus very limited predictability), or even indeterminacy, results in the insight that the ambition towards scientific supremacy is at an end.

Apart from the consequences, from an epistemological point of view mentioned above, of limits to understanding an object, the recognition of non-linearity transforms any scientific activity into a political activity.

A science that sees itself as no longer inherently able to aid decision-making by making reliable predictions stresses the need for a management of complex systems that involves not only scientific and technical advisors, but a much larger group of stakeholders from a variety of backgrounds. In particular, this management style calls for an involvement of government, with regulation setting a socio-political framework. This view is opposed to pure "hands-off" science that favours a *laissez-faire* political system with ideally minimum government involvement. In view of the complex nature of the socio-political system and its biophysical underpinnings, a *laissez-faire* approach may well be more detrimental than helpful (cf. Arthur 1993). This proposition is founded on a search for an appropriate methodology for a science that has to embrace uncertainty (Funtowicz and Ravetz 1991) and indeterminacy (Popper 1990, cf. Mageau et al. 1998, also O'Connor 1994, Faber et al. 1996). The idea of a common standard for economic valuation from an ecological point of view has to be abandoned, as discussed above: there is no universal theory of value. Arbitrary assignments of monetary values to externalities cannot act as sufficient basis for "rational" environmental planning and policies. On the other hand, policies cannot be based just on an ecological rationality in terms, for instance, of carrying capacity, an energy theory of value, or an index of "sustainability". Because of such incommensurability, the economy is inseparable from politics (Martinez-Alier 1994, p. x), and thus economic decision-making cannot be separated from political decision-making anymore. It is the view of the latter as a process of agreement, opened up to a greater number of participants, that can overcome the danger of being locked into a development path that only serves minority interests.

3.2. Conceptual differences between neoclassical economic theory and new approaches

Ecological economics, concerned with studying the relationship between economic and ecological systems, has become a gathering point for a wide umbrella of economists and other scientists who work on extending the focus of mainstream economics. The following part is not intended to be a critique of mainstream neoclassical economics, and with it, environmental and resource economics, as this is done in many places elsewhere (e.g., Hussen 2000, and especially Daly 1992, 1996). It has the purpose of outlining fundamental differences in the conceptual basis of ecological economics in comparison with neoclassical economics and the latter's environmental endeavours. This in turn will serve to illustrate the change that Industrial Ecology, in leaving behind neoclassical economic thinking and becoming grounded in ecological economics, will have to undergo. There are, however, areas where a careful consideration of industrial ecological thought finds it already outside standard economic doctrine. The discipline of Industrial Ecology has nevertheless been a technical tool that does not take an explicit stake in any economic theory, as it aims to be employed by business enterprises. As of now, it has thus underwritten the *status quo* of conventional economic decision-making.

There are various schools of economics differing from neoclassical economics, the canon of current economic theory: the most important to be mentioned here, besides ecological economics, are evolutionary, non-equilibrium, political and institutional economics. These other branches have benefited from cross-fertilisation with each other, a transfer of ideas in the form of metaphors from other sciences, much as it

happened to classical and neoclassical economic theory in the 19th century. Uniting in the critique of neoclassical economic theory as unduly stressing the individual and the predictable, the above branches of economics, in particular institutional economics, recognise that for addressing specific economic problems, the whole of the social system needs to be taken into account, especially the "distribution of power in society, ... economic, social and political stratification and indeed, all institutions and attitudes" (Myrdal 1978). Consequently, the economic system is characterised by interdependence between social factors (as in the discussion of the *ceteris paribus* assumption further above in this chapter), and because of this interdependence of all with all, institutional economists do not feel to be in a position to observe equilibria in economic processes.
This acknowledgment places them in close vicinity with researchers who have studied complex systems, a field of science that expanded rapidly from the late 1970s onwards (with the availability of increasing computing power), beginning with Nicolis and Prigogine's work (where complex systems were described as "far from equilibrium self-organising dissipative structures", "FFESODS", cf. Nicolis and Prigogine 1977). From this field, which includes research activity in nearly all natural and social sciences, evolutionary economists came to dispute the static equilibrium assumption (based on the theorem of diminishing returns) of orthodox economic theory, and suggested to replace it with dynamic models that show path dependency in the development of all complex economic and social systems (cf. Allen 1996). These development trajectories arise from processes that "lock-in" (Arthur 1988, 1993) economic actors in functions of increasing return, where a development path, once it has been chosen, cannot be left, or only by incurring significant costs. Ecological economists took this acknowledgement of non-reversible development as an argument against seeing the market as an efficient tool that worked best when left undisturbed (cf. Nelson 1997). The balancing function of market allocation towards an efficient equilibrium could not be upheld anymore in the face of the dynamic self-reinforcing economic processes that were diagnosed by evolutionary economics.

Whereas neoclassical environmental economics places considerable emphasis on an economic valuation of ecosystem services, ecological economics stresses that valuation should occur from the other end: an endeavour in valuation should encompass human impact on the biosphere and study resilience of ecosystems. Daly's proposal of a steady-state economy (Daly 1992) can serve as an illustration of several other ecological economic concepts that are in contrast to the standard neoclassical theory: Whereas neoclassical theory has at its heart the concept of maximising utility, especially after the introduction and widespread use of differential calculus in the economics profession from the 1860s onwards, ecological economics, mindful of the dependence of the human system on the biosphere, stresses the incompatibility of the maximisation principle with the aim of adjusting to ecological constraints, and thus disputes the former's usefulness. Daly (1992, 1996) suggests instead to base economic decision-making on the ideas of sufficiency and optimality, parallel to developments in ecological systems (cf. Odum 1999). Embracing sufficiency instead of maximum growth as an organising principle has an impact on the basic function of private enterprise: with increasing constraints as to resource availability and sink capacity, the assumption of "infinite wants" (that private enterprise aims to convert into needs, and ultimately, into sales, via advertising) of standard economic theory comes under scrutiny by ecological economics. To the same extent as neoclassical economic theory and related policy-making concentrates on the supply of the goods and services that satisfy those wants, ecological economics devotes its efforts increasingly to understanding the nature, behaviour and scale of the demand side.

In another departure from orthodox scientific canon, ecological economics realises the importance of recognising and stating openly its underlying value system. Since the end of the 19th century, economics has traditionally seen themselves, and in return been seen, as a value-free science. Gunnar Myrdal (with Friedrich von Hayek Nobel prize for economics 1974), whose works have exerted considerable influence on ecological economists, contests the validity of this proposition:

> "Values are always with us. Disinterested research there has never been and never can be. Prior to answers there must be questions. There can be no view except from a view-point. In the questions raised and the view-point chosen, valuations are implied." (Myrdal 1978, p. 5)

Ecological economics thus makes explicit room in its canon of theory for normative questions that complement its analysis, serving further to blur the boundary between this science and others (for instance, philosophy), and also between ecological economics and political decision-making, as discussed above.

3.3. Conceptual similarities between IE theory and EE: steady-state and "type III" system

The "type III" system advocated as the aim of industrial ecological endeavour for the economic system and Daly's steady-state economy can be seen as synonyms for an economic system that is solely reliant on the influx of solar energy for its transformation processes from production over consumption to recycling, feeding again into the production process. Wastes in the form of by-products that can be utilised as inputs into production processes will not cause pollution, and the pollution that is still caused by inherent wear and tear of products (an unavoidable consequence of matter) will have to be eliminated using solar energy.[22]

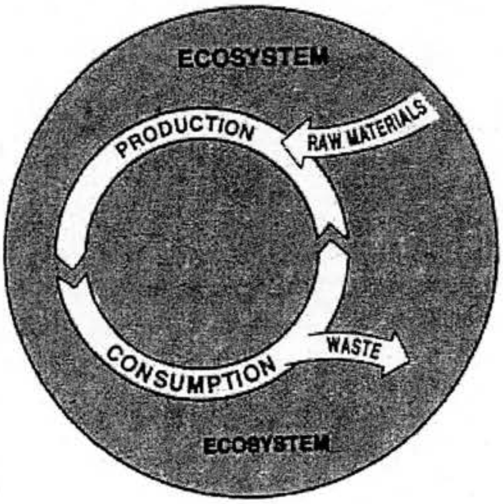

Figure 2.1: Daly's representation of the steady-state economy.
It considers "cycles of production and consumption that take the surrounding ecosystem into account" (Daly 1992, p. 180) and that try to fit with its overall scale.

However, at present there is no serious statement or in-depth evaluation of sustainable development in Industrial Ecology – the 'science of sustainability' does not concern itself with elaborating what that means for a sustainable society. The position of Industrial Ecology on sustainable development hinges therefore on how industrial ecologists incorporate "type III" system characteristics in their work.

Economic growth, as the measurement of increasing conversion of resources exploited and energy utilised into products (and subsequently, waste) is not a characteristic of a true "type III" system. Economic activity in such a system that is fuelled by solar energy only would not be impaired and welfare would not be reduced by pollution. In that vein, Ayres (1996) proposes a "reverse substitution" of labour for fossil fuels that is required to change the present economic system into a system more in line with the "type III" characteristics.

The economic system's throughput, a linear flow (today measured e.g., in GDP), will become a cyclical one in a "type III" or steady-state system. Solely based on solar energy, it will have to support "optimum biomass" (Odum 1999) in the form of more people and "larger" people (i.e., people with a higher consumption of goods and services).

As can be seen when relating back to the discussion at the beginning, due to the cyclical characteristic of the "type III" system at its heart serving as the goal for industrial ecological applications, Industrial Ecology can go further than advocating increasing efficiency, a proposal that could lead to increasing environmental impact instead of reducing absolute consumption of resources and energy.

4. Chapter conclusion: The need for "detritus" economics

The commonalities between Industrial Ecology and ecological economics discussed in the previous section can be taken as an opportunity for developing a relationship of mutual benefit: in the same way as ecological economics can provide the much needed theoretical foundation, and therefore, direction, to Industrial Ecology, the latter can furnish the largely theoretical discipline with a coherent application in which ecological economic thinking can be fruitfully employed.

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[22] The problem of entropic dissipation of matter will be addressed in chapter 3.

For putting forward a proposal for embedding Industrial Ecology in ecological economics, let us return to the question of the bottleneck that is facing an economic system with linear flows underlying the use of resources, production and emission of wastes:

As briefly mentioned above, resources are supposed to follow a linear pattern of availability that is determined both by the cost of extraction and by substitution on the basis of changing market prices. The resulting idea of substitutability and therefore, independence of economic processes from particular resources is seemingly a testimony for human ingenuity, leading many economists and most environmental and resource economists to the conclusion that biophysical limits do not apply to human activities.

Sink capacity, on the other hand, does not follow these mechanic and predictable patterns, since it cannot be "expanded" by new discoveries as can the resource end be replenished or substituted. Furthermore, the biospheric sink also stores the pollution emitted in the past, which affects present and future sink capacity. This memory effect is notable, for example in the case of chlorofluorocarbons in the atmosphere. Assimilation, and thus, neutralisation, of pollutants is a crucial function of the biosphere that does not conform to simple linear behaviour, unlike resource depletion and discovery of new resources, which can be forecast. Sink capacity thus represents the ultimate, "Malthusian", frontier, with no linear relationship between marginal cost and reduction of capacity.

Sink capacity is under pressure from two points: increased pollution through increasing consumption per capita in the North (via economic growth that is strongly correlated to material throughput), and increasing population in the South (out of which more and more persons increase their consumption per capita as well). We have to take this relationship as the foundation for formulating the dependence of the human economy on the natural system: environmental load (or impact) is a function of population numbers, material affluence (consumption per capita), and technology. This relationship is expressed in the so called Ehrlich-Commoner equation (cf. Hussen 2000).

We propose to use "Industrial Ecology" as a synonym for "detritus economics" or "sink economics"[23], emphasising the move away from concentration on natural resources, as in the remit of environmental and resource economics.

"Detritus economics" puts an emphasis on practised Industrial Ecology according to the "type III" system postulate, as such an Industrial Ecology focuses on resource and energy productivity and labour intensity:

The strategy of repairing, reusing, recycling is an alternative that supplants linear flows by cyclical ones and reduces the overall scale of the material flows. Sustaining these processes by continuous energy comes another step closer to the aim of a "type III" system.

Facing a much more complex situation than resource economics, "detritus" or "sink" economics would not be able to concern itself with a valuation of sink capacity, as a value would not have cardinal qualities, illustrating the problems connected with nonlinear behaviour that were outlined above. Rather, a more appropriate management approach would incorporate a significant margin of error in the understanding of natural systems and their resilience, and therefore call for taking the precautionary principle seriously for economic and political decision-making.

It becomes clear that Industrial Ecology in its present form can only be concerned with evaluating and counteracting scarcity of resources rather than sink capacity, as the flows into and out of industrial ecosystems, parks of business enterprises, are still linear, with cascading within the system merely improving the efficiency of the linear resource flows. A truly cyclical industrial ecosystem would be forced to devote at least as much attention to the detritus it produces as to the resources it consumes, as ideally, these two would collapse into one, as the catchphrase of "waste as food" suggests.

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[23] The ensuing chapter, on the behaviour of natural ecosystems, will clarify the connection between resource economics on the one hand and "detritus" or "sink" economics on the other with developing stages in ecosystems.

The "type III" model as a goal necessitates a shift away from the "ends" of the economic process towards cycles, where one process's output feeds as input into another one. Connected to this is the overall scale of the economy within the biosphere (Daly 1992): Exploitation of stocks of resources and sink capacity gradually give way to tapping solely the biogeochemical flows of the natural system. The overall scale of these flows then comes into consideration and the maximum amount of human participation in the biosphere's flows will have to be considered.

Included in the switch from exploiting stocks towards tapping cycles is the recognition that environmental protection cannot happen just on the supply or production side of the economic process. It is consumption of goods and services that is the destination of industrial production where resources have been mobilised, and it is consumption as well which causes environmental degradation in waste disposal, pollution involved with use of goods and services, and resource depletion.

Nevertheless, addressing demand in the light of care for the environment has always been regarded as a difficult, if not an impossible issue: preferences were regarded as given by mainstream economic theory. Furthermore, "managing" demand, in the form of influencing or educating private households, can be seen as infringing the basic rights and liberties of consumers (similar to corporate advertising which is regarded as legitimate).

If, however, the needs of private households are better understood, and can be satisfied with product or service solutions that place the least burden possible on the environment, supply and demand in an economy will have to be regarded in a more integrated fashion. Distinguishing between needs and wants, the role of advertising to create demand, and the satisfaction of the latter in the light of ultimate ends (welfare, happiness) and ultimate means (low-entropy matter-energy, cf. Daly 1992, Meadows 1998) will become a difficult question that policy-making towards sustainable development cannot avoid for much longer.

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Chapter 3

The thermodynamics of evolution in complex systems:

Socio-economic systems degrade energy more effectively than natural ecosystems

From the second law of thermodynamics to the energy implications of evolution and change - theoretical physics as the basis for understanding industrial ecological systems

1. Chapter introduction

Growth in economic activity is the cornerstone of today's economic policy-making, both for developed and developing countries. Economic growth has for the last half century had the shape of higher output of industrial manufacturing mainly in the developed countries and "mobilisation" of natural resources chiefly in developing countries. On the other hand, environmental damage has been caused to natural systems by increasing pollution and stress. Economists would like to see economic growth continuing on this trajectory, if not accelerate. Ecological scientists have been pointing out that natural systems have a limited capacity to yield resources and assimilate or store pollution. The point of the previous chapter was that the human economy, in order to carry on functioning in the future, should adapt itself to the constraints of natural systems.

The present chapter aims to take a fresh look at the seemingly contradictory nature of economic activity and natural processes. Opening up a common ground which both share will bring more clarity to the discussion of how the human system can be embedded in the natural system, especially by way of the application of Industrial Ecology.

This chapter will bring together three important strands in research where the laws of thermodynamics play a prominent role, from works of economists, of ecological scientists, and of physicists. The aim is not to lead to the introduction of yet another set of indicators for measuring distance from sustainability, but to provide a perspective that does not focus only on individual species or contributors to an energy and resource processing system. Instead of looking at these natural or economic agents, this system is concerned with processes and flow directions. It aims to develop an understanding of the very *raison d'etre* of the behaviour of complex systems. From there on overall characteristics of natural ecosystems and statistics of their behaviour can provide indicators not for the current state of the environment affected by human beings, but for future development projects that endeavour to be as sustainable as can be found in natural systems. For the purpose of providing a basis for a thermodynamic understanding of ecosystems behaviour, the whole chapter is divided into two sections: in the first, the important role of the laws of thermodynamics and their unique character will be discussed, in the second, this understanding is used to analyse complex systems behaviour in thermodynamic terms, uncovering the reason for the dynamic change they are subjected to. The second section also contains an application of thermodynamic thought for systems in the field of Industrial Ecology, as it will emerge that human and natural systems are characterised by the same dynamic relationships in the use of energy.

The chapter, however, will also show a crucial difference between human and natural systems: the aim for perpetuity of human development, in a stable social environment, leading to steadily increasing numbers and increasing material consumption. What does that mean for any sustainability strategy that tries to be as compatible to the workings of natural systems as possible?

One of the strands of research mentioned above, mainly inspired by the works of the economist Nicholas Georgescu-Roegen and owing to his perseverance over 30 years, can now be counted among the more conventional research interests of ecological economic researchers, making up, in fact, the core of ecological economic theory: the biophysical dimension of economic transactions. The two others, theoretical ecology and thermodynamic transformation in physics, come from outwith economic theory and should enrich it by inspiring innovative theoretical thinking.

The study starts with the one particular strand of research suggesting a biophysical perspective for observing the economic system, which is traditionally believed to be driven by circular money flows. The thesis of linear flows of resources and energy supporting cyclical money flows is being put forward by quite a number of researchers whose aim has been to rebase or enrich economic theory (cf. e.g. Jacobs 1991). With work in that area proliferating, it cannot anymore be called an alien one to economists[24]. It will become clear in the course of this discussion that in fact the system of socio-economic activity is a subsystem of the natural ecosystem and sustained by it. However, the biophysical dimension will have to be developed further; it is intended here to show that indeed human economic activities and natural processes stem from the same root and still are closely related.

That insight will aid the restructuring of human-made systems, away from mere extraction of natural resources to go into production and waste (Martinez-Alier's 1994 "Raubwirtschaft"[25] or Boulding's 1966 "cowboy economy") towards compatibility with nature in terms of resource and energy usage, as envisaged by the concept of Industrial Ecology's "type III" system.

For that reason, the ideas and insights mentioned above will be linked to recent research into the behaviour of natural ecosystems, and the underlying reason, in thermodynamic terms, for this behaviour, found to be exhibited by all complex systems, be they living or non-living. Both strands of research are established in their fields; the synthesis of these two, though, will enable a new perspective focusing on the transformation of resources and energy in economic processes. The third perspective brought together here originates from physics where scientists are involved in research into the speed of transformation of matter and energy, and again, the consequences of this transformation in thermodynamic terms.

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[24] the UK's pilot environmental accounts are a first step in that direction.

[25] German for "predatory" or "exploitative" economics.

These insights will be useful for restructuring towards an economic system where thermodynamic activity is accounted for in its tools and workings, and which exhibits, in terms of the flows and efficiency of resources and energy, the same behaviour as natural complex systems.

It is hoped that insights into the speed of transformational change (that is production, allocation, and consumption in the economic system) will then provide a sound basis and facilitate a line of research work in economics that focuses on the transformation of resources and energy and the speed of which, and that is aware of its fundamental consequences for socio-economic structures.

The thesis emerging in the course of this discussion is that in order to reduce or prevent environmental degradation, economic theory will have to be augmented by a biophysical dimension based on thermodynamics. As a consequence of recognising underlying flows of material and energy, transformation of resources and energy, the objective of any economic activity, has to be either reduced in quantity or in its speed, or redirected. These factors will then have to be considered in sustainable development strategies and lead to planning and implementation of appropriate concepts, which will be discussed here.

Before we start with the analysis, a brief definition of some important terms for this study is in order. The scientific community is teeming with writings about systems, about efficiency and effectiveness, adding to their individual meanings and interpretations, but also blurring a precise understanding. The terms that need to be defined for this chapter's purposes came up in the title already, and their correct understanding in this context should help to provide the right direction for the ensuing discussion. Especially the terms "efficiency" and "effectiveness" could easily deceive, as they can carry a seemingly precise meaning, according to the context. Normally, efficiency and effectiveness in the world of human thought and endeavour suppose a purpose being the objective of a process with certain means to achieve it. Attributing purposeful behaviour to complex systems, whether they are of a non-human or even non-living nature, is disputed. However, as we will come to see in the subsequent sections employing a thermodynamic viewpoint, one can find a purpose broad and general enough to even take it as the objective of non-living systems. If this objective is accepted, then the ways and means to achieve it can be compared and evaluated. "Effectiveness" in this context is understood as the underlying aim in the choice of the strategy that will most certainly lead to the desired result, "efficiency" is then meant to denote a subservient perspective to a chosen strategy, which is carried out with the least costs.

A "system" for the purpose of this chapter is understood in very broad terms to be a meaningful structure with unique characteristics, comprised of several elements, assembled in an orderly way. The system cannot be disassembled into its elements, as it would then cease to be a system and lose its uniqueness.

2. The position of the laws of thermodynamics among the natural laws

2.1. Circular money flows: the traditional view of the economic system as a perpetuum mobile

The flux of money in the economic realm between producers and consumers, between households, enterprises and the state has been the predominant object of research in economics over the last two centuries and is incorporated in the canon of established economic theory. The hypothesis that these money flows alone constitute the foundation of any economic system and especially the successful capitalist market economy has long attained the status of an undisputed fact, for it has transcended the domain of the professional or scientific economist and entered public knowledge. Money is thus traditionally seen as the abstraction of all goods and services, a universal and permanent agent. Its flow between the participants of the economic system is a circular one, and consequently, the economy in general, in its most abstract sense being a money economy, is still seen as circular as well.

Since the last three decades, however, severe shortages in resources have been experienced in the world and entered the public consciousness, most notably during the oil crises in the 1970s. At the same time, increasing pollution began to point towards the limits of nature's assimilation capacity for the wastes human activity produces. These incidents have put pressure on the traditional perception of a circular money economy, now needing to be revised and augmented. Most importantly, the biophysical aspects and consequences of human economic activity are now being scrutinised and first attempts are being undertaken to incorporate them into economic theory. The circular money flows, it emerged from this different perspective, could only be sustained by an underlying linear flux of energy and resources in one direction, from resource extraction to transformation in the production processes and via consumption to waste disposal. Georgescu-Roegen, one of the most influential writers on the biophysical aspects of the economy, compared the study of economics concentrating on the circular money flows with trying to understand biological organisms by only looking at their circulatory systems as objects of research, and totally neglecting their digestive tract (cf. Daly 1995). For a lucid analogy to illustrate the shortcomings of contemporary economic theory, another metaphor lends itself for comparison, this one being a concept well known in European history: the image of the *perpetuum mobile*, the ever-moving machine which does not need to consume any fuel to remain in motion. Numerous scientists and mechanics, sometimes famous, of the Middle Ages and the early modern times devoted their efforts to the invention of this machine, which was believed to exist in theory. Only owing to technical difficulties, it was maintained, had humankind not yet succeeded in building one. Human ingenuity and technological progress would eventually remedy this.

Even as late as the second half of the 19th century, this impossible concept was debated, albeit to show its ultimate futility, by renowned scientists such as J. Clark Maxwell with his Maxwell's Demon. The concept of the mechanical *perpetuum mobile* may sound comical to modern ears, however, the underlying assumption for the perpetually flowing money economy not using up ever more resources can be seen as the same idea in a different guise. Similar arguments to relying on human ingenuity above are being voiced, for the purpose of promoting technology as the panacea to human suffering on Earth and the need to conduct research into it and distribute it through a market-driven economic system that then can grow indefinitely, as resources then apparently do not constitute a limit on economic activity. Standard economic research and theory recognises only one continuously linear characteristic in the economy which underlies and sustains the circular money flows: growth in output. In neo-classical economic theory, continuous growth in output is held to be needed for keeping up the level of economic activity (the logic behind the computation of the GNP and its flaws need not concern us at this point).

The present-day economic system is plagued with occasional depressions which, however, do not occur frequently enough or with sufficient strength to counteract the main thrust of economic growth (as measured in units of GDP[26]) and put the whole system or the economic theory it rests on into jeopardy.

These two analogies, of the animal without digestive tract and the impossibility of the search for a *perpetuum mobile,* make it quite clear that in any socio-economic activity nothing can be gained without expenditure; the human-made socio-economic system thus conforms to the first law of thermodynamics. It is, however, a matter of the appropriate perspective of investigation to acknowledge this fact. Following from that, both the biophysical and monetary implications of human economic activity will have to be taken together in order to arrive at a proper economic investigation and to devise economic tools and policies appropriate for the long-term space-time framework.

An increasing number of recent research projects show that economic growth and fossil fuel use measured by carbon emissions are closely linked. Once these findings, still debated and fought over, enter the realm of theory as established facts to give support to a reconfiguration of economic policy-making, the need for perpetual economic growth can ironically be seen as the nearest traditional economic theory can get towards recognising the underlying continuous and linear flows of resources and energy without which, it seems, there would not be any economic activity at all.

A very important research topic in economics comprises the problem of inflation, its emergence, how inflation is linked to other economic factors (like growth of GNP, employment), and how to fight it. The reasons for the occurrence of inflation are still not thoroughly understood in economic theory, which is a bit surprising after three-

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[26] Other indicators, e.g. the Index of Sustainable Economic Welfare (ISEW), put forward by Daly and Cobb (1989), show a different picture: For the industrialised world, the indicator can be observed to decline since the 1970s, despite significant growth in economic output.

quarters of a century of research into monetary flows and appropriate policies to steer them. However, might it be that reasons for inflation are to be sought outwith the traditional realm of economic enquiry? Daly (1992) provides a possible explanation: inflation could very well be caused because economic activity is still perceived to take place in an isolated economic system, free from ecological limits. And it is the incongruency between accumulating capital which is no longer a reflection of underlying physical resources (for example, through earning interest without physical resources being involved) and accumulating actual physical resources, where the former by far outperforms the latter in value, that can cause inflation once the two are brought into congruency again. Then abstract exchange value will be devalued to reflect truly again real concrete wealth. This incongruency does not only comprise different rates of growth, but is also a reflection of different modes of scarcity: physical resources in Nature are subject to absolute scarcity, whereas resources, products and money in the economy are only scarce in relation to each other. If this hypothesis is supported by research findings, economists and policy-makers should have another reason to use an economic theory for their work that is augmented by taking use of natural resources into account and abandoning the search for the ultimate *perpetuum mobile.*

2.2. The laws of thermodynamics and their unique position in the canon of natural laws

For a discussion of the hypothesis that human-made systems and natural systems have in common the most fundamental characteristic as their reason for being, it is suggested that the employment of a thermodynamic perspective is necessary, as living systems like all complex systems are subject to its laws. Thus, in order to be able to see behaviour of economic systems from a thermodynamic perspective, a review of the nature of these laws and their significance has to be undertaken. This review will centre on Georgescu-Roegen's work, and the work of physicists that he incorporated into his.

In the latter part of the discussion it will be possible to show how human-made systems have evolved gradually from natural systems, and why both types of system do not have to be antagonistic or incompatible with each other at all.

The laws of thermodynamics, particularly the second law, stand out from the canon of laws of physics: they are examples of a so-called dialectical law as opposed to arithmomorphic laws like the laws of mechanics and geometry. The latter category alone, according to Georgescu-Roegen (1971) belonging to a very restricted class of concepts, is governed by logic, by which unproved postulates are separated from theorems. The chief objective of that arithmomorphic class of laws is measurement. In the same way, arithmomorphic concepts would be discretely distinct from each other, "as a single number in relation to the infinity of all others." (Georgescu-Roegen 1971). The majority of concepts of the mind, however, Georgescu-Roegen maintains, is concerned with forms and quality rather than with measurement. These concepts he calls dialectical, because they and their opposites are not discretely distinct from each other, but overlap and share a common area of definition. On Galilei's claim, that the book of the universe was written "in the language of mathematics, and its characters are triangles, circles, and other geometrical figures" (Galilei 1960, p. 184), the sciences of the emerging modern era were founded. These sciences' rashness in dismissing the characteristics of Galilei's "second order" (the qualities and forms of objects rather than their size and weight, cf. Galilei 1960, p. 184), as it is being exposed by numerous writers up to the present day, is then consequently constituting the major obstacle to a genuine understanding of the world around us[27]. Thermodynamics is a truly unique field because it evolved out of physics, the very discipline which Galilei's thoughts helped to found, and whose laws are thus mainly arithmomorphic and based on logical structure.

Furthermore, the laws of thermodynamics occupy a special position in the canon of natural laws confounding the assumptions of mechanics pertinent to all the other laws of physics, as the former are of an evolutionary nature, and what is more, they are the only examples of evolutionary laws (Schrödinger 1955). An evolutionary law is concerned with a time's arrow in so far that in its workings it only provides one

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[27] Cf. chapter 4, however, for the context in which Galilei's writing was placed: he wished to deny alchemy, a field that was built around comparing objects from different spheres (e.g., by likening metals in their attributes to planets), scientific credibility, and move to a more serious and systematic inquiry. This context has been lost and Galilei's writings taken on a perhaps unintended rigour.

direction in which time flows. Involving the arrow of time makes way for laws describing irreversible processes:

Nearly all laws of physics describe situations of reversibility, most of them in terms of locomotion. Their realm of explanation covers quantitative changes brought about by cause-effect relationships. Within their remit, quantitative changes are mechanical, because they are regarded as being reversible.

Geometry, astronomy, and classical mechanics are examples of sciences, which from the understanding of laws of motion, seek to ascertain where and when a definite event will take place (Georgescu-Roegen 1971, ch. vii). Quantum mechanics is a discipline where the idea of determining specific points in space-time had to be abolished. Instead, probabilities had to be used, revealing, compared to the first group of sciences, a concept of much reduced certainty, but increased explanatory power.

As a further step away from precise determination in space-time, the second law of thermodynamics, concerning itself with the conversion of energy, is unique in that it does not aim to ascertain when one system's bound energy will reach a maximum, and what exactly will happen. The transformation of free into bound energy is not even a measurable process. The only answer the second law gives is to "determine the general direction of the ... process [of reverting free into bound energy] of any isolated system." (Georgescu-Roegen 1971, ch. vii). What is clearly visible is a downward gradient in precision from mechanic laws via probabilistic ones to the second law of thermodynamics. However, this tendency is complemented by a reverse relationship: the second law of thermodynamics is the only natural law, and the other two categories (mechanic and probabilistic laws) are increasingly remote from observations in the real world, as both describe idealistic situations which would not generally happen *in vivo*.

The laws of thermodynamics are the only laws of physics which explain a qualitative and irreversible process and incorporate a singular direction of change, the arrow of time. This change is expressed by the conversion of free energy into bound energy, that is, from a useful into a useless state. As discussed in detail below, bound energy, that is unavailable energy, in one particular place can only be made available again, that is some of it converted back into a free state if in some other place more energy is converted from a free into a bound state.

2.3. Conservation, degradation, and irreversible processes

The effects of the laws of thermodynamics on the biophysical world are profound and can be summarised with the discussion of the two laws:

The first law of the conservation of energy and matter states that neither can be created or destroyed, only transformed. Applied to the natural ecosystem and a perspective on resources, this means that there is a finite and constant amount of matter in our biophysical environment. The Earth has to be regarded as a closed system with respect to physical matter, as it does not exchange matter with its environment, if we disregard the odd meteorite from the solar system impacting on the Earth's surface. It is energy in the form of continuously inflowing solar energy (continuous for all human purposes: the sun's energy store will be exhausted in about 5 billion years, see below) to which the Earth is exposed.

As the first law states that there cannot be anything made out of nothing (rendering *perpetua mobile* of the first order an impossibility, as Söllner 1996 states), the socio-economic system with its transformation of resources into useful products then ultimately transforms natural resources and energy into products, a process leading to a reduction of the amount of natural resources available. This can easily be seen in the fact that ever more new types and stores of resources have to be utilised, the ones formerly mined or extracted having been exhausted. Resources are used to create and assemble the material objects in our society we call human-made capital. To introduce a simple explanation of the second law at this stage, we can observe that this human-made capital, however, does not merely accumulate steadily, as more resources are transformed. If a longer time frame, say, a hundred years, is used, we can clearly see that everything that is built up in the socio-economic system, even items with a long period of usage as buildings, roads and power plants, heads for disintegration and decay and has to be replaced by newly built or created items. This is not only due to the increasing pace of technological progress: the used material ages and maintenance costs go up. In buildings or bigger projects of any kind the security risks increase. Moreover, the results of this decay are of a sort which cannot be used for any purpose: waste is created whose energy content, unlike in natural products, to an overwhelming extent cannot yet be replenished through processes of assimilation and recycling. Not only are the end products of transforming resources into temporary human-made capital mainly true "end products", that is wastes without any value, furthermore, many of these waste products are widely dispersed, which makes gathering and recycling them even less economically viable.

The comparison of durability and type of free energy embodied in natural and human-made capital brings us to an important point in environmental economic thinking in the process of conceiving and implementing a sustainable economic system, the hypothesis of the commensurability of natural and human-made capital (cf. Pearce 1989, also Perrings 1986). It is the sum of natural and human-made capital, it is claimed, which is to be kept constant or to be increased in order to arrive at a sustainable economic system. Consequently, human-made capital and natural capital are being seen as perfectly substitutable, and hence, only the sum of both matters. If the first law of thermodynamics holds, perfect efficiency (or corresponding valuation of human-made capital) is needed to transform natural into human-made capital and to keep the sum constant. Moreover, as argued before, human-made capital is subject to decay into wastes, and thus to depreciation. Therefore, in the light of the discussion of the natural ecosystem's biophysical nature and its obeisance of the law of a fixed total of matter and energy, the point substituting human-made capital for natural capital that keeps overall capital at an equal value must be clearly seen as being fundamentally flawed[28].

In the socio-economic system's use of resources and energy, a substitution of a specific resource only circumvents the problem of its increasing scarcity temporarily, for substitution of one resource for another cannot escape from the overall limit of the total amount of resources: there cannot be an infinite substitutability.

Not only can any matter or energy neither be created or destroyed and only be transformed with less than perfect efficiency, moreover, as the second law of

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[28] as acknowledged by Pearce himself, however, research continues, for want of a better concept.

thermodynamics states, there is a direction in the processes of transformation[29]. As we saw already in the decay of human-made capital, nothing which was produced by a transformation of resources and energy stays the same and maintains the same quality and usability over an unlimited period of time.

The implication of the second law of thermodynamics is ultimately that not even can an output larger than the corresponding input not be obtained due to the conservation of matter and energy derived from the first law, but every time when a transformation process is happening, it is with less than maximum efficiency: a part of that energy is converted into a useless state, mostly heat (Söllner 1996 calls this relationship the recognition of the impossibility of *perpetua mobile* of the second order). As mentioned briefly above, the result of this transforming process will be subject to slow disintegration, an irreversible process. The singular direction of transformation in converting free into bound energy is generally acknowledged today. However, earlier this century Max Boltzmann tried to show that there is not necessarily a fixed direction from free towards bound energy. He maintained that there could also be reverse processes, although they would only occur at an extremely low probability. His research gave rise to the field of statistical mechanics, or, statistical thermodynamics, as it was called more appropriately. The main challenge of this field was that there are no irreversible processes. Establishing this hypothesis would mean that all processes would conform to the laws of mechanics, being reversible in theory. However, Boltzmann failed to establish proof of the hypothesis of the existence of reversible processes that would take the opposite direction from thermodynamic decay, from bound to free energy (however, the discipline of statistical thermodynamics, unperturbed, is still a very active one). The irreversible nature of thermodynamic processes is acknowledged today by scientists

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[29] In this chapter, the second law of thermodynamics will not be discussed with the help of the concept of entropy. As Schneider and Kay (1994a, b) contend, entropy is only defined in equilibrium situations, which never occur in nature's processes. Yet, Prigogine and Stengers (1987) point out in their attack on statistical thermodynamics proposed by Boltzmann that it is entropy as the number of complexions, the probability of the microstates, that is only defined in equilibrium. Entropy being an expression of the conversion of free into bound energy always holds, even in non-equilibrium thermodynamics. However, to not confuse matters by the employment of an ambiguously used term, the effects of the second law are being described by simply stating that in all processes of transformation free energy is irrevocably converted into bound energy.

who concern themselves with research into the behaviour of biological, physical and chemical systems.

As we have seen, the second law of thermodynamics governs every process of transformation, leading to the free energy used therein reverting to a bound and useless state. With the change of state, the matter that energy is tied to inevitably loses its resource status and becomes waste. A socio-economic system which primarily uses - ultimately meaning transforms into waste - resources like metals, minerals and fossil organic energy carriers will not only encounter an end to these resources, but the timespan they will be available naturally would be the longer, the more moderately and sparingly they are transformed. Recycling can extend the period these resources will be available, but it cannot be the solution to the problem of dwindling resources overall. In any biochemical transformation there will be a percentage of the input matter which will be rendered unusable either because it is dissipated and cannot be retrieved or because its structure is broken down and its energy content exhausted and cannot be replenished. Recycling facilities require material resources to construct and to operate, and as long as it is non-renewable energy which fuels recycling processes (gathering of waste and transforming them back into resources), it might rather aggravate than alleviate the problem by resulting in more negative than positive impacts on the natural ecosystem, as Jacobs convincingly points out (Jacobs 1991, p. 13).

Georgescu-Roegen even maintained that there are entropic limits to recycling, as matter becomes dispersed and cannot be concentrated and replenished in its energy content. He called this postulated relationship of entropic dissipation of matter the "fourth law" of thermodynamics. His position, however, is not universally accepted, and a series of authors have used criticisms of this principle to discredit and dismiss Georgescu-Roegen's writings entirely. Ayres (1998, 1999) and Craig (2001) make the point that given sufficient energy (solar energy) and a big enough "wastebasket" (the environment that takes up the dispersed materials), there are no limits to recycling, therefore depriving Georgescu-Roegen's "fourth law" of its standing.

The fact that non-renewable resources commonly do not have the facility to have their energy contents replenished distinguishes them from the renewable building blocks the natural ecosystem uses in its cyclical flows of matter and energy, which could continue perpetually, as they are sustained by a flow of continuous solar energy. In general, we could call non-renewable resources the stocks or deposits which are being depleted, and renewable resources the flows that are being tapped by humankind. However, even renewable resources one day could cease to be renewable: They are plants or plant-derived products which grow on the soil and depend on the soil quality to be truly renewable, and furthermore, organisms and organic biomass depending on those plants that fix carbon. The soil being used for that purpose of carbon-fixing and all the related ones, though, is not a continuous resource, as it appears to be when seen in a macroscopic context. On the microscopic level, however, the soil has a mineral and energy content which is used, that is, diminished, by growing plants. This mineral and energy endowment also has to be replenished to continue being of use for vegetation. For this purpose, there has to be enough organic matter that can decompose into minerals, the presence of appropriate micro-organisms, and a climate which provides the soil with some humidity, to aid decomposition and to prevent erosion or dispersion by strong winds.

These conditions can easily be negatively affected by agricultural enterprise with an output-maximising objective. Exhausted soils, erosion and ensuing desertification are a common feature in the agriculture of our modern times. Surveys over a period of time show that the arable land area diminishes indeed. Renewable resources then can only be truly renewable when the burden on arable land is not too high, not too much land is used for agriculture at one given time, and the overall ecosystem is not too much stressed, so that critical cycles enabling and supporting the replenishment of farmed soil are still fully functional. These limiting factors constrain the overall human load on the planet, and are a result of the direction of free energy converting to bound energy as described by the second law.

In the last fifty years up until the present day, agrochemical products, fertilisers, have had an extraordinary success in raising the yield of one given patch of farmed land at a given point in time. The idea behind these products is to substitute the natural processes of keeping the soil fertile by artificial processes. As these products are not natural, they have some detrimental effects on the soil: they leave a residue, they exhaust it even more (through the increased productivity there are no periods of leaving the land fallow any more, so that it cannot replenish its fertility) and thus these products make the soil dependent on even more technology leading to potentially harmful effects on food and the other renewable resources grown.

The above discussion had the purpose to show that nothing at all is exempt from degradation, entropic decay, and thus all processes of transformation are governed by the second law of thermodynamics. The only exception is the sun, when we look at it from a human perspective with a timeframe well below its remaining lifetime, an estimated 5 billion years. The sun, of course subject to using up its own resources, nevertheless can be regarded as a continuous input factor, as far as living beings on the surface of the Earth are concerned. It is the only important *external* source of energy and thus is the only factor in the network of the planet's ecosystems that has only a one-sided cause-effect relationship, as it cannot be affected by the other factors, chiefly among them complex living systems. To rely on this absolutely independent continuous source of energy to revert wastes into resources by converting bound into available energy is nature's ingenuity and the reason for the resilience of life on Earth.

Thus in time this central position of solar energy (in its direct form of solar radiation, but also in the indirect form of wind and wave energy, as well as hydropower) also will be very likely to become sustainable practice for human-made systems, once either the sources and the sink capacity for fossil fuels become less abundant. The purpose of the next part will be to elaborate further how natural ecosystems depend on that influx of energy and how the amount of that principal energy source influences the development of the whole ecosystem. The insight gained from this analysis concerns understanding the role of resource and energy flows of natural ecosystems in different stages of development, a valuable tool for creating a sustainable economic system in the form of Industrial Ecology applications.

3. Thermodynamics can provide an explanation for the directed dynamic activity of all complex systems

The previous section finished with the statement that solar radiation is the principal energy flow on which the whole of the Earth's living systems have come to depend. The purpose of this section is to broaden the understanding of this dependence, firstly to include all complex systems, living or non-living, in the influence of that energy flow, and secondly, to show these systems' dynamic reaction to the energy influx in their development.

To be able to provide a possible explanation why complex systems, living and non-living, evolved in the way they did in this environment, is a most important finding for assessing the role of human systems in the context of all complex systems in the biosphere.

The following analysis is based on insights from recent research in theoretical ecology. It was the two theoretical ecologists E. D. Schneider and J. J. Kay who developed pioneering ideas for understanding ecosystems in their dynamic nature and development (Schneider and Kay 1994a, b). Their work builds on and extends research findings and writings by Lotka (in the 1920s), Odum, Georgescu-Roegen, Ulanowicz and Hannon (since 1970s), among others. All these authors, however, stay in the realm of ecological theory and natural ecosystems. Apart from Hannon et al. (1995), who discuss energy transformation in the implications for sustainable agriculture, and suggest a possible measure for sustainability in that case by comparing sustainable agricultural production to mature ecosystems like the tall grass prairie, there is no direct application to human-made systems, and in particular the industrial economic system.

Building on the research in theoretical ecology, and with the aim to fill that gap by applying ecosystem theory to human-made systems, it is this chapter's objective to take Schneider and Kay's work as a foundation for revealing that our socio-economic systems display the same characteristics as other complex systems when they react to change. Natural systems and human-made systems will be compared as to their energy transformation characteristics. The intention is to show what natural systems and human-made systems have in common in that respect and where they differ, and by doing so, to shed some more light on the root of the problem of environmental degradation. An appreciation of the role of human systems in the light of energy transformation will provide Industrial Ecology with a better basis to develop its applications that thrive on the natural ecosystem analogy. The next section is therefore devoted to showing that it is a much higher level of effectiveness in energy transformation that distinguishes human-made systems from natural systems in the view of systems ecology. However, it will become clear that it is exactly this higher effectiveness which can be seen as causing the stress on all systems in the biosphere we are currently experiencing.

3.1. Complex systems or Schrödinger's "order from disorder"

Before we can look at ecosystems and their thermodynamic behaviour, an excursion with a brief look at complex systems theory is necessary for appreciating the conceptual differences between linear systems, on the one hand, that could be understood by traditional science, and on the other hand, complex or non-linear ones that pose problems for analysis and prediction with conventional tools of scientific analysis.

Erwin Schrödinger (1955) postulated two principles of development for living systems: "order from order" and "order from disorder". It is the second principle that has captured the attention of systems scientists and theoretical ecologists, as it has potential for explaining evolutionary dynamics in the course of the development of life.

In a seminal article and a following book, the physicist Ilya Prigogine (Prigogine 1972, Nicolis and Prigogine 1977) founded and popularised the concept of the far-from-equilibrium self-organising dissipative system, the "FFESODS". These systems take in energy and remain in a state of continuous change and fluctuation, which is nevertheless stable.

Ecosystems belong to this class of systems that are increasingly discovered to underlie all real-world situations, such as social interactions, weather phenomena, etc. These systems do not conform to the assumption of finite and differentiated elements coming together in a situation of a static equilibrium which would have made such systems predictable by standard mathematical analysis. Instead of a static equilibrium, dependency on the initial development path chosen is observed, leading to the recognition of past dynamics and history as important factors for understanding current development (cf. Arthur 1988).

Prigogine and his associates devoted work to showing that ecological systems have an evolutionary tendency towards higher complexity and increased energy flow-through. This propensity is the result of dissipative structures arising in complex systems that take in energy: In order to not be rendered instable by the continuing influx of energy, the system reorganises to a higher level of complexity, that is, a higher amount of embodied energy (Prigogine et al. 1972). This fundamental insight into systems behaviour provided a further challenge to Newtonian physics (after quantum mechanics) and quickly entered other disciplines such as mathematical modelling, systems ecology, theoretical biology, and tentatively, economics. Further below in this chapter, the recognition of complex systems tending towards even more complex structures will be discussed in the light of ecosystem development (ecological succession) and the link between the evolution of plants, animals and humans.

3.2. Emergence of complex systems as a reaction to the continuous inflow of solar radiation

The effects of the inflow of solar radiation do not comprise just the heating up of the atmosphere and the surface, that is the soil, the rock, and the oceans: it is the resulting gradients, the differences in temperature between two different points of location, that are the cause for the whole of the climate and its many characteristics, the formation of clouds and winds, sea currents, and the many cyclical flows, the most noticeable being water evaporating from the oceans, forming clouds, falling back onto the Earth as rain and eventually flowing into the oceans. These flows constitute intricate means of transportation and exchange for minerals and biomass. Through the climate system, which is subject to Nernst's Law[30], these gradients of temperature give rise to gradients of pressure.

The work by Schneider and Kay focused on a restatement of the laws of thermodynamics, for they concentrated in their research on open non-equilibrium systems. The classical formulation of the laws covers equilibrium situations in closed systems. For understanding complex systems in the Earth's biosphere, however, the laws have to be restated in order to apply there. As there are no isolated and/or equilibrium systems in the real world, research into open non-equilibrium systems has much more relevance to practical reality. We will see that all of these open systems depend on an influx of matter and energy, and chiefly solar energy, to maintain their thermodynamic order and structure.

Schneider and Kay's work results in a new understanding of energy degrading processes, namely that thermodynamic systems resist movement away from their states of relative equilibrium. This finding has to be seen as one of the most fundamental insights in theoretical ecology and a definite move forward to understanding the nature of resource and energy processing in all complex systems, be they natural or human-made. The authors argue that the more a system is removed from its temporary thermodynamic equilibrium, the more sophisticated its mechanisms become to resist that very move. Self-organisation into complex structures is the most important and most effective of these mechanisms in the appropriate dynamic or kinetic conditions to resist mounting gradients of temperature that push systems further away from their thermodynamic equilibrium.

This hypothesis had its origin in work (Schneider and Kay 1994a) on the second law of thermodynamics. That work was based on basic research during the 1960s, which saw three laws, the zeroth, first and second, being restated in one, called the "law of stable equilibrium" by Hatsopoulos and Keenan, and the "unified principle of thermodynamics" by Kestin.

Hatsopoulos and Keenan synthesised the laws of thermodynamics as follows:

"When an isolated system performs a process after the removal of a series of internal constraints, it will reach a unique state of equilibrium: this state of equilibrium is independent of the order in which the constraints have been removed." (Schneider and Kay 1994b, p. 630).

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[30] The universal gas equation (pV=NRT): pressure and volume of a gas are proportional to the number of gas particles and their temperature.

This extension is especially important for the second law of thermodynamics, as it does not have to rely on the concept of entropy, which is only defined in equilibrium situations, as discussed in the first section. It was exactly this limitation of the entropy concept which led some scientists to disclaim completely the validity of the laws of thermodynamics. The validity of the main statement of the (classical) second law, specifically that structures in dissipative systems have to be maintained at the expense of the quality of inflowing energy, remains unaffected by the extension of the law. In Schneider and Kay's work based on the reformulated unified law of thermodynamics, this not only remains true, but must be seen as the organising principle of complex systems when turned on its head: inflowing energy causes complex structures to emerge in the first place. These structures enable the larger system to degrade energy, and at the same time they depend on that influx of energy. Both causal relationships are not only true and possible, but also dependent on each other, a good example of cyclical processes of feedback loops[31].

3.3. The concept of ecological succession

The extended unified law of thermodynamics, as it is termed in Schneider and Kay's work, now states a cause-effect relationship, or a sequence of action-reaction (in either of both ways of the causal relationship, as mentioned above). A thermodynamic system resisting gradients pulling it away from its original state of relative equilibrium and in doing so instigating and subjecting itself to structural change, constitutes an appropriate response to an action: a rather purposeful behaviour that can be attested to complex systems, even non-living ones.

The science of ecology has been emancipating itself from biology, since Haeckel in 1866 provided it with its working scope by defining ecology as the study of the relationship of organisms with their external environment. The science has made advances mainly by describing interactions focused on either organism, population,

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[31] These processes were traditionally interpreted as linear processes, when only one dimension of causality was explored and understood, and a single or a bunch of factors could safely be called "cause" leading to occurrences called "effect". Complexity theory, however, concentrates specifically on just these mutually dependent processes that make up self-organising structures. There is no simple hierarchical or time-space distinction between causes and effects anymore, rendering that distinction obsolete. As research in complexity theory proliferates, the underlying complexity in seemingly well understood linear or apparently reversible processes is more and more exposed.

or community levels. The focus has mainly been on an analysis of single participants and their living conditions. Only with the work of the brothers Odum since the 1950s did ecologists begin to develop a perspective for studying ecosystems in their entirety (cf. Schneider and Kay 1994b). Eugene and Howard Odum began to understand developing ecosystems in a phenomenological way, and also created the first methods for an analysis of energy flows in ecosystems. It is endeavoured here to describe the development stages of ecosystems from earlier to mature stages, and point out the implications for energy flowthrough from that development.

The development of ecosystems takes place in two different stages: the early colonising or pioneering stage and the ensuing mature or climax stage, the end stage of ecosystem development (cf. Odum 1969). All ecosystems are wont to develop along this path, however, it depends on external circumstances, mostly disturbances (by humans or from natural causes such as fire or seasonal changes), whether the climax stage can be reached. Even then the development of an ecosystem does not come to an end, as the dynamic environment (and sometimes factors within ecosystems themselves) continuously provides stimuli for disturbances, so that a mature ecosystem could be thrown back to a less advanced state and exhibit pioneering characteristics again. Ecological succession therefore is a directional and thus, a reasonable predictable activity.

What are the general characteristics of these two stages in ecosystems development? In the early stage, ecosystems are characterised by the abundance of fast growing and reproducing organisms, both plants and animals. These species, called r-strategists (r is the coefficient for population growth, cf. Odum 1999), very rapidly accumulate biomass and mobilise a maximum of mineral resources. They devote more energy to reproduction than to individual survival purposes. We can think of them as rather simple organisms, both in the case of plants and animals. These organisms dominate in an "empty" ecosystem that does not experience pressures on population growth. The food chains in such cases are rather simple (linear) and are predominantly based on grazing relationships (plants-herbivores-carnivores). As the ecosystem accumulates biomass and increases the diversity of species, different organisms are favoured by selection: these are plants and animals that are higher developed, in that they devote more energy to the development of individuals and their upkeep and less to achieving a high number of offspring. They occupy all available niches in the ecosystem, which becomes much more complex. These organisms are called K-strategists (K being the saturation coefficient for a population, cf. Odum 1999), as their survival strategy relies on feedback control. Food chains become more complex, resembling networks with a high number of participants. They are predominantly based not on grazing, but on detritus chains, living off excretions or decaying organic material (detritus-detritivore-small carnivore-larger carnivore).

As an example, let us assume a stretch of land (for convenience of explanation; ecological succession takes place in every ecosystem on Earth) which was agriculturally productive, but has been abandoned. In the first few years, weeds would cover the plot, transforming it into grassland. These plants spread rapidly, but are short-lived. They provide, however, ideal living conditions for shrubs and after a further 20 years, the first species of trees, like pine. The latter do not reproduce as rapidly as the former r-strategists, but devote more energy to individual development: the organisms become larger, more complex and live longer. The last stage, the climax stage, is accomplished after more than a hundred years by oak and hickory trees, which grow much slower than pines, but live much longer. Although the development of an ecosystem is most noticeable in its plant cover, the same parallel development occurs for the related fauna, the animal species, among them particularly birds playing an active role in the reproduction of plants (through spreading seeds).

These are not entirely new aspects discovered by ecologists, as some scientists almost a hundred years ago described how vegetation reclaimed paths and roads abandoned by settlers in the United States (cf. Odum 1999). What is new, however, is the insight that this behaviour is ubiquitous in every ecosystem on the planet, and thus constitutes standard (and both generalisable and predictable) activity.

We have to compare ecosystem behaviour as it is understood by ecologists today with behaviour that is taken as a model by Industrial Ecologists in order to see how successful the latter discipline can apply ecosystem concepts to industrial activity. Industrial Ecologists make much of foodwebs in ecosystems and try to portray industrial structures in the same manner as ecosystems with their trophic levels (cf.

Graedel 1996). The reasoning is that this perspective, illustrating ecosystem dynamics, similarly explains industrial structures. It is hoped that a complex network of waste and product exchanges leads to the creation of a sustainable industrial ecosystem. For this reason, ecological succession is mentioned within Industrial Ecology, however, without leading to a profound discussion or policy implications (The work of Odum 1969 is merely copied without comment, as mentioned above in chapter 1).

Even at this stage of analysis, however, some interesting conclusions could be drawn for the behaviour of human systems with respect to natural ecosystems: the steadily expanding human economy is taking up ever more room of the biosphere that would be occupied by natural ecosystems, thereby exerting stress on the surrounding ecosystems[32]. Where natural systems have a tendency towards a steady-state climax stage, stabilising their biomass on a high level, and sustaining it on a low energy flow per unit of biomass supported (Odum 1969), human systems expand inexorably, both in numbers of population and matter and energy requirements per unit of population. The human system therefore can be likened to a pioneering stage in an ecosystem, with no apparent tendency to turn into a mature stage, stabilising its biomass.

Decker et al. (2000) apply ecological succession to urban systems, arguing that in premodern times cities approached a climax state, where further growth was checked by local availability of resources. Today, the climax state may only be reached on a global scale, owing to the ability of human systems to spread their footprint and import or appropriate carrying capacity. The vehicle for this growth is the growing interconnectedness of national economies and the vastly increased role of transport. On the earth scale, the climax state would be approached "when global energy sources are maximally utilized, energy flux is at steady state, and infrastructure growth has ceased" (Decker et al. 2000, p. 721).

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[32] Vitousek et al. 1986 contend that humanity appropriates circa 40% of terrestrial net primary production (NPP), that is solar energy captured in photosynthesis less energy expended for primary producers growth and reproduction. NPP is the source of energy for all heterotrophic organisms.

Before modern times, cities may have reached a climax state when "energy and food sources were strictly renewable, and transport time on foot limited the extent of a town's hinterland from which it could draw food, water and fuel and recycle its waste" (Decker et al. 2000, p. 721). Cities' different levels of dependence on transport and trade then symbolise the different scales at which a climax state will be reached - be it voluntarily, by restructuring, or involuntarily, by negative feedback from the surrounding ecosystems.

3.4. The purpose of energy degradation for ecosystem behaviour

Is it appropriate at all to compare human and natural systems in this way? A group of economists has argued over the last 30 years that the human economy is exempt from these constraints and dynamics that affect the surrounding biosphere.

We have to return to the application of energy analysis to ecological succession in order to uncover the underlying reasons for the structures of an ecosystem, in particular its foodwebs.

It was only in the 1980s that theoretical ecologists, spearheaded by the aforementioned Schneider and Kay, started to apply energy theory to dynamic ecosystem behaviour. What was missing at that time was an underlying theory that could explain the reasons for ecological succession - behaviour that was clearly outwith the scope of analysis for single species and required an holistic approach, trying to understand the energetics of an entire ecosystem. Schneider and Kay's theory of maximum energy degradation as the objective of all complex systems had its precursor in Lotka's law of maximum energy in biological systems (Lotka 1925). The main purpose of this branch of research is to introduce thermodynamic analysis into ecosystems research and by doing so reconcile the apparent contradiction between the imperative of the second law of thermodynamics (all transformation processes result in a loss of available energy, leading to an ultimate dissipation of all structure) with the observation that life creates evermore complex structures in its evolution. It became clear that whereas the prediction of the second law of thermodynamics is true for completely closed systems, the Earth does constitute an open system with respect to the influx of solar energy, as discussed in this chapter's first section. Solar radiation, an abundant source of very high quality energy, leads to the creation of gradients of temperature (and pressure), as we have seen. The important question is, how does this energy source impact on ecosystem behaviour, and can ecological succession be related to the effects of insolation?

Solar energy is utilised by plants for assimilation of inorganic matter into biomass, the process we call photosynthesis. They build up advanced structures on the supply of solar energy, which is degraded in the process - plants give off the by-products of photosynthetic activity, oxygen and heat, and embody energy in their complex structures, thereby complying with the second law that postulates that a system increasing its energy content does so at the expense of the energy content of its surroundings. The waste heat emanating from photosynthetic activity is radiated back into the atmosphere (and from there into space). Plants are therefore effective dissipators of energy. In the same vein can the other biological systems be understood: herbivores assimilate plant biomass, therefore also degrade energy into embodied energy and dissipated heat (as also this transformation process cannot be completely efficient), and carnivores do the same with the biomass coming from herbivores and other carnivores that are lower down the food chain. Human beings are at the end of food chains, and therefore consume the highest amount of embodied solar energy. From a distant observation point it can be seen that the Earth receives high-grade solar energy and radiates back low-grade heat, with the difference in energy potential embodied in the planet's biological structures.
The whole network of food relationships in the biosphere degrades energy. Lotka concentrated only on the intake of energy, and maintained that those systems that maximise utilisation of inflowing energy will be favoured by natural selection. He called this the law of maximum energy in biological systems - "entropy increases faster in the presence of life" (Lotka 1925, also Odum and Pinkerton 1955, and Ulanowicz and Hannon 1987).

The merit of Schneider and Kay's work lies in turning this insight on its head, by postulating that entire ecosystems will be in a position of higher stability if they develop relationships between species that dissipate energy most effectively. The authors made use of Hatsopoulos and Keenan's restated law of stable equilibrium to apply to natural systems. They found that non-living systems of cloud-surface interactions degraded incoming solar energy, and that living systems performed the same task much more effectively. Life, in that respect, can be seen as the answer to the need for stabilising complex systems. Living systems would be more effective means than non-living ones for dissipating gradients of temperature built up by the influx of solar energy. What is important to bear in mind is that, although living systems are qualitatively different from non-living systems, they still share the same basic purpose of energy degradation.

The field of Industrial Ecology can apply these findings of theoretical ecology in its depiction of food chains in natural and industrial systems. Industrial ecologists until now have been content merely to describe food chain structures, but did not venture further than that. Industrial Ecology does not ask the question, why are there foodwebs in the first place, and why are they very often highly complex?
The concept of degrading of energy makes it clear that the mere depiction of food chains is not a very profound analytical activity: Food chains are present in natural ecosystems for a specific purpose, and this purpose is removed from the level of individual species that take in energy: the stability of the whole ecosystem (and through the whole, also its parts) is enhanced by the entirety of ecological relationships (and also geophysical relationships for the non-living complex systems that living systems are related to) that degrade inflowing solar energy. The underlying reasons for the existence of foodwebs thus need to be understood by Industrial Ecology in order to use the foodweb concept constructively and not just superficially.

Accepting Schneider and Kay's proposal that whole ecosystems develop to degrade energy more effectively has a profound consequence for the understanding of the role of species in biological evolution: In the Darwinian and Darwinist theories, the focus of analysis is on the individual species which fought for survival, if need be, against other species which were seen as one species' competitors. Darwin's theory was very much the result of the individualistic perspective on the sciences at the time of its conception (cf. Young 1985, Worster 1985, Trepl 1994, Ekschmitt and Breckling 1994). "Fitness" for survival was then attributed to species individually (although all attempts to quantify that failed). Looking at whole ecosystems and their underlying purpose of degrading energy with ever higher capacity, as

Schneider and Kay's paper suggests results in a very different understanding and observational perspective of evolution. The focus on "fitness" as an evaluation of a species' survival potential changes to describe an ecosystem's ability to degrade energy by dissipating gradients. One single species is only significant in the whole energy-degrading web of species making up that particular ecosystem. The direction of evolution then, as Schneider and Kay contend, would irrevocably point towards the development of more mature ecosystems which could degrade more energy and exert a bigger pull towards equilibrium (which in nature is never really reached, as disturbances through gradients of pressure and temperature are perpetual). This hypothesis fits well with work done at the Santa Fé Institute, New Mexico, the most prominent research institute dedicated to exploring all manifestations of complexity. Kauffman calls it a fundamental fact of life that organisms have become more complex since life began. However, in contrast to Schneider and Kay, Kauffman and his colleagues, still in the Darwinian tradition, try to ascertain advantages for individual organisms or species that develop more complex body plans and structures (cf. Waldrop 1992).

Theoretical ecologists, reacting to Schneider and Kay's theory, have recognised this departure from an individualistic focus on single species in their analysis, and are exerting an influence on other ecological scientists, for instance ecological modellers to improve their understanding of complex situations (cf. Grimm 1999).

3.5. Energy use in ecological succession

The tendency for complex systems to move towards more advanced structures that degrade energy more effectively explains the dynamics of ecological succession. Climax ecosystems are the end stage reaching a local maximum in complexity, which is embodied in individual species' bodies and in the complex relationships between them. In the absence of external disturbances, the climax stage is a steady-state degrading a maximum amount of inflowing energy. For evidence of this phenomenon, Schneider and Kay (1994b) use temperature measurements by the NASA over mature forest ecosystems such as 400-year old douglas fir ecosystems. These systems, compared to less mature ones, showed the biggest decrease in temperature between the stands of trees and adjacent clear cuts (26 degrees), indicating that the energy coming from the dissipation of that temperature gradient was embodied in their ecosystem.

Furthermore, Odum (1969, 1999) and Schneider and Kay (1994a, b) assert that the dynamic development exhibited by ecological succession is mirrored in the evolution of the biosphere over the last 4 billion years. The change from simple ecosystems toward more complex ones that are populated by much higher developed organisms (culminating today in the dominance of Earth's systems by mammals, and in particular, *homo sapiens sapiens*) follows the same trajectory of increasing potential for energy degradation and resulting in a "full world" (Daly's description of human economic development) whose ecosystems approach a mature steady-state condition, and contain a high diversity of species which engage in complex relationships with one another.

There are two immediate consequences arising from this understanding.

The first concerns the fact that natural ecosystems are self-organising and always continue in the development towards a climax stage. A concept of care for natural systems that is built on the idea of ecosystem management might be more detrimental than beneficial: a tendency to conserve a certain ecosystem in its temporary state (Odum 1999 discusses the Everglades in Florida) would try to make it independent from rhythmic disturbances like seasonal changes. This kind of management would increase the ecosystem's brittleness and its susceptibility to catastrophic change. The idea of stability as immutability, rigid persistence in one condition, has to give way to "pulse" stability (Odum 1999), where a certain flexibility as the ability to change with the rhythm of minor disturbances prevents the ecosystem from succumbing to major disturbances.

The second consequence from the insight of energy dynamics in ecological succession concerns human systems: Natural ecosystems conform to the strategy of maximum protection by building up the most complex structures that are locally possible. This conflicts with the current strategy of human systems, maximum production (which can be likened to the pioneering stage of ecological succession). Theoretical ecologists maintain that the recognition and resolution of this conflict should lie at the heart of policy-making for sustainable development (cf. Odum 1969).

From a theoretical ecology point of view, a sustainable system can be understood as a system that can support a high amount of biomass indefinitely on a constant flowthrough of energy from continuous sources in a steady-state relationship. We can apply the adjective "sustainable" to such an ecosystem, as it has become self-sufficient through ecological succession, an ecosystem that can exist in perpetuity (in the absence of external disturbances). In a climax ecosystem, Schneider and Kay maintain, "material flow cycles will tend to be closed to ensure a continued supply of material for the energy-degrading processes" (Schneider and Kay 1994b, p. 635). This finding of theoretical ecology mirrors Daly's steady-state economy, as discussed in the previous chapter, and Graedel's "type III" system as the desired end state of a sustainable industrial ecological system, introduced in the first chapter.

Although human systems degrade energy in the same way[33] as natural systems, it would be a mistake to compare directly the workings of both. The crucial difference between modern human systems and natural systems lies in the fact that humans, because they have become the most successful energy degraders, have found other sources of energy, which are used (and degraded), today predominantly being energy derived from fossil fuels. By utilising in high rates these stores of solar energy that accumulated in earlier geological times (and exploiting resources in a very short time scale that were built up over a very long time span) rather than participating in the continuous and immediate flows of solar energy, humans effectively disconnected themselves from their natural environment[34]. Thus, their

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[33] They, however, do this to a much higher extent: human systems, firstly, are at the top of ecological food chains and secondly, are the only species utilising to overwhelming effects tools that do not belong to their bodies - "exosomatic instruments" (Georgescu-Roegen 1971) that enable them to degrade energy even more effectively. These "exosomatic instruments" have been changed and improved over a very small time scale, in the course of technological development rather than biological evolution. All other species make almost exclusive use of "endosomatic instruments" that an individual started life with as the tools for degrading energy. Examples for these instruments are the ability to capture energy, and the ability to use the captured energy for building up more complex structures that embody more energy.

[34] It could be argued that this disconnection happened already much earlier with the control and use of fire, enabling further inventions and discoveries by which humans came to shape their environment and expand their population numbers unchecked by other ecosystem variables. The predominant use of stores of energy instead of flows, though, constitutes a qualitative change that ultimately led to the notion of the independence of human development.

superior ability to degrade energy changed from being a boon for the surrounding environment to becoming a problem, as the climatic cycles of the Earth became overloaded with the waste products of human activity. Most importantly, it is carbon dioxide that was removed from the carbon cycle and is now returned to the carbon cycle at unnatural rates.

The process of energy degrading itself has not changed in all the time passed since these earlier geological times. The important fact in connecting the degrading of continuous energy in the case of natural ecosystems, and the use of non-renewable energy by human society is that the latter resulted from the former by evolution during the course of 4 billion years. Likening this process of evolution to the "boiled frog" syndrome[35], one can perceive it as change in very small increments into the same direction, that is, more effective degradation of energy, until the qualitative change towards predominantly depleting stocks of non-renewable resources took place. This qualitative change then changed the human ability to use energy from a support mechanism for stabilising natural ecosystems to a threat that disrupts the latters' stability (and ultimately, the stability of human systems and humans themselves).

Hence, the attempt of Industrial Ecology to equate food chains that are built on the use of solar energy with industrial relationships that are founded on the use of energy from fossil fuels (or other non-continuous sources) can be seen as flawed. Any statements derived from industrial ecological analysis that views industrial systems as ecosystems can only have value for environmental policy-making if these industrial systems degrade energy from continuous sources (and no material resources at all). Sources of renewable energy, such as biogas or rapeseed, fall in between the two categories of continuous energy and energy from fossil fuels: Renewables such as growing biomass, under proper management, do not have to face depletion of resources. They do, however, result in the emission of carbon

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[35] An experiment which involved testing a frog's reaction to environmental conditions slowly turning hostile: a frog was put into a pot of cold water that was then heated. The animal could not perceive the incremental change in temperature and remained in the water until killed by hot water. The frog, being thrown into a pot with hot water, however, would try to get out of it and save its life. The lesson for humans might be to find out whether *homo*

dioxide that must be managed by removing it from the biogeochemical cycles via carbon-fixing.

3.6. The speed of transformation and the cycle length for energy transformation – an analysis of "thermodynamic efficiency"

After having ascertained the energetic basis for the dynamic behaviour of complex systems, the last part of this chapter will look in particular at the energy implications for natural and human systems of two phenomena that are commonly found in complex systems: the first, changes in the speed of transforming matter and energy towards higher speed, the second, the creation of longer cycles of transformation with more system participants involved. Both these characteristics play a role in ecological succession and the development of food webs. These dynamics apply as well to industrial structures, not just because the similarities between the two are postulated by Industrial Ecology, but more importantly, because social systems have come to be understood to be sharing the same energy dynamics with natural systems.

In ecosystems developing towards a mature stage, dissipation of high-grade solar energy into low-grade heat is accomplished, among other factors, by the development of increasingly complex cycles of energy and biomass, the ecosystem's food chains or webs. These cycles increase in length (the number of participants). One can envisage the effectiveness of a food chain by considering one somewhat idealised example:

A chain might consist of grass that is eaten by grasshoppers that are in turn eaten by frogs. The latter are consumed by trout on which ultimately, humans feed. After Schneider and Kay, the purpose of the development of this food chain is to maximise transformation of biomass and associated dissipation of energy. The energy requirements of the individual steps of that food chain are the following: Let us assume that per year, 1 human needs 400 trout, which need 160,000 frogs, which eat 64,000,000 grasshoppers, which in turn feed on 2,500 tons of grass. The annual upkeep of one human thus results in the dissipation of the energy stored in

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sapiens sapiens is prone to the same reaction, and consequently should try to avoid a similar

2,500 tons of grass. If humans were merely feeding on grass, this amount would have been sufficient to sustain many more than just the one human that occupies the top of this pyramid-shaped food chain with 5 different participant species. Industrial Ecology, as it is concerned with imitating food chain relationships in economic structures, should take notice of what is dissipated by the food chains in natural systems: ecosystem structures degrade the energy embodied in biomass that in turn was built up by diverting from the global nutrient flows (elements like C, N, O, S, P). Food chains are therefore the embodiment of energy flows, and the individual participants of these chains subsumed into the overall flow of energy. The introduction of evermore complex and advanced organisms participating in more complex food chains in maturing ecosystems has, as was shown earlier, the purpose of increasing the entire system's capabilities of energy degradation.

The situation is very different in industrial structures: the latter dissipate not just energy, but predominantly minerals from the earth's crust with the help of fossil fuels that themselves result in dissipative wastes (CO_2 emissions). Furthermore, the individual participants cannot be regarded in their status as subservient to overall energy flows (in natural systems the *raison d'être* of the entire ecosystem). The creation of industrial structures that are resembling food chains only out of the fact that different system participants pass wastes and by-products (in very small amounts compared to the system's total output) on to each other can therefore be regarded as a rather superficial undertaking that in itself will not be of significant help towards aligning industrial structures with natural constraints.

Furthermore, the human economy has made itself independent to a significant extent from constraints imposed by the immediate environment. Thus, the cycle of succession in natural ecosystems, where a pioneering phase is followed by a climax phase that again leads to a new pioneering phase is broken in the case of the human system. Presently, the socio-economic system is engaged in a supposedly perpetual pioneering phase, pursuing an economic growth that is believed to be without limit.

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reaction to slowly and steadily worsening environmental conditions.

Rebane (1995) connects the survival of an individual participant of a complex system to the speed in changing entropy due to its life activity. Thus, he holds, the faster this actor (itself a complex dissipative system) uses low entropy resources and energy, the higher its chances for survival[36]. However, in the case of the human economic system in its entirety this leads to a faster decrease of non-renewable resources and a faster increase of waste. Thus, the faster a human system transforms resources, the more likely it is to grow and develop, that is in the short term, but in the long run the environment is destroyed and incapable of sustaining any life. Rebane maintains that throughput that has been maximised in the course of the evolution of life needs to be reduced, and the only way of slowing down this process is to emphasise modesty, modest consumption, altruism and responsibility. Reduction in throughput conserves energy that is predominantly derived from fossil fuels and enhances the economic system's compatibility with natural systems. The need for increasing throughput, however, has been the driving force behind the evolution of ecosystems and individual species up until the present day.

Dürr (1993), a physicist like Rebane, argues in the same vein when he maintains that every increase in value is coupled to a deterioration in value at a different point, if the economic system depends chiefly on the exploitation of non-renewable resources. The faster processes occur, he maintains, the more syntropy is wasted and the more entropy rises. In natural systems, though, processes take place much slower and thus ecosystems can sustain a very high amount of biomass on a given flow of energy. The now intricately linked structures of biological organisms and their communities, however, had the time of 4 billion years to evolve. Human systems, on the other hand, are dependent, as pointed out above, on the use of exosomatic instruments with which energy is captured and used, tools that were developed in a very small timescale, compared to biological evolution. Human systems then have also only a very short time to change in order to retain the Earth inhabitable for human beings. Dürr advocates a shift in economic activity towards

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[36] Connected to Schneider and Kay's thesis of energy degradation as the main purpose of life (Schneider and Kay 1994a, b), the struggle for survival of individual organisms as competition for available energy for maintaining ever higher degrees of ordered structure results in maximum energy degradation for the biosphere as a whole (the maximum entropy production principle of Swenson 1989).

slower transformation of resources and energy. This strategy, he maintains, is more efficient in the long run - a maximum speed in transformation is efficient in the short run. Sonntag (2000) connects the increasing competitive activities of business enterprise with ever increasing speed of transformation of resources into waste, for keeping ahead in the competitive game. She maintains that this process is diametrically opposed to sustainable economic activity, which she views as a slowing down and diminishing in scale of resource flows.

This relationship will be further discussed in chapter 5, as industrial ecological organisation is regarded in the broader context of international business activities.

This third chapter has served the purpose of laying the foundation for regarding natural and social systems in their energy-degrading character, a behaviour they both share. In this commonality is rooted the translation of natural systems characteristics into social systems. It is in the following chapter that rules for this translation are recognised.

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Chapter 4

The use of metaphor in Industrial Ecology

Hypothesis: the image transfer at the heart of Industrial Ecology, comparing economic structures with structures in natural ecosystems, constitutes an application of metaphor. Metaphors are becoming recognised as dominating not only language, but also thought processes. The field of Industrial Ecology thus will benefit much from work that recognises this metaphor and employs it properly and productively. Concepts and rules governing metaphor use in the sciences need to be applied to Industrial Ecology's founding image to reveal a consistent or otherwise build of theory and applications.

1. Chapter introduction

Industrial Ecology has at its heart a translation of understanding from the realm of the natural to the domain of the human-made. This translation is often expressed in notions of the "natural ecosystems analogy", "industrial symbiosis" or "industrial metabolism", all of which are images, metaphors, which are used by researchers and practitioners of Industrial Ecology to describe natural systems and their composition and behaviour, and by understanding these, apply them to human-made systems, especially the economic system of industrial production and consumption.[37] The aim is commendable: Industrial Ecology strives to help creating a human system that is ecologically sustainable. Such a system can be perceived as not being in conflict with the surrounding natural system anymore, a conflict that can only be lost by the majority of the human system's participants. The idea of

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[37] In the course of the first chapter, agreeing with Graedel (1994), the system of reference of Industrial Ecology was taken to be the entire human economy consisting of industrial producers, and consumers such as private households.

Industrial Ecology is to fashion a human economy after the behaviour of natural systems, and thus to achieve this compatibility with the larger system.

An aim, however, can only be as sound as the means for achieving it and the basic assumptions and values that underlie not only those means, but also the aims. Thus it is felt to be expedient for this chapter to turn to the image that holds Industrial Ecology together, and to examine it as to its appropriate use in the effort of translation.

This translation, though, still comprises only the upper layer of the scientific basis to Industrial Ecology. As was discussed in the previous chapter, the real justification for applying insights from natural ecosystem dynamics to economic systems is grounded on the commonality of dissipating energy[38]. This latter characteristic is the mainspring for all complex system behaviour. Once the basis for seeing economic systems in the light of natural systems is established, the translation mechanism, the metaphor, comes under scrutiny. That evaluation effort, completing the scientific basis to Industrial Ecology, is the purpose of this present chapter.

Industrial Ecology is the prime example for a scientific discipline that abounds with natural images - not the only example, as Mirowski (1994) has shown that economics has borrowed, and is still doing so, from biology for developing its own concepts. Industrial Ecology, however, seems the only discipline with that kind of operation at the heart of its endeavour; this can already be concluded from the name of the discipline that combines the realm of the human-made with the natural: *Industrial* Ecology and Industrial *Ecology*.

The usefulness of Industrial Ecology as a scientific discipline, thus, depends on the appropriate use of its central image, the comparison of human-made systems with natural systems. This chapter is devoted to exploring and evaluating this central tenet of the discipline, and while doing so, to deriving rules as well for the use of translations from the natural to the human-made realm in Industrial Ecology. These rules can subsequently be used to inform, support and evaluate current and future applications of Industrial Ecology.

The chapter commences with an exposition of that central tenet in current theory and practice of Industrial Ecology, discussing and evaluating research work in Industrial Ecology that explores that natural imagery. Establishing that there is a need for further, more profound work, and pointing out the danger of an Industrial Ecology without a clear understanding of its central position, the discussion will then be concerned with showing how human mental constructs govern insights in the sciences of ecology and economics. Both these fields, but not only these, are found to be highly metaphorical in their concepts. The problem of recognising and applying metaphor, therefore, is the theme of the ensuing part of this chapter; finally, these insights and rules need to inform Industrial Ecology in its theory and applications.

2. A metaphor as the founding idea of Industrial Ecology

As discussed in the first chapter, research and applications in Industrial Ecology are based on the idea that understanding of the structure and behaviour of natural ecosystems can be employed in the development of a sustainable economic system in general, and industrial structures in particular. This proposition exerts some degree of fascination on researchers and practitioners in Industrial Ecology: Industrial Ecology's energy and motivation lies in "implementing Nature's lesson" (Schwarz and Steininger 1997). The translation from the natural to the economic realm is found in the discipline's name, and more importantly, in its applications, foremost the research into industrial ecosystems. Wernick and Ausubel (1997) already came to call Industrial Ecology's central idea a metaphor, whereas Vellinga et al. (1998) see the central idea rooted in "intuition and beliefs" that nevertheless find their way into derivate principles and research tools.

Some first steps are being taken to understand this founding idea better, and more research has been called for (e.g., by Wernick and Ausubel 1997). This call, however, has not been heeded widely: there is only isolated work putting out some tentative

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[38] The author acknowledges gratefully Mr Ralf Isenmann's comment on the separate nature of the contexts of description and justification.

feelers for the issue, examples of which can be found in Allenby and Cooper (1994), and Côté (2000).

It is not too much to say that, by promoting the image of industrial systems in the fashion of natural ecosystems, Industrial Ecology has bound itself to the natural/human system translation - thus, the discipline can only engage in successful work if the translation at its heart has been made clear and is put to good use. Currently, however, there seems to be a feeling among researchers and authors in the field of Industrial Ecology that the "underlying theory is only emerging" (Korhonen 2000) and that for the moment, work is considered only "loosely based on the natural ecosystem idea" (Manahan 1999, quoted in Isenmann, in press). Hence, there is a tension between the clearly inspiring vision of Industrial Ecology and its use in applications. At present, examples for the use of natural ecosystem images include the "natural ecosystem analogy", "industrial symbiosis", and "industrial metabolism" mentioned above, but also the idea of industrial scavengers seen to fulfil recycling functions (Côté 2000), and the concept of ecological succession (Allenby and Cooper 1994). Finally, Graedel's "type III" system should not be omitted: his is the most comprehensive image for a restructured human economy that was borrowed from the realm of the natural sciences.

In the following, three articles from the domain of industrial ecological research are examined, for evaluation of their use of natural imagery in Industrial Ecology, particularly the founding idea of comparing natural systems with industrial or economic ones. Whereas Allenby and Cooper (1994) employ the natural ecosystem analogy in order to concentrate on system characteristics underlying natural ecosystem behaviour, especially dynamic state changes, Côté (2000), and Schwarz and Steininger (1997) take the same image for focusing on the roles of different system participants both in natural and in human-made systems.

In their article, Allenby and Cooper (1994) champion a "biological systems perspective" for clarifying the aims and means of Industrial Ecology. The authors find resemblances between the current economic system and a rapidly developing biological community on the one hand, and their proposed sustainable economic activity and a mature biological community on the other hand. Allenby and Cooper advocate a restatement of the "industrial ecology analogy" towards describing a mature biological system. They speculate whether a tightly integrated, connected system of industrial activity, such as the Japanese economy, might be more sustainable. "Similarly" (the term the authors use for introducing a metaphor), the "biological analogy" is further used to legitimate any economic system's strong reliance on market forces, and to discredit the economic system in former Eastern Europe and the ex-Soviet Union, with the argument that centrally planned economies are not the right way for achieving a sustainable human economy, as there is no central authority in natural ecosystems, either. Market economies are seen as self-organised systems much in the same way as natural ecosystems, and moving away from "efficient" market economies would make the transition to a sustainable economy more difficult.

Allenby and Cooper draw upon the natural ecosystem analogy in order to justify their speculations: some isolated, and thus not necessarily representative, characteristics of natural ecosystems are employed supposedly to support economic policy-making in the manner of Industrial Ecology. In their conclusion, the authors have the good grace to admit that their work is "necessarily speculative". They exhort the research community to explore the relationship between natural and human-made systems further.

Côté's note (Côté 2000) can be seen as one of the attempts to shed some more light on the analogy itself: he suggests that eco-industrial parks lack recycling businesses. Resorting to the triangle of producers-consumers-recyclers in natural systems, he assigns the roles of biological producers and consumers to enterprises, and finds the role of recyclers largely vacant. An example for Côté's producers is the coal-fired power plant in the Kalundborg industrial park; all other enterprises are seen as "primary or secondary" consumers. Schwarz and Steininger (1997), proceeding with more caution, assign the same roles of producers and consumers to industrial actors, putting forward their thesis that industrial activity relies too much on "production", whereas "composition and decomposition" in natural ecosystems are seen to be balanced. Here, industrial "production" is likened to "production" in natural systems, that is, photosynthesis by plants. Schwarz and Steininger, and Côté thus compare participants of food chains in natural systems directly with economic actors. Although there can be some similarities, depending on the perspective taken, there are also some important differences: First, industrial producers and those in natural ecosystems cannot be equated: although they share the same description (the term "producers"), the manner of "production" is very different in both systems. Production in the biological sense relates to the mobilisation of mineral resources and gases, with the employment of solar radiation as energy source. This photosynthetic activity produces plant biomass from inorganic matter. The plants are at the base of the food web, as their biomass is transferred via primary consumers and secondary ones, until it reaches an organism at the end of the food chain, where, after the death of that organism, the biomass is decomposed back into minerals by recyclers (such as bacteria). Production in economic systems refers to the mobilisation chiefly of non-renewable resources and energy, both of these are combined into products that are utilised by other industrial producers and e.g., household consumers. The economic actors affect each other in a very different way than natural ecosystem participants: the former do not eat each other and thus, do not incorporate each other's biomass. Following from that, the relationship between economic actors themselves cannot be made clearer by resorting to the natural ecosystem analogy. In terms of resource use, in the human economy there are no producers as understood in the natural ecosystem: enterprises rely on and exploit a finite stock of resources, which they transform into waste.

From the above examples, which can be taken as representative for industrial ecological thinking, it has to be concluded that the overarching idea of Industrial Ecology cannot be regarded as thought through properly in its research and applications. It is probably for this reason that the comparison between natural and human-made systems is not taken very seriously by a number of industrial ecologists themselves[39]. Industrial Ecology's founding concept serves for little more than a rallying point, a romantic idea uniting some engineering efforts. If the aim of the human economy to be made compatible with the surrounding natural system (and consequently, the acceptance of the "type III" system condition) is to be taken as a strategy for attaining sustainable development, this fundamental idea deserves much closer attention for understanding and using it in Industrial Ecology's applications. The "circular waste flows" that are diagnosed in nascent industrial

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[39] Frank Boons, personal communication June 2000.

ecosystems were already revealed to being nothing more than a cascading of resources from high to low quality. They should be considered correctly as a linear flow of resources with improved efficiency, emanating from a source of virgin resources and ending in a waste stream that leaves the industrial ecosystem (cf. chapter 1, and also the more in-depth analysis in chapter 6). These flows thus are not deserving of the attribute "circular". Further, as was mentioned in the chapter introduction, industrial ecologists do not seem to agree on (or are unsure about) the system under observation, whether it is the entire human economy or the system of industrial producers only (cf. also chapter 1). This confusion needs to be resolved as well, if Industrial Ecology aims to have a consistent and coherent scientific basis. These examples are all indications for the central tenet of Industrial Ecology, the translation from natural to human systems, not being employed to a great extent or with sufficient assiduity. Following from Welford (1997), endeavours in science and public and business policy-making towards sustainable development need to be carefully examined whether they actually contribute towards that aim. Misdirected applications can very easily result in the aim of sustainable development lost from sight and subsequently, becoming jeopardised.

It will be argued in this chapter that the problem at the heart of Industrial Ecology lies with recognising, accepting and working properly with a conceptual transfer that constitutes the field as a metaphor.

The following section discusses the role of metaphor in the sciences of economics and ecology, resulting in the insight that in both these disciplines metaphors play a very important part, and that this role currently is beginning to be recognised.

3. Use of metaphors in the scientific discourse of ecology and economics

Scientists have traditionally regarded metaphor use as anathema to the validity of their discourse, as metaphors were seen as belonging to the realm of poets rather than scientists: the ambiguity conjured up by metaphors would contribute to the richness of language and meaning in poetry, but was assumed to lead to confusion in the sciences that strove for rigor and precision in their language (cf. Klamer and Leonard 1994). This perception sprang from the view of metaphor as being a "figure of speech" (Moore 1982), an orator's tool for manipulating his or her audience. Metaphor having a rhetoric (and also a poetic) function traces back to Aristotle, whose definition of metaphor in his *Poetics* is the oldest and best established:

> "Metaphor consists in giving the thing a name that belongs to something else; the transference being either from genus to species, or from species to genus, or from species to species, or on grounds of analogy." (*Poetics* 1457 b 6-9, quoted in Ricoeur 1978)

Ricoeur (1978) argues that both this definition of metaphor and Aristotle's subsequent list of "facts of speech" revolve around the *noun*, which can be manipulated by metaphor use. This leads to the established position of metaphor:

> "Thus the destiny of metaphor is sealed of centuries to come: henceforth it is connected to poetry and rhetoric, not at the level of discourse, but at the level of a segment of discourse." (Ricoeur 1978, p. 14)

Since McCloskey introduced literary criticism to economics (McCloskey 1983, quoted in Klamer and Leonard 1994), scientific discourse and creation of scientific theory has been subjected to linguistic scrutiny. Although the original reaction (e.g., the "so what?" by the economist Robert Solow, cf. Klamer and Leonard 1994) consisted of little more than bemusement, in the intervening years the proof of the existence of metaphor in their communication has caused scientists to start their own inquiries: "how do metaphors work?" and "why are they necessary?" have now become important questions prompting either highly complex or uncertain answers in theory-building (Martin and Harré 1982). The reason for this shift in attitude came as metaphors were found not just in language that is deliberately chosen for its effects (what Cameron, 1999, calls the linguistic perspective of metaphor), but rather, that metaphor use has to be seen as inherent in underlying thought processes (Cameron's cognitive perspective). Owing to much work devoted to the subject of metaphor appearing in the last two decades, but starting with a single collection of lectures, Richards' *The Philosophy of Rhetoric* (published originally in 1936), this latter position has now come to be seen as uncontroversial (Cameron 1999), and complements the linguistic perspective, rather than superseding it.

Klamer and Leonard (1994) contend that the position of metaphor in the sciences is both a pervasive and an ambiguous one, enabling both critics and supporters to evaluate examples for and against its importance, within their respective viewpoints.

Klamer and Leonard divide the plethora of metaphors in scientific discourse into three basic categories with different function: pedagogical, heuristic and constitutive metaphors. These are a better attempt at understanding metaphors than the linguistic-cognitive debate, as the three categories of metaphors put forward by Klamer and Leonard straddle that divide.

The existence of pedagogical metaphors points towards a non-essential use of metaphors as embellishments, tools of language. These are used as mental images "with which the audience can visualize an otherwise complicated concept" (Klamer and Leonard 1994, p. 31). As an example, the "circular flow diagram" is presented as an attempt at showing connectedness in economic processes. Pedagogical metaphor is applied to enable an audience to "see something that already exists and is well understood if not easily grasped" (Klamer and Leonard 1994, p. 32).

This last point is crucial for distinguishing this class of metaphors from the next two, heuristic and constitutive metaphors: where pedagogical metaphors clarify a concept that can also be understood without the metaphor, heuristic and constitutive metaphors only make possible basic understanding in the first place.

Klamer and Leonard call heuristic, "thought-propelling", metaphors those that help "to approach a phenomenon in a novel way" (p. 32). In the example of the metaphor of "human capital", the authors show that using this concept results in the beginning of a scientific inquiry, not just the communication of the concept once it is understood as pedagogical metaphors do. The metaphor of the "market" for aggregate economic activity, falling into the same class of heuristic metaphor, can be seen as one of the most important images economics relies on.

Constitutive metaphors, the third and most fundamental class of metaphors in Klamer and Leonard's typology, provide the source to heuristic metaphors. This last class of metaphors permeates strongly any thought process it is argued, so that it is very difficult to give specific examples. As an example, the authors ask for the reasons of the economist Samuelson to choose the heuristic metaphor of optimisation over others, such as "satisficing or chaos" (Klamer and Leonard 1994,

p. 40). In these authors' opinion, the foundation of 19th century economics on physics at that time represents an employment of a constitutive metaphor.

Summarising, a continuum can be observed ranging from pedagogical metaphors that belong to the realm of Cameron's (1999) linguistic processes, to constitutive metaphors that firmly belong to the realm of cognitive processes. The pedagogical metaphors are the poetic embellishments, the figures of speech that can be left out; scientific discourse would not be the poorer. However, the existence of constitutive metaphor shows that language is inherently metaphorical when it strays from the observance of simple physical facts. The assumption of the difference in language between the literal and the figurative, Lakoff (1993) argues, is thus not tenable.

Following the categorisation of Klamer and Leonard, the concept of the ecosystem can be found to be a heuristic metaphor: the term was coined by Arthur Tansley in 1935 (cf. Worster 1985), replacing the term "community", which was then felt to be too anthropocentric to describe relationships within the biosphere adequately. Trudgill (2001) holds that the term "ecosystem" is a mental construct, employed by human beings for understanding, and thus it is not verifiable by observation in nature itself. "Ecosystem" is a metaphor as it denotes a concise object (a system) in the biosphere (or rather, when incorporating the earth's climate-surface-water system, the biogeosphere), which is a system generally without boundaries, only gradients of difference in spatial extension. It is impossible to show where an ecosystem has its precise boundary with others; that judgement depends on the criteria that observers employ to separate in their minds systems that are intricately connected.

Industrial ecologists should become aware that the concept of the "ecosystem" that plays such a central role in the discipline should be well understood: not only is it in itself a metaphor, a mental construct, an abstraction to understand a complex phenomenon in a more or less adequate manner, what is more, this concept is applied to describe a different type of system. What needs to be made clear is the double translation, and therefore, double imprecision and vagueness, that underlies Industrial Ecology's central tenet.

The last paragraph anticipated already the following argument, that metaphors are not only constituted and used within one field of science, but that metaphors have been and still are the vehicles of cross-fertilisation and influence between different fields of science. These metaphors, due to their vagueness or "elasticity" of meaning enabling easy application, have lent themselves to importing ideas from other fields of science to fertilise scientific endeavour.

In the following, the aim is to show how two fields of science, biology/ecology and economics, proven to be highly metaphorical in their respective theories, facilitated by their metaphorical nature in the first place, came to take over concepts from their neighbour's theoretic foundations. This was done by applying each other's concepts in the manner of metaphors. Taking the example of the concept of competition, this section discusses how biology/ecology, constituting itself in the 18th and 19th centuries, was influenced by economic thought that underwent a constitutive period during the same time. This influence between these two fields of science was mutual, as economists as well have looked to biological and organic metaphors for enriching economic theory. As a consequence, Mirowski (1994) argues, the two realms of science, the "natural" and the "social" have come to be regarded as inherently unstable and insecure in their theory-building, and the transfer of metaphor between them a result of, not a cause for this instability.

The most important of the metaphors common to the disciplines of economics and ecology is arguably the idea of "oikos", the Greek term for the (human) household, lending itself to the descriptors of the disciplines of both economics and ecology. Thus, at least in the perception of the founding figures of the two sciences, a commonality in the respective subjects and the devising of applications shared between these two fields was envisaged. Both disciplines received their descriptive titles in the 18th and 19th centuries, economics first as the "political economy" of J. S. Mill's writings, for example. The term "ecology" was coined in 1866 by the natural scientist Ernst Haeckel.

The metaphor that has first crossed the boundary between economics and ecology can be taken to be the term "nature's economy", describing the intricate links between organisms in grazing and detritus chains. The expression was first recorded in 1658 (cf. Worster 1985), but traced with certainty to scientific writings of the 18th century. The concept was already in the public domain when the naturalist Gilbert White published his treatise *The Natural History of Selborne* in 1789 (cf. Worster 1985). He saw the connections between organisms in nature as the proof for an organising principle of efficiency in the natural world. The period of the end of the 18th century for the metaphor of the "economy of nature" appearing in scientific writings is significant: both the fields of political economy and biology/ecology emerged as scientific disciplines and became more prominent in the scientific domain at this time of Enlightenment, with Adam Smith's *Wealth of Nations* published in 1776, Malthus' *Essay on Population* in 1798, and naturalists like White and Carl von Linné (who also published an essay *The Oeconomy of Nature* in 1749, cf. Worster 1985), all against the backdrop of the rapid industrialisation of Britain. As scientific and public discourse were not as fragmented as they are today, firstly from each other and also, within each domain, the two sciences *in statu nascendi* of economics and ecology had significant contact with each other (Young 1985 argues that Malthus was regarded equally a political economist and a biologist). Due to the proliferation of scientific knowledge since then and subsequent specialisation of scientists into much narrower fields of enquiry, this contact is now much diminished, as individual disciplines can now shield themselves from others, whether intentionally or not, by erecting a barrier of specialist language and highly specialised concepts.

The concept of competition has fared in a similar way as the term "ecosystem", both crossing between different sciences. As far as insights into the historiography of the sciences reach today, the concept of "competition" emerged first in the writings of political economists on observances of human economic behaviour in the 18th century (with Hobbes' "war of all against all" in his *Leviathan* as only one of several precursors). Young (1985) shows convincingly how Darwin, in his perception that gave rise to the *Origin of Species*, was influenced by economic thought, especially Malthus' writings (cf. Mirowski 1994, p. 15).

This link is mostly overlooked today: economic thought seeks confirmation from biology/ecology to argue that competitive behaviour is inherent in living systems. The latter perspective dominates, and as such is seen as constituting a one-way transfer of concepts, from the natural sciences to economics. As Mirowski (1989, 1994) shows, this transfer first came about in the 18th and 19th centuries, when theory-building in economics (or rather, political economy) relied on Newtonian physics for guiding principles, such as "equilibrium" (a heuristic metaphor as well). With the establishment of the Darwinian theory of natural selection as a dogma, however, competition that was "observed" in the natural world became a bedrock of current economic theory: the concept switched domains another time. These adoptions took place without the awareness of a circular argument. There does not seem to be an academic perception existing at that time for this potentially serious hindrance to scientific enquiry. For each boundary crossing of, for instance, "competition", the concept was assumed to be accepted and observed in the field of science it was imported from.

For the latter concept, the crucial point for theory-building was that an adoption in either ecology or economics from the neighbouring science meant that the metaphor of competition was taken as the only or the predominant constituting idea. Thus, in the 20th century ecological and economic theories could evolve around "competitive exclusion" in biology/ecology and "perfect competition" as the ideal in economic theory. Owing to research in ecological modelling in the last decade without this preconception, a different picture of the role of competition in ecosystems is emerging: in natural ecosystems, today, competition is seen as neither the only one, nor the most important factor constituting behaviour of ecosystem and their participants. Ekschmitt and Breckling (1994) draw a picture of ecosystem activity where competition is only one of a multitude of factors.

4. Putting the "natural ecosystem analogy" to work: a system of mapping across different systems and its application in Industrial Ecology

In the previous section, the position was considered that metaphor and its use were commonplace in many sciences. Furthermore, the language-thought duality of metaphor was dissolved into Lakoff's (1993) system of pedagogical, heuristic and constitutive metaphors, finding a place for both poles, but basing the system on constitutive metaphors that are inherent in human thought processes. Therefore, the cognitive perspective was established as the fundamental one, and the linguistic perspective not as the cognitive perspective's opposite pole, but contained in it.

Does the insight, though, that metaphors belong to the innermost circle of intellectual tools not only for communication, but even for understanding of abstract concepts mean that it is impossible to devise a set of rules for metaphor use, since those would also be nothing but metaphors?
Martin and Harré (1982) distinguish in their discussion of the role of metaphor in science between metaphors and (analogical) models, choosing for the former the narrow understanding of metaphor as a figure of speech. However, as metaphor comes to be understood as a far more fundamental concept of thought processing, the distinction between metaphors as figures of speech and models collapses: the former are found to be nested in the latter, as metaphors within metaphors. This is important for the creation of rules for rendering metaphor use a valuable tool in scientific endeavour.

Metaphor research is not a straightforward endeavour: Gibbs (1999) maintains that scholars tend to feel intimidated to immerse themselves in metaphor research, owing to the considerable number of different theories of metaphor, probably owing to different perceptions of the role of metaphor in language or in thought. In the field of cognitive psychology alone, where most research on metaphor is concentrated, Gibbs (1999) lists salience-imbalance theory, domains-interaction theory, structure-mapping theory, class-inclusion theory, and the conceptual metaphor theory of Lakoff (1993) that was already discussed earlier[40].

From Aristotle's quote from the *Poetics* above we can conclude that reasoning by analogy is regarded as one of the several uses of metaphor; indeed, Lakoff (1993) defines metaphor as describing a "cross-domain mapping in the conceptual system", the very function that reasoning by analogy is employed for. Lakoff calls the "surface realization" of this cross-domain mapping "metaphorical expression"

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[40] cf. also Eggs (2000), and Lyon (2000) for an overview of the various approaches to understanding metaphor. Goatly (1996) already discusses the influence of ecological thought on theories of metaphor.

(what is commonly called *the metaphor* itself). In Lakoff's understanding of metaphor, the mapping of one domain onto another - the "source" onto the "target" - is carried out within a conceptual system that Lakoff calls "huge, highly structured, fixed" (Lakoff 1993). His work enables metaphor to be seen closer to its sibling, analogy. Analogical reasoning has been recognised and accepted in the sciences, whereas metaphor has been traditionally seen as belonging to the realm of poetry (cf. Martin and Harré 1982).

For the purpose of this work, clarifying the role and use of metaphor in the scientific endeavour of Industrial Ecology, the structure-mapping approach championed by Gentner (Gentner 1982, 1989, Gentner and Jeziorski 1993) that is resonant with Lakoff's domain-mapping, was chosen as the basis for analysing the transfer of images in Industrial Ecology. The image at the heart of Industrial Ecology, expressed, for example, as the "natural ecosystem analogy", constitutes a conscious application of a heuristic metaphor. It belongs to Lakoff's (1993) classification of a heuristic metaphor, as there is no other expression to characterise the intricately linked structures of the aspired sustainable socio-economic system (and any possible alternatives to it would have to be characterised by a metaphor as well). Heuristic metaphors, furthermore, are employed with the intention to understand a concept. Therefore, it has to be deduced that, for being a useful tool for understanding, the image transfer of Industrial Ecology needs to be made clear and its quality evaluated.

Gentner's approach for understanding and utilising metaphor, in terms of a conceptual structure that is mapped from one context onto another, has the advantage of providing a coherent framework that incorporates both metaphor and analogy, thus diminishing the distinction between the two that Martin and Harré (1982) were still wont to observe. Gentner has carried out work on the use of analogies in science, with the intention of showing that the analogies used in scientific discourse are really metaphors, in the same way that Aristotle perceived analogies as part of the wider family of metaphors. A framework bringing analogies and metaphors closer to each other is appropriate for Industrial Ecology, since the field is divided in its perception of the idea at its centre: should the ecosystem metaphor be regarded as a mere romantic *stimulans* or rather as the nucleus of a coherent theory? Gentner's structure-mapping approach for analogies-as-metaphors enables Industrial Ecology and its practitioners to do both.

Gentner and Jeziorski (1993) maintain that a modern view of metaphor emerged in the 17th century with the writings of the chemist and philosopher of nature Robert Boyle, breaking away from the earlier pre- or proto-scientific tradition of alchemy. Alchemists were using metaphors profusely, however, without a coherent system that enabled their domain mappings to become ana-"logical" reasoning. Rejecting the unbridled use of metaphor by alchemists, the scientists spearheading the modern way of handling metaphor introduced a system that both enables and structures metaphor use in scientific reasoning.

The most profound difference between the alchemists' and the modern tradition in theory-building lies in the recognition that it is relationships that are transferred in scientific analogical reasoning, not merely object attributes. Gentner (1982) defines relationships in analogical reasoning as predicates with at least two arguments ("A relates to B"), whereas object attributes are predicates with only one ("A is red"). Relationships thus allow the construction of systems whose objects are connected to one another. Alchemists' transfers of images, on the other hand, infer relationships from object attributes, or object attributes in the target system from object attributes in the base system. Their use of metaphors and analogies was by any account rich, but unstructured.

We can see Galilei's assertion, "the book of the universe is written in the language of mathematics, and its characters are triangles, circles and other geometrical figures" (Galilei 1960, p. 184), in this tradition of strengthening the logical framework for scientific inquiry: Written at the beginning of the 17th century with the intention of suppressing characteristics of the "second order" of objects (colours, sounds, smells, forms, all non-measurable aspects), Galilei's statement constituted a response to and departure from the alchemist way of employing metaphor. This was achieved by concentrating more on the exploration and understanding of the relationships (chiefly in the mechanical domain at the time) of objects in a system at the expense of object attributes.[41]

In the following analysis, undertaken as a structure-mapping exercise, the relationships and attributes of the image transfer in Industrial Ecology come under scrutiny. The analysis adopts Gentner's method (Gentner 1982) for carrying out structure-mapping for allowing analogical reasoning and evaluating that analogy. This method comprises a mapping of the relationships of a base system onto relationships of a target system. The first step thus consists of specifying the base system:

Base system:
Entire global biogeosphere
- consists of organic participants, linear energy flows, gas cycles,
- exhibits dynamic changes (ecological succession) towards a steady-state.

In some industrial ecological work (e.g., Graedel's "type III" system, cf. Graedel 1994), this natural system is mapped across the system onto the entire industrial system, and the cycle of solar energy/biomass (cf. Figure 4.1) onto the resources flow, pictured in a cyclical form as an ideal (cf. Figure 4.2). Other authors can be found to map the natural system onto a subsystem of the economy, the industrial producers (cf. chapter 1).

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[41] His statement, separated from its immediate temporal context, however, has been supporting a science that grew to be based on measurable (positivist) characteristics only, leading 300 years later to a physics-dominated "hard" stance that hampers today's scientific endeavours to develop a systems understanding (cf. chapter 3).

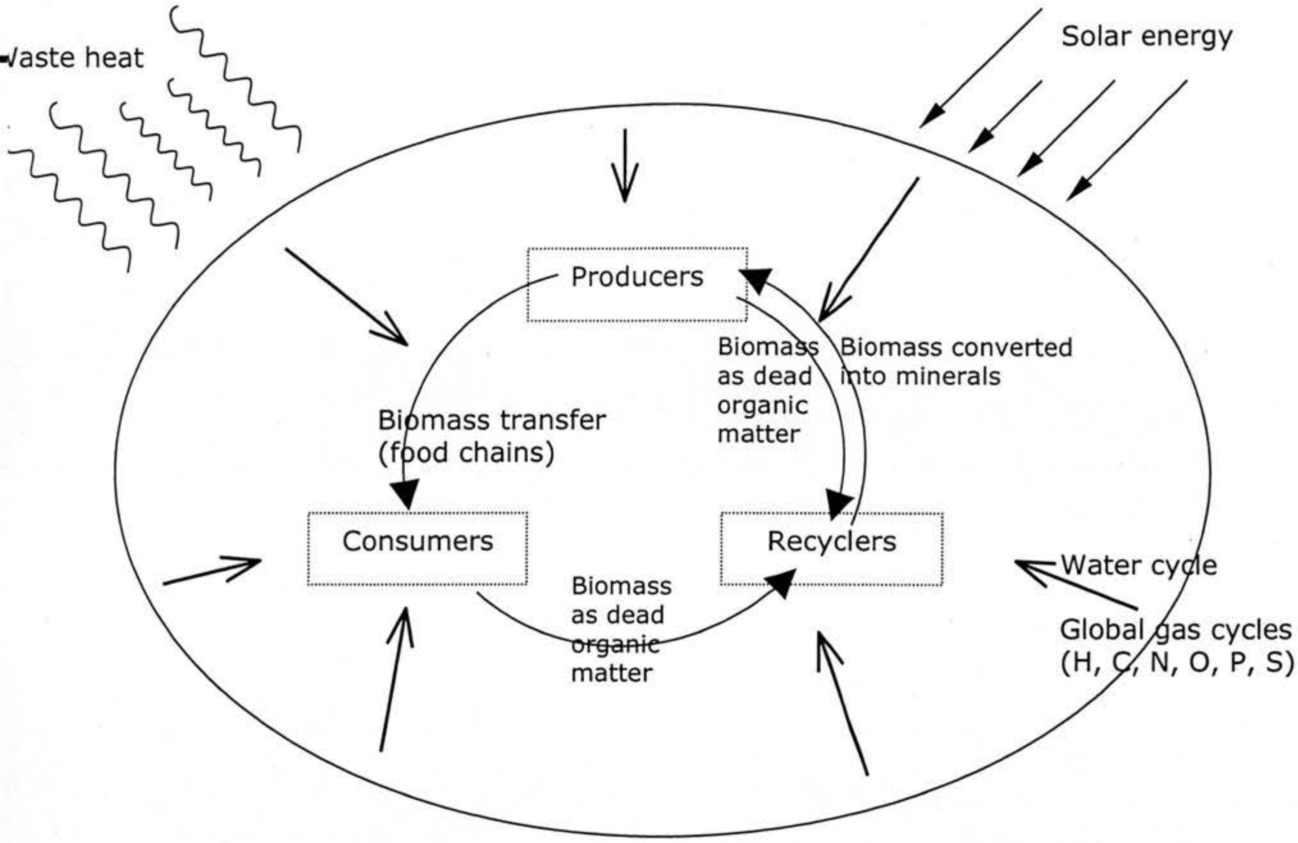

Figure 4.1: The solar energy/biomass cycle of the biogeosphere (base system)

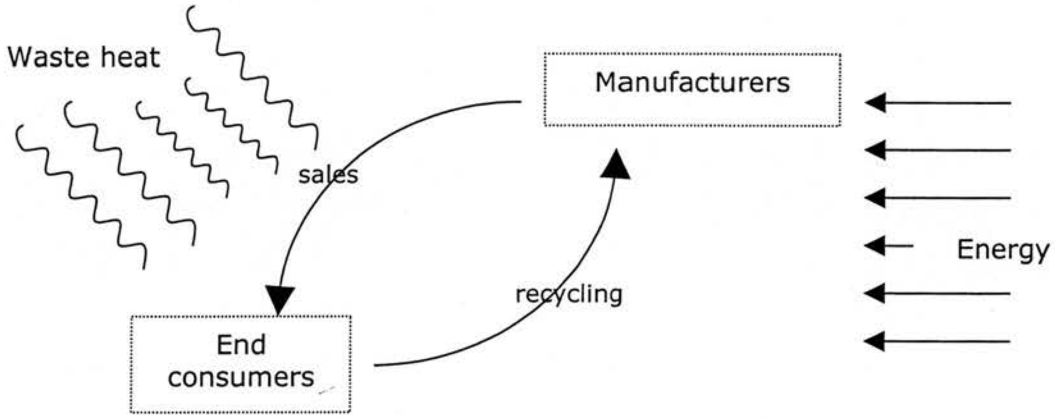

Figure 4.2: The resources cycle of the economy/industrial ecosystem (target system)

Gentner (1982) defines the use of a scientific analogy as consistent mapping of one system onto another: if the whole solar energy/biomass system with its circular flows is mapped ("learning from nature"), the target system must be larger than just a subsystem of the economy. The latter subsystem would have a system boundary across which resource flows would pass (of natural resources to industrial manufacturers, and of finished products from industrial manufacturers to end consumers). These flows, passing into and out of the target system, would be a linear and not a circular characteristic.

Target system:
Entire economy/industrial ecosystem
- consists of economic actors, cyclical resources flows, linear energy flows.

The problem lies in understanding which nodes exactly are being mapped when the natural system is used as base system: traditionally in Industrial Ecology, the focus was on the organic system participants of the natural system (parts A). The parts of the biogeosphere have the following characteristics:

Parts of the base system:
A. Organic participants of the global biogeosphere (plants, animals, bacteria etc.)
- consist of biomass, consist of embodied solar energy,
- dispose of endosomatic instruments,
- participate in global gas cycles,
- producers create biomass from gases and solar energy,
- consumers eat other consumers and producers,
- recyclers transform dead organic matter into minerals for producers.

B. Energy flows
- give rise to ecosystem participants (dissipators of solar energy that consist of biomass),
- are embodied in participants,
- occur as linear flows from solar energy to radiation into space of waste heat.

C. Atmospheric gas cycles transporting basic chemical building blocks (H, N, C, O, P, S)
- are driven by climate (water cycle powered by solar radiation).

In industrial ecological research and applications, these parts are being mapped as nodes onto participants of the economic system. Depending on the target system selected for this mapping - either the entire economy or just the industrial production subsystem - the target nodes comprise either the entirety of the participants in the economy, producers and consumers, or the industrial producers only. In either target system, the analogical relationships of the base system are disregarded: biomass and embodied solar energy are *transmitted* through grazing or detritus chains in the base system, the natural system. The organic participants are thus the *embodiments* of the biomass/energy flows (parts B). This is not the case for the largest part of the target system[42]: resources and energy are *passed on* by

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[42] To a small extent (compared to the scale of mineral resources processing), economic actors do embody biomass and solar energy, as they are also part of the base system, as consumers within the global biosphere, where they occupy the top of several food chains.

participants of the resource-centred economic system, as the participants do not embody them. The above relationship is manifest in the crucial difference between the endosomatic instruments of natural ecosystem participants and the exosomatic instruments of economic actors. In the solar energy/biomass cycle of the natural ecosystem, the participants, including their endosomatic instruments as part of their bodies, comprise the cycle flows themselves; in the resources/energy cycle of the industrial system, the participants handle and channel the cycle flows.

Thermodynamic analysis of ecosystem behaviour, as discussed in chapter 3, has brought to light the fundamental function of life in the context of the system "earth's surface-atmosphere": life provides for faster and more effective degradation of the incoming solar energy by dissipating gradients of temperature and pressure than non-living systems do (e.g., the system rocks-clouds-water). Organisms are thus a manifestation of underlying energy flows, and it is those energy flows that then have to constitute the nodes of the base system. The energy flows are the nodes that are mapped across to the target system, not the organic system participants themselves.

Socolow's (1994) postulate of the "centrality of the firm and the farm" thus has no ecological equivalent in the base system. The firm and farm, in the form of the individual human participants owning and running them, are not only embodiments of the solar energy/biomass cycle, but they are also, as humans' exosomatic instruments, embodiments of the natural resources flows.

In both realms, the flows are the underlying forces, the firm and farm (and the associated human beings) only their manifestation and surface. It is the resources flows which must be manipulated into cyclical form and possibly constrained in order to attain ecological sustainability, the existence of the firm and farm is secondary to that.

Parts of the target system (entire economy/industrial ecosystem):
A. Human participants
- consist of biomass, consist of embodied solar energy,
- eat other organisms,
- possess manufactured objects, financial capital,
- dispose of exosomatic instruments linked to resource flows,
- are only embodiments of the solar energy/biomass cycle, not of the resources cycle (exosomatic instruments are embodied resources).

B. Energy flows
- linear (emit waste heat), underlie any transformation,
- circular flows of mineral resources and gases that are associated to energy flows.

C. Resource flows
- circular and internal to human system: no resources mined, no wastes produced.

Energy and biomass flows from the base system can be mapped onto the target system: the circular biomass flows are mapped onto the circular resource flows; the linear solar energy flows are mapped onto the linear energy flows of the target system. In the case of energy sources other than continuous ones, the associated resource inputs and wastes are contributing to the parts C, resource flows that have to be in circular fashion.

Throughout the mapping carried out above, Gentner's second stipulation for a valid mapping of "substantial parts of relational-operational structure of [the base system] apply in the [target system]" has been adhered to (Gentner 1982, p. 109). Relationships - double-argument predicates - between objects or nodes take precedence over attributes - single-argument object or node predicates.

The target system, however, is also a part of the base system, as part of the biogeosphere's consumers, which rely on producers and recyclers. The consumers within the base system are part of a linear flow of energy and circular flow of biomass. These flows are the integral parts of the overall system, and they keep all three organic components, producers, consumers and recyclers, in check. As the human system has proliferated in scale, it has assumed its own system-wide characteristics: in the economic system, participants are not just passing on biomass from producers to consumers (e.g., from cereals to cattle to humans), but also creating resource flows, which, if in linear fashion, create availability and disposal problems at their respective resource and waste ends.

As a yardstick for an evaluation of the image transfer in Industrial Ecology that has just been undertaken, Gentner's dimensions of a good scientific analogy are applied (Gentner 1982, p. 113ff):

1. Base specificity: the degree to which the relationships in the base are sufficiently understood.

In this example of structure-mapping, the basic understanding of the object under examination, "natural ecosystems", is that it has one real form that can be understood by scientific endeavours through successive theory approximation. Kuhn (1993), however, disputes this view. The "real world", he maintains, is inherently unknowable (parallel to Faber's "irreducible ignorance", cf. Faber et al. 1996), and what human beings take for "the world", the result of an interaction with the human senses. This latter statement mirrors also the insight from Trudgill 2001, who discussed the ecosystem concept as a mental construct.

Therefore, in metaphor research and application for science, and in particular Industrial Ecology, caution has to be exercised in evaluations of base specificity. The idea of the unknowable world, championed by Kuhn, among others, drew inspiration from the works of several philosophers of the 18th and 19th centuries, not the least Kant (*"das Ding an sich"* - the thing in itself) and Nietzsche, who poured scorn on the idea of absolute truth:

> "There is no 'real' expression and no knowing apart from metaphor. But deception on this point remains... The most accustomed metaphors, the usual ones, now pass for truths and as standards for measuring the rarer ones. The only intrinsic difference here is the difference between custom and novelty, frequency and rarity. Knowing is nothing but working with the favourite metaphors, an imitating which is no longer felt to be an imitation" (*Das Philosophenbuch* of 1872, p. 149, quoted from Cantor 1982).

Gentner (1982) maintains that the predicted target structure cannot be better specified than the base structure, which is normally derived from a familiar domain. Bearing the above concerns in mind, the system of the biogeosphere can be said to be observed correctly in its circular behaviour at the global level, at least in general terms of the mapped relationships of the parts discussed above.

2. Internal-structural characteristics:

a. Clarity of mapping: the precision of object mappings.

If one base node could be mapped to several target nodes, or several base nodes mapped to only one target node, the analogy would suffer in clarity. In the above example, energy and biomass flows were mapped onto energy and resources flows: in this mapping, there is no ambiguity between base and target nodes. The situation is different for applications of the analogy in most industrial ecological literature: as an example in Côté (2000), organic participants of the biogeosphere (producers-consumers-recyclers of the base system) are mapped onto human participants of the industrial production system - different types of companies only. In the light of the resource cycles system, several nodes of the base system were mapped onto one node of the target system - industrial manufacturers.

b. Richness of mapping: the quantity of predicates mapped.
For mapping ecosystem participants, the predicates <embodies solar energy, embodies biomass> from the base system could not be mapped onto the target system, as resources are not embodied, rather, they are processed and passed on by the target system participants. Mapping energy and biomass flows onto energy and resource flows does not have this shortcoming of predicates omitted: it is richer. However, for evaluations of scientific rigour of an analogy, emphasis lies more on clarity and systematicity than richness.

c. Systematicity: predicates imported belong to mutually constraining system.
The biogeosphere system used as base system is highly systematic, as its relationships form a connected system.

3. External-structural characteristics:
a. Validity: model valid (relationships imported from base true in the target).
The energy and biomass flows mapped from the base system onto the energy and resource flows in the target system are valid relationships. Circular biomass flows, sustained by linear energy flows, are mapped validly onto circular resource flows, which are equally sustained by linear energy flows. Again, mapping organic ecosystem participants onto human participants would conjure up the problem of mapping <consist of biomass, consist of embodied solar energy><consumers eat other

consumers and producers> onto the resource cycle (target system), which is not a valid mapping.

b. Scope: number of different cases to which the model validly applies.
The base system in all mapping attempts in Industrial Ecology is only mapped onto one target system. The question of whether the subsystem of the industrial manufacturers is to be used as target system or the entire economy is a question of clarity, not of scope, as the realms (natural onto social) stay the same.

4. Explanatory analogy versus expressive analogy:
The mapping of the Industrial Ecology idea is an explanatory analogy that is utilised to explain and possibly to predict. It consists of a coherent and well-clarified set of abstractions that can be taken apart in the course of an examination. An expressive analogy, often found in poetry, is communicated in a whole that is not meant to be analysed and taken apart for evaluations of clarity and consistency.

As a general concern that affects several of the above categories, the analogy of the "type III" system is not quite correct: circularity in the base system model is depicted to come about at the global level, as it is assumed in the target model. In reality, however, in the same way as there can be observed different system levels from the single-cell organism level to the overall biogeosphere, the stark boundary between circular and non-circular behaviour must be regarded as an observation artefact. It is highly likely that what is observed to be feedback between individual organisms, between species within ecosystems and between ecosystems themselves, as the outcome of local and global energy and biomass flows, is a continuum of circularity. Hence, whereas circular system behaviour can only be observed with certainty on the global level, where the nutrient and gas cycles connect all lesser systems through the climate system, it would be wrong to assume that all other levels are characterised by the reverse, non-circular behaviour. The difference between these two categories is a matter of sorting that is undertaken by the observer, and a matter of imposing the categories themselves.
This *caveat* affects base specificity and clarity of the base system, and therefore, the quality of the scientific analogy in the target system. The consequences come to the

fore in the question: sustainability at which level, the global, national, regional or local? The answer that draws away from the position that sustainability is to be attained the global level only is a pragmatic one: as transport inherently causes environmental impact chiefly via dissipation of chemical residue from fuel consumption processes that can only be mitigated to a limited extent, there is a requirement for local circular systems in sustainable industrial and economic organisation.

5. Chapter conclusion

The central tenet of Industrial Ecology emerges from this analysis as a mapping of systemic relationships rather than a series of one-to-one translations: these relationships are displayed by flows of solar energy and biomass that underlie not only individual behaviour of producers, consumers and recyclers, but also behaviour of whole ecosystems. The central role of the firm and the farm as a postulate of industrial ecological work and engrained in economic doctrine, cannot be sustained by the mapping of the two systems. Nevertheless, the above postulate reflects current reality. This conflict is an expression of the central problem of sustainable development: how can private initiative and profit-seeking be made compatible with the health of the greater system?

Humans as the participants of the economic system process energy and resources in a fashion that mirrors the solar energy/biomass flows of the biogeosphere: the flows themselves, as they require management, take precedence over the economic actors. To implement a shift in awareness leading to such a precedence in political decision-making is difficult to envisage in the current social and political climate, where the pursuit of individual self-interest takes precedence over communal interest.

The problem with applying natural ecosystem characteristics as metaphors to human systems lies with the fact that the latter are partly outside of the natural system, meaning, not constrained by availability of any single local source of biomass. Human beings as omnivores are not specialised in their food intake. Both their position at the top of a large number of food chains and their capability to tap deposits of faraway mineral resources leads to an elimination of negative feedback on the local level. The ultimate negative feedback threshold for expansion of the human species lies on the level of the global biogeosphere.

Thus, the biomass and resource-using systems of human beings have to be led back into compatibility with the natural system where sustainability is not an issue itself: what is to be maintained in the human system is a scale of population and material accumulation that is unique in the surrounding biogeosphere. In the natural system (without human beings), there is nothing to be sustained, to be kept at a certain level, as species and populations adjust to external changes in their environment in a permanently dynamic flux. Therefore there is the issue of comparability: can parts of the natural system be taken as a model for human systems where certain characteristics (e.g., quality of life) need to be kept constant? The pursuit of sustainable development is the expression of the (enlightened) self-interest of the human race to survive at least in its present state, material wealth, and population scale, in an overall magnitude that dwarfs every other organic participant of the global biogeosphere.

The issue of sustainability then becomes an issue of continuing this difference between natural and human systems. As discussed above in chapter 3, sustainability of the human sphere within the biogeosphere can be maintained by reaching a permanent climax state of the human economy. In that situation, a large population and a high level of material wealth can be sustained in a steady-state, where the underlying resource and energy flows are circular, and throughput, and thus impact on the surrounding ecosystem, is minimal.

Wernick and Ausubel's (1997) assertion that the merit of Industrial Ecology not only lies in its potential for creating an environmentally friendly industry, but also in the understanding and application of "the analogy" can finally be taken rather as an unintended admission of ignorance of the importance of metaphor: As metaphor use is now understood as being in a central role for theory-building in the sciences, and especially in Industrial Ecology with the natural ecosystem analogy at its heart, Wernick and Ausubel's two propositions are conflated into one: an environmentally friendly industry deriving from valid scientific endeavour, and proper understanding and employment of the metaphor on the other hand can only be attained together.

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Chapter 5

Industrial Ecology in the context of global economic activity

1. Chapter introduction

Restructuring of economic activities in the form of industrial ecological systems has been established in the course of this doctoral thesis as involving not just the system of industrial manufacturers and service providers, but also relationships between producers and both intermediate and end consumers of goods and services. If industrial production is to be called "sustainable" (the emphasis lies on the resource and energy implications, therefore, on an ecological sustainability), it needs to be met by sustainable consumption to result in an overall sustainable economic system. For the same reason, industrial ecological restructuring must involve all industries and consumption systems, if sustainable development is envisaged as the development trajectory of human activity, and the model of Industrial Ecology seen as a reasonable approach to achieving it. As a blueprint of such restructured production and consumption systems, Graedel's "type III" system depicts an overall state of all economic activity that is compatible with the process of sustainable development.

Industrial Ecology at present, however, only concentrates on a very small sector of industrial activities, clustering mostly around combined heat-power production in the case of industrial ecosystems, or charting some isolated resource flows on a national scale, e.g., in the glass and steel industries, but without including the crucial stages of market allocation and end consumption (and the aim of that consumption) in that analysis. As such, the discipline of Industrial Ecology was found to be mired in an engineering and technicist perspective. The business enterprise as seen from a managerial perspective does not receive attention from industrial ecological research.

It is the international activities of business enterprises, however, that constitute the most important development impetus in the present economic environment, a set of processes that Industrial Ecology needs to address in its research and applications. Materials flows and energy use caused by these worldwide business activities constitute the largest economic and physical flows in the global economy, and are superseding in importance some global natural flows.

Employment, industrial production, national wealth (as measured by GDP), all these indicators are regarded nowadays as being directly based on the health of business enterprise. Competitive activity by corporate actors has its own rationale, and this rationale needs to be clearly understood to assess on the one hand its contribution to sustainable development or otherwise, and on the other, to evaluate the potential for industrial ecological structures to encompass economic activity in a much more comprehensive manner.

Thus, it is the aim of this chapter to point out the realities of industrial production and consumption on a global scale, as this economic activity is conducted and orchestrated mainly by very large business enterprises. The activities of businesses affect the circular money flow of an economy through employment of workforce and supply of goods and services, ultimately to end consumers. It is attempted here to link global economic activity to resource and energy use, employment, and creation of waste and pollution.

Industrial Ecology places a focus on local integration between economic actors, both between business enterprises and, as is advocated especially in this work, between businesses and their customers. How can this focus become feasible at all in the current system of international trade and competition?

The phenomenon of globalisation or internationalisation of economic activity and its consequences for resource availability and mode of utilisation does not receive attention from industrial ecologists (cf. e.g., compendia such as Vellinga et al. 1998). As pointed out above, Industrial Ecology examines local fluxes (eco-industrial parks) and some overall fluxes in the economy (material flows analysis through and within a national economy), but not large-scale industrial organisation, especially one that straddles national borders, and thus would have to include international trade. In the field of Industrial Ecology, an engineering perspective takes precedence over an economic or managerial perspective.

The present trends towards globalisation of economic activity thus will have to be discussed, particularly with respect to the leeway of political actors. These comprise, for instance, governments that devise regulation to foster local and regional initiatives towards sustainable development. Furthermore, industrial ecological restructuring involves organisational learning and opening towards cooperation with other actors, as has happened, for example, at the eco-industrial park of Kalundborg, Denmark. Can Kalundborg serve as a blueprint for future industrial organisation on a much wider scale? Is such openness towards cooperative activities a reality among the strategic activities of business enterprises?

These questions are discussed in two sections: the first examines tendencies towards global economic activities and the consequences for power constellations between economic and political actors. Furthermore, the physical dimension of that development, different resource use patterns arising from internationalisation of economic activities, will be considered. In the second section, the competitive activities of business enterprises come under scrutiny, which are regarded as occurring on the back of global or international economic integration. It is argued that intensifying competition and business activity in saturated markets have implications as well for resource use and environmental degradation, and that these developments might stand in the way of industrial ecological restructuring on a larger scale.

2. Industrial Ecology and Sustainable Development in the context of structuring processes towards globalisation

Although international business activities can be diagnosed for at least the last five centuries, and, indicated for instance by the dependence of the economies of industrialised countries on imports and exports that has been higher in 1913 than in

1995 (cf. Hirst and Thompson 1999, pp. 19-27), an international business environment has apparently been a reality for a long time, "globalisation" has become a politically sensitive phrase only in recent years. According to Leisinger (2000), this has happened for the reason that globalisation today differs qualitatively from forms of world development in earlier ages. As such, he maintains, the increasing impact of transport, financial transactions and electronic communication (all results of rapid technological progress) on the global economic landscape has led to unprecedented changes, especially in the number of and interaction among the actors involved, and in the "rules of the game" itself (Leisinger 2000, p. 1). This points to an increase in competitive behaviour, which will be discussed in the second section.

The term "globalisation" is difficult to define precisely. The argument over a definition has become a battlefield, where definitions of globalisation and assessment of its impact on human societies constitute political statements. Thus Leisinger (2000) states that commentators in the debate exhibit a bias that is "immense, immediately apparent and very confusing". This bias, he claims, is based on a position of interest that is explicitly or implicitly represented in any argument and that underlies all of the standard literature on the topic. As such, it is surely not an easy, if not nearly impossible, task for this present work to establish a perspective on globalisation that is free from any political influence. The tendency of authors on globalisation to fit facts to their theories can be observed in Chomsky's (1997) rejection of Hirst and Thompson's figures: Chomsky regards these figures bolstering the argument for a world economy that was more internationalised a hundred years ago as irrelevant statistics that mask the underlying tendencies to the contrary.

Giddens (1990) divides proponents of theories on globalisation into the two camps of the free-market enthusiasts on the one hand, who claim that globalisation is happening, the nation state is losing political power, and furthermore, that globalisation is of benefit for human development. On the other hand there are the sceptics, whom Giddens sees as both disputing the extent of the process, its influence and denying its benefits. The former are represented e.g. by Ohmae (1990) and Levitt (1983), the sceptics, for example, by Hirst and Thompson (1999). In this author's opinion, though, the dimension of the existence of globalisation should be distinguished from an evaluation of its effects: writers like Chomsky (1997), who acknowledge the existence of globalisation, but deplore it, and Rugman (2000), who deny the existence of globalisation but welcome international economic interdependency, are part of a host of different positions on a subject that is increasingly perceived to be highly complex in nature. As in many fields of science, especially the social sciences, the observer's viewpoint determines the outcome of the observation, as Myrdal (1978) reminds us[43]. As an exploration into different understandings of globalisation, comprising different viewpoints and evaluation, a few definitions will be mentioned in the following.

A narrow, but therefore rather precise, definition of globalisation that is centring on business activity is employed by commentators who disregard or dispute the social or cultural implications globalisation might have: Rugman (2000) understands globalisation as the process towards an integrated economic system purely in terms of substantially increasing capital flows in foreign direct investment (FDI) to be observed throughout the entire global economy; he consequently rejects the reality of globalisation on that evidence. Instead of a global market economy he diagnoses the existence and further emergence of several international trading blocs. Judging just from the political significance of the discussion and the impression of voiced fears of potentially negative consequences that were aired for the first time during and after the WTO meetings at Seattle in 1999, Rugman's viewpoint cannot be regarded as anything else but a too superficial way of analysis that does not give justice to the broader economic and social change apparently under way. Why would the term "globalisation" attract so much interest and heated debate from very different groups, if it was "merely" an economic phenomenon, and furthermore, one that was not regarded as exerting important influence? His focused perspective of globalisation as just the extent of foreign direct investment, though, is prevalent among business writers.

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[43] cf. also chapter 2. The relevance of the observer's position to the subject observed is very often forgotten in the debate on nature and impact of globalisation. Rugman (2000) thus claims to be "convinced by the evidence" (p. xi), which is in turn not so convincing for a reader interested in the self-perception of science.

Writers from different domains, such as the social theorist Hirst together with the political economist Thompson (Hirst and Thompson 1999), stressing the difference between "global" and "international" would come closer to Rugman's position, even though they do not just concentrate on flows of foreign direct investment. Hirst and Thompson as well reject the existence of a global economy and in its place rather diagnose an internationalisation process that is centred in the triad of North America, the European Union and Japan.

Giddens (1990) provides a very different view from the exclusively economic focus on globalisation discussed above. For him as a sociologist, economic globalisation is only one facet of a highly complex phenomenon that touches social, economic, cultural and political development processes. Giddens refers to globalisation as "the stretching process ... in the relations between local and distant social forms and events" (Giddens 1990, p. 64). This process has led to a shift in the power relationships between internationally mobile forces (predominantly, capital) and those who are committed to a specific location (among others, labour and natural resources), towards the former at the expense of the latter. In a keynote address, Giddens (1998) calls globalisation the "most fundamental set of changes" currently under way in the world. To observe globalisation from the perspective of the local versus the distant has the advantage of a viewpoint that can include more than just select financial criteria. To Giddens, the difference between a global and an international market economy is thus not an important one; it is the disembedding of local processes and their transferral to extra-local institutions that for him constitutes globalisation. Similar positions are adopted by researchers active in the relationship between globalisation and sustainable development, e.g., Hey and Schleicher-Tappeser (1998) and van Veen-Groot and Nijkamp (1999). The latter authors view globalisation as the "opening up and increasing internationalisation of markets, worldwide communication and mobility, changing consumption patterns and lifestyles, key positions of international firms in world markets, and shifting of industrial activities all over the world" (p. 331f). Hey and Schleicher-Tappeser (1998) see the three dimensions of the natural environment, the economy and culture, as increasingly being in the thrall of intensifying global interdependencies, which they call globalisation.

For the purpose of this work, rendering clear the environmental implications of business enterprise, the broader understanding of globalisation is regarded as being most appropriate: economic development and business activity is viewed as being closely linked with social and environmental development. Indeed, the working definition of sustainable development as the "triple bottom line" of environmental quality, social equity and economic performance (cf. Elkington 1997) acknowledges exactly this link.

Wackernagel and Rees (1995) underline with their ecological footprint assessment tool the ecological or physical dimension of globalisation, in particular the increased capacity of national economies to import and export natural resources and pollution assimilation capacity (sink capacity), or in general, carrying capacity. The importance of this physical basis to economic activity becomes clear when claims like that of Watanabe and Zhu (1999) emerge, of Japan having achieved sustainable development in the past four decades. The dimension of physical or natural resource and pollution accounting is missing completely from these authors' analysis, and thus the role of international trade as the means for Japan of importing carrying capacity is ignored. In fact, Japan has closed all her bauxite smelting and processing facilities, and now imports refined aluminium only (already 90% in 1994, cf. Korten 1995). This leads to a local improvement in environmental performance in Japan, at the expense of environmental quality in the countries where the bauxite is processed and from whom Japan obtains her aluminium supplies. Ecological carrying capacity of Japan thus has been increased by imports, and environmental damages and costs externalised. For the analysis of such a development of overcoming national and local physical constraints, Giddens' position as the changing relationship between local and non-local actors is a much more valid perspective than a narrower viewpoint could provide. Thus, an evaluation of local environmental or economic performance only makes sense against the background of such performance on a worldwide scale.

Which would be the industries and businesses that would be exposed to a globalisation viewed as Giddens' distancing processes and that, on the other hand, in their business activities lead to substantial environmental impacts? If we take as one part of the contributing factors towards globalisation the increasing interdependence of trade relationships, the picture in the example of Germany is as follows[44]:

Table 5.1:Trade relationships of environmentally sensitive industries in Germany

	Environmental Inv/total Investment	Workforce	Exports/ total sales	to W Europe	Imports/ total purchases	from W Europe
Chemicals	13.8	5.9	51.2	67.7	35.3	77.8
Mining	6.2	1.7	13.0	76.9	15.9	78.1
Steel and iron	7.7	1.7	47.9	73.0	40.5	84.4
Smelting	10.2	0.9	10.6	77.2	8.9	80.5
Non-iron metals	6.7	0.7	54.9	79.4	81.1	58.1
Cellulose and Paper	11.6	0.5	45.0	81.0	80.2	81.9
Wood	9.1	0.4	14.2	85.5	23.4	71.0
Mineral oils	12.3	0.3	10.0	69.0	26.5	76.0
Comparison with manuf. Total	4.9	79.4	37.9	70.2	32.7	67.5

(for 1992, all numbers percentages. Source: Hey and Schleicher-Tappeser 1998, p. 73)

These figure show a high proportion of import and export dependency of the German economy, and environmentally sensitive German industries in particular, on Western European trading partners. In other words, these industries are not subject anymore to just national policy-making and national economic performance, the German economy in environmentally sensitive industries is to an overwhelming extent linked to its most important trading partners, other countries within the European Union. What these figures do not show directly is the proportion of extracted natural resources as primary inputs.

As pointed out by business analysts and economics researchers, it is industries from the Triad that dominate world business activity. An examination of the goods comprising international trade to and from developing countries and within industrialised countries, however, shows some significant differences. Although the trend in the economies of developing countries goes increasingly towards exporting finished products, the contribution of industries and countries outside the Triad involves mainly the provision of resource inputs for business operations of international enterprise within the Triad, centring to an overwhelming extent on raw materials, that is, natural resources. These extracted natural resources that

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[44] The overall trends of international dependence should be similar to other national industries within the Triad.

developing countries trade for hard currency might be part of the imports from outside Western Europe that are not further detailed in the table from Hey and Schleicher-Tappeser (1998).

Naredo (2001) sheds some more light on the physical basis for industrial production in the industrialised world. He analyses the net resource flows into and out of industrialised countries not in monetary, but in physical terms. This helps to provide a solid basis for comparison, by eliminating changes in monetary value of exports and imports from year to year, which are very often due to currency fluctuations and changes in the terms of trade between developing and industrialised countries.

Table 5.2: Net commercial flow in physical terms for developed countries

Tonnage (thousands of metric tons)

Exports	Imports	Net	
Industrial extraction			
1981	18592	184842	-166249
1990	25863	208110	-182247
Fuels			
1981	33633	868793	-835159
1990	47951	995250	-947298
Manufacturing			
1981	64048	19447	44600
1990	71218	35312	35906

(Source: Naredo 2001, p. 185)

Globalisation now has to be understood not just as growing interdependence of economic activity, but more importantly, as the worldwide sourcing of natural resources for industrial production and on the other hand, dispersal of waste resulting from processing and utilising these resources. These activities are concentrated in the industrialised countries and are conducted there by European, North American and Japanese business enterprises. With the help of international trade, the population of these countries can continue with their resource and energy-intensive lifestyles, while at the same time being able to observe an improvement in local environmental quality. Developing countries, on the other hand, increasingly specialise in 'dirty' industries that provide raw and processed materials for industrialised countries, who effectively externalise environmental damage (cf. also Muradian and Martinez-Alier 2001, Andersson and Lindroth 2001, and Rayadevappa and Chhatre 2000. Anderberg 1998, on the other hand, dismisses what he calls the "hypothesis of industrial flight" as a myth). A further characteristic of trade relations between South and North is the huge debt-load of developing countries. Structural adjustment programmes to address that problem require developing countries to increase their exports, by specialising on a narrow range of exportable goods. These are natural resources that are extracted on a large scale, leading to oversupply on the world markets and consequently, decreasing prices. The latter situation can only be met by even faster and increased extraction of natural resources, which exacerbates the terms of trade for the developing countries even more. At the same time, manufacturers in the Triad come to depend on low prices for their raw and processed materials imports, and at the same time increased availability of these, thus, without any economic incentive to conserve virgin resources.

In the understanding of some ecological economists, economic and political instruments for international trade such as the proposed, but for the moment failed, multilateral agreement on investment (MAI, cf. Opschoor 2001), cement further this situation of a transfer of natural resources at low cost (without any consideration of the internalisation of environmental costs) from poor to rich countries, and the resulting dependence of manufacturers on cheap resources. This constitutes a transfer of wealth of from developing to industrialised countries. Muradian and Martinez-Alier (2001) see the resulting externalities not so much as the market failures (that are diagnosed by environmental economists and that ought to be remedied for sustainable development to be achieved in a free market economy) but as cost-shifting successes. The overall picture of the global economic system emerges as a linear system of resource extraction (mainly taking place in developing countries), production and sale (mainly in industrialised countries) and waste disposal (much of it exported back to developing countries). The current logics of international financial markets do not provide incentives for changing this linear system towards a more self-contained cyclical system, where resources and waste capacity would be utilised at the local level of production and consumption. In such a system, local carrying capacity would quickly reach a ceiling, providing the incentives that Industrial Ecology would need for complete cycling of wastes and by-products, thereby tackling the twin problems of resource availability and waste creation simultaneously.

In the face of overall consumption of natural resources by the population of industrialised countries (cf. also Norton 2000), Industrial Ecology thus needs to be applied to the production, marketing and consumption of consumer goods, if sustainable development is pursued in earnest. These consumer goods are produced by enterprises that strive for standardisation and homogenisation of demand and supply for the purpose of establishing economies of scale and advertising, that is, cost advantages resulting in competitive advantage. It is the production and sale of consumer goods that lead to the dominant economic and environmental impacts (cf. Chakraborty 2000). Consumer preference sovereignty cannot be upheld anymore in general terms in the face of dwindling global natural resources and pollution assimilation capacity. The notion is not quite as democratic at its core as is widely believed: Haake and Jolivet (2001) point out the contribution of industry not just in the satisfaction of demand, but also in the creation of it, an insight that is not new (cf. the discussion of the novelist D. Sayers below), but whose lesson seems to have been forgotten. Therefore, advocating the sovereignty of consumer preferences is not just part of every citizen's democratic right to self-fulfilment, but must also be understood in its role for supporting a lobbying for wider powers and higher profits for business enterprises.

The problem of Industrial Ecology at present lies in its inability or unwillingness to address these mass consumer goods industries and the meaning and nature of consumption itself. The focus on technical issues and specialist case studies in select industries renders Industrial Ecology both politically harmless and potentially irrelevant for sustainable development at large. Thus, a commendable effort for helping to achieve sustainable development can be blunted and utilised to support a system of unabated business activities, contrary to the aim professed by the majority of industrial ecologists. As was shown before (cf. the discussion of environmental efficiency in chapter 2), Industrial Ecology is not the only environmental initiative in danger of being used not as a tool for change, but for preserving the unsustainable status quo. For this doctoral project, this is the reason why the overall aim of

Industrial Ecology, recognised as the creation of a "type III" economic system, is so important for evaluation of existing applications in the field, and the proposal of new fields of analysis, such as the nature and physical basis of demand for goods and services.

Increasing globalisation of economic activity at present in this work is regarded as being related to the increasing competitive activities of business enterprises. To create and improve shareholder value, large corporations strive for access to ever-bigger markets. Market shares can be increased by geographical expansion, or by including non-monetary sectors of the economic system (for instance, housework or neighbourhood help) in the economy proper, e.g., by provision of new services. In the face of substitution of labour for capital, the economist Keynes held, stable employment can be maintained only if economic activities are increasing. The larger markets that are resulting from the globally expanding economic activity, integration of tastes and lifestyles through global media, are becoming a hotbed of intensive competition. This is mostly due to the fact that the attractive large size and the homogenic nature of the global markets, promising economies of scale for market leaders, equally attracts more competitors that try to attain a dominant position, or has those established firms competing in an ever-intensive way in order at least to keep their current market position. Thus, with the link between the structure of global markets and international trade with their relationship to overall consumption of natural resources and energy apparent, it is now expedient to turn to a discussion of the nature of competitive activities and point out some recent trends and their possible environmental impacts that arise from an increasingly liberalised global business environment, where multinational corporations can engage in largely unrestrained competitive behaviour.

3. Industrial Ecology in the light of competition between business enterprises, and the physical consequences of competitive interaction

In the manner of structure influencing behaviour and vice versa in complex systems, the shape of the global economic system that was outlined above needs to be seen as being directly linked to the dynamic activities of the economic actors in that system. Obviously, the reverse relationship is also true, so that structure and behaviour are co-evolving together (in the field of strategic management, this relationship is known as the "structure-strategy debate", cf. Chandler 1962). How does the behaviour of business enterprises as individuals and as a group fit into the structure of an international economic system that enables dispersion of production, sourcing of raw materials and environmental impacts from pollution?
Economic activity is traditionally viewed as the outcome of the interplay of competitive forces, and the following section discusses the economic and ecological effects of the competitive activities that business enterprises are engaged in.

The idea of competition as a basic organising principle of human activity needs to be discussed: with respect to what different ways of competition can be found in markets and whether an emphasis on competitiveness in economic activity could potentially or actually be counterproductive or even harmful for the welfare of human society as a whole, when seen from a social and environmental perspective.

Economic theory assumes the existence of competition to be a factor exogenous to its field, a given mode of behaviour that is inherent in human nature (e.g., as can be witnessed by the expression of h*omo oeconomicus* or *homo competitor* as a synonym for *homo sapiens sapiens*, cf. Group of Lisbon 1995), and as such, the assumed normal mode of allocation of economic resources. For some historians, however, competitiveness is not just a standard procedure of interaction between business enterprises or other economic actors. Fernand Braudel and the Annales school (discussed in Auerbach 1988) hold, for example, that the idea of any single aspect of a civilisation can only be comprehended via a knowledge of its totality: thus, competition and its relative prominence have to be regarded as forming a part of a larger social development, and consequently, as one of the contributing factors of dynamic change. From the end of the Middle Ages onwards, the pursuit of individual self-interest came to be embraced as a predominant mentality just as economic evolution was a part of a broader change in the consciousness of social actors in Europe. In the previous chapter it was pointed out that the concept of competition as a predominant principle of organisation was supposedly observed in the two fields of biology/ecology and economics, and that observation used in a translation between the fields as evidence for its existence. Writers like Trepl (1994) and Ekschmitt and Breckling (1994) aim to have a fresh look at ecological systems without that preconception, in order to escape the circular argument that was presented so far in favour of the ubiquity of competition.

Returning to the point of how system structure influences individual behaviour, Auerbach (1988) connects the economic structures of international markets to the behaviour of business enterprises: competitiveness between corporations has been increasing in step with the expansion and the internationalisation of markets, an assessment which Ekins (1998) shares. Markets increased not just in size (through international economic integration), but also proliferated in number: more and more social activities that were once part of the non-monetary, voluntary, economy come into the sights of enterprises that aim to convert them into lucrative outlets for the commodities they produce. Furthermore, Ayres (1995) draws attention to the Salter Cycle (Salter 1960), referring to growth in demand as an engine of further expansion of demand: the growth in the size of markets through increasing demand enables businesses to pursue economies of scale, that is increased production, where the initially high fixed costs are contained in the low variable costs of mass production. The resulting reduced unit costs can then be translated into lower prices, which lead to increased demand. The eventual saturation of the demand in a specific market results in businesses to seek and exploit new markets and opportunities, for which they use the financial clout and other resources developed during the exploitation of the previous market.

The transformation of energy and resources into products and ultimately into waste is the purpose of any economic activity: From the above discussion of the role of thermodynamics for understanding the behaviour of complex systems the insight was gained that human exosomatic instruments carry on the work of endosomatic instruments with greater scope and higher efficiency, that is, the human tools enable the degradation of much more energy. The difference, however, lies not just in the quantity of energy degraded. Exosomatic and endosomatic instruments are qualitatively different from each other, where the use of mineral resources is considered: For exosomatic instruments, degradation of energy has a component of natural mineral resource use, and an increasing efficiency of human-made tools in degrading energy thus means an increasing level of resource use and waste creation. Endosomatic instruments, as was discussed in the previous chapter, consist of biomass and embodied energy only.

Competitive activity has been traditionally regarded by economists as focusing chiefly on price and quality. This understanding was placed in a static environment of allocation, where supply and demand meet on the market and an equilibrium is reached. As will be discussed in the light of "hypercompetition" further below, competitive activity in increasingly large and global markets takes place in terms of timing, of being the first in the market with a new product. Not just diminishing returns that lead to a balance in supply and demand are at play in such dynamic situations, but development trajectories where lock-in processes lead to the creation of increasing returns for the market leader. The recognition of such relationships places more emphasis on timing issues. It can be observed that more and more high-tech products that previously were regarded as one-off investments, and thus subject to saturation, have become fashion articles and thus are very quickly subject to obsolescence (at least in the mind of the consumer). Examples are cars, stereos, computers, and mobile telephones. Advertising serves the purpose, it is argued, to "educate" consumers into regarding goods as fashion items, and thus, creating demand (as the novelist Dorothy Sayers, working in the advertising industry, observed already in 1923). Hence, supported by advertising, industrial competition becomes the motor for economic growth and increase in ecological consumption, that is, of natural resources and sink capacity.

Competition is traditionally held to promote efficiency of production and marketing: Only the goods which have a chance on the market will be produced (in the 1970s the motto for industrial production hitherto, "sell what you can make" developed into "make what you can sell" as a consequence of the transition from the age of production to the age of marketing when consumers were becoming highly aware of brands and their status - the transition towards marketing also indicating that the products coming to a market are not easily absorbed by it, demand is not pre-existent and exogenous, but has to be created and maintained). Economic theory assumes the existence of a regulatory mechanism (ideally smooth, continuous, proportional and reversible) between unsuccessful goods on the market and adaptation of production behaviour, feedback mechanisms which drive market forces towards equilibrium.

This is not entirely true beyond the theoretical realm: Nowadays, industrial goods require ever more investment in money and time to get them to the market, be it in terms of research and development, in marketing, in technology of production, or in rising wages. This raising of the competitive stakes increases the risk to the competing businesses. It can lead to the lock-in previously mentioned, in this context where production processes cannot be changed easily anymore and up-to-date market information does not constitute relevant feedback (cf. Arthur 1988, 1993).

As competition governs the process of allocating produced goods on the market and their transition from the producers' hands to the consumers', it is the major transformation process - transformation of resources and energy in production processes serves only this purpose of transformation from production to consumption.

If the thermodynamic observation of an increasing speed of transformation is considered in economic terms, speed and intensity of competition and market allocation, together with the consumption of goods and services can serve as indicators for the irreversible dissipation of natural resources and energy.

In many industries, the reaction to markets growing ever bigger and becoming saturated forms a new mode of competitive behaviour that aims to increase the dynamic changes in such markets. D'Aveni (1994) calls this phenomenon "hypercompetition" in his eponymous book. Traditional competition is characterised by the quest for a sustained advantage of the players at the top and the establishment of a stable equilibrium among the competitors in a market, where the players behind are allowed find a stable position as market followers, to retain profitability and survive. This in turn leads to the creation of rather stable environments. In the words of D'Aveni, hypercompetition is comparable to traditional competition "like a hurricane to a strong wind". Hypercompetitive players do not commit themselves to one market, they disrupt the structures of the market they are in at the moment, then shift their activities rapidly and move on to the next opportunity. Competitive advantage cannot be sustained any longer; it exists only on a very short-term basis. Competitors left behind are not allowed a position of coexistence, but are crushed. Hypercompetition, once arrived at in an industry, will not disappear again, D'Aveni maintains. This is due to the fundamental difference to traditional competition in a traditional environment. There is no competitive equilibrium or stable environment anymore when hypercompetition appears in an industry. The methods of hypercompetition fall into the arsenal of competitive behaviour available to all businesses, competition on cost-quality issues, timing and know-how, market strongholds protected by entry barriers and lastly, financial clout built up through previously successful strategies (D'Aveni's "four arenas of hypercompetition", D'Aveni 1994, pp. 13-16). The difference between hypercompetition and other modes of business behaviour lies in the dynamic nature of the former, where surprise action and timing advantages in the four strategic arenas are used to disrupt, not sustain competitive advantage. Competition thus becomes a process of rapid interaction and constant irreversible change rather than a quest for a market equilibrium.

This insight is radically different from most of the authors on competition, who analyse competitive situations using the paradigm of equilibrium, like Appelbaum and Lim (1991). Together with the idea of attaining a competitive equilibrium, trust vanished as well, D'Aveni points out. Once this culture is abolished together with the competitive environment specific to it, there is no going back, when a culture of hypercompetition sets in. Trust cannot as easily be restored as it is destroyed. Effects of hypercompetition include predominantly a shorter life span of products in the market, lower quality, and a propensity of the consumer to buy a new product rather than repair the old one. All these effects have profound environmental impacts. D'Aveni compares the escalation into hypercompetition to an arms race between two countries. In the manner of a prisoners' dilemma situation, nobody wants the escalation, but no one knows how to stop it. This comparison with a military-political situation alone might be a good insight into what can happen in a hypercompetitive environment, why it is so dangerous and wasteful. D'Aveni maintains that hypercompetition is an extension of the ideological view of "competition as a Darwinian struggle that leads to survival of the fittest" (D'Aveni 1994, p. 226).

D'Aveni is not the only author observing an increase in competition: It seems to be a widely agreed fact that competitiveness, together with economic instability and uncertainty, has been rising during the last two decades. Sengenberger (1992), from the perspective of the labour market, points out what changed the economic environment towards rising unemployment in industrialised countries: Intensified competition and rigorous cost-cutting by the competitors as a result, especially labour costs. This scenario supports both D'Aveni's and Korten's arguments.

However, researchers using so-called "entropy techniques" for measuring competitiveness and concentration come out with a whole spectrum of different conclusions. Saghafi and Attaren (1990) hold that according to their analysis a shift towards concentration took place in the U.S. in the 1980s and thus claim that American aggregate industry has become less competitive. Nissan and Caveny (1985, 1988), on the contrary, arrive at the conclusion that there has been no significant difference in concentration of the Fortune 500 companies in the period between 1967-86. Both teams used techniques belonging to the same family of tools. Saghafi's and Attaren's claim that an increase in concentration in the national industries of the U.S. leads to a decrease in competitiveness may be flawed, however: As D'Aveni shows convincingly for American and Japanese businesses, a rise in global competitiveness and intensity of competition is complemented by concentration at the national level of markets and industry. D'Aveni's statement resonates with Auerbach's (1988) assertion that the degree of concentration in one industry is not a sufficient measure for competitiveness, thus, instead of this static measure, dynamic ones need to be employed.

In the micro-economic perspective of the processes happening in one market, Auerbach (1988) lists modes of competition other than price or quantity competition, such as competition by innovation and timing. Emphasised already by D'Aveni's writings on hypercompetition, the basic model of supply and demand in a market is enhanced by adding a time dimension, thus creating a dynamic model. In this sense, competition, especially in technological implementations, is viewed as corporations out-innovating each other. A new product on the market might be technological superior and thus renders all the other products obsolete. Arthur (1988) takes this a step further, when he models the processes taking place when two new technological solutions enter the market to take on each other - the standard configuration in a corporate battle where two product standards fight for domination of the market, as there is only room for one standard, to be adopted by either the competition or the industries which are connected to that specific product. Arthur calls that process of competing technologies a random walk process with increasing returns, as the benefits from one technological solution increase with the rate of adoption. As a consequence, the structures of fast-moving markets call for a strategy that is based on very quickly attaining market leadership or a dominant position in that market in order to compete effectively. The stratification into winners and losers among the competing businesses in such situations is marked: those that do not attain a dominant position in the market will disappear soon, no matter how good the product offering was. Thus, in line with Ayres' (1995) assertion of the validity of the Salter Cycle, companies in such situations will be forced to grow quickly and increase demand just in order to survive.
Moreover, hypercompetition leads to even less commitment for regions, employees, communities and resources, and can be regarded as a driver towards globalisation in the understanding of Giddens (1990) as "disembedding".

Furthermore, the tendencies for increasing availability on the market and falling prices of natural resources that were observed in the previous section do not encourage resource conservation by themselves, but on the contrary, are compatible with the development trajectory of hypercompetition. Both situations (which have evolved together) thus combine into a regime where the proposals of resource conservation, reduction of throughput through the economy and slowing down of economic transformation processes have no economic logic at present.

The development of larger markets that exhibit structures of hypercompetition leads businesses to develop a focus on their internal structures in order to gain as many synergy effects as possible. Information technology enables a very high degree of integration and control in large multinational corporations, and restructuring (for example, via business process reengineering) is carried out with the aim of increasing the strength of intra-company networks in their effectiveness and efficiency, to enable the corporation to compete in its markets. D'Aveni (1994) maintains that in a regime of hypercompetition other companies are viewed as hostile forces: the option of "cooperating oneself out of hypercompetition" is not available in such markets. The structuring factors for global markets (exploring new markets, large geographical distances between different business units, between competitors, and between producers and consumers, pursuit of economies of scale, large size) place an external focus for companies on capturing and defending individual market share and combine with the internal focus for cost-cutting and tight integration.

Structuring factors for industrial ecological organisation, on the other hand, comprise integration among co-located businesses of different ownership, integration between production and consumption on a local scale, and thus, through the fragmentation of markets via creation of niches, a lessening of standardisation and competition with economic forces outside that locality. For exploiting cost-saving potential in increasing overall resource efficiency within the whole local system, a proximity to markets (requiring less advertising expenditure), a focus external of the individual business is needed.

Clearly, in the current set-up of the global economic system, which is driven by the activities of multinational enterprises, a shift in focus on organisation structures more akin to industrial ecological principles must be regarded as unlikely to happen at the moment to any substantial degree, as the achievement of internal control in the face of a "hostile" environment was the reason for expansion by mergers and acquisition for domination, leading to the acquisition and the control of market share.

The rules of hypercompetitive markets stipulate that large companies need to compete on price, speed and product differentiation. For car manufacturers for example, it is not an option to do otherwise, as they would endanger their entire business. They are going along a specific development trajectory that compels them to go into China and India for opening up new markets. Only when everybody on earth has a car, society realises that cars pose more of a problem than a solution: this is the climax point of economic activity (cf. chapter 3, Sonntag 2000, Decker et al. 2000) where demand cannot be expanded anymore. It will happen to more and more industries, when either resources and waste assimilation capacity run out (externalised from the businesses' operations and transferred to governments who cover them via taxation, these are costs impacting on the buying power of the consumers the companies rely on), or when product differentiation, creation of new wants, and thus creation of new businesses and jobs does not happen fast enough to offset capital substitution for labour. At this point, industry is "eating its customers", ridding themselves slowly of the work force, the customers on which the businesses ultimately depend.

The remedy to this situation, prompting a reorientation of business, might be seen in the implementation of an ecological tax reform that renders international transport much more expensive (cf. chapter 6). An ecological tax reform in its ultimate remit and scale aims at the heart of the current mode of expansive capital-intensive business, so it will be clearly opposed by powerful business interests that benefit from the status quo, as the main means of global organisation of business activities are transport (that thrives on externalised costs, thus appropriating subsidies from governments) and information technology. Contrary to that, the ecological tax reform strengthens a local scale. The ecological problem thus can be regarded as a political problem, where political actors attempt to hold or strengthen their position of power.

4. Chapter conclusion: a niche for Industrial Ecology in an international economy

The global economic framework of integrated financial markets and implementation of free trade measures in many industry sectors was created to enable a high mobility of venture capital and subsequently, an expansion of business activity. It was attempted to demonstrate that such an economic system favours different modes of organisation for businesses than a system that takes an industrial ecological seriously.

As a consequence, industrial ecological organisation would be possible in today's business environment only as an exception, not as a rule. Fitting industrial ecological structures into a niche in the present economic environment that is characterised by international rather than local economic relationships means that the model of the "type III" system is not taken to heart.

It becomes quite clear that sustainable development through the development of mostly self-sufficient local socio-economic units that integrate into a global sustainable system of socio-economic activity will not be encouraged under the present rationale of business activity and regime of international legislation. The overriding of the local imperative for sustainable development by the international one of continuous expansion of markets, however, is made possible by a transport system that does not account for the full cost of its activities. Increasing fossil fuel prices to account for environmental degradation and to provide incentives for substitutes is the cornerstone of an economic development along different trajectories. An ecological tax reform, the policy instrument discussed in the following, thus might lead to profound changes not just in preferences of transport, but more importantly, in the way economic and social infrastructure is organised.

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Part III

The previous part had as its objective to clarify the understanding of systems that are touched by and underlie industrial ecological thinking, by looking at both ecological and economic systems. As Industrial Ecology aims to translate between the two, the rules for that translation effort were also made explicit. This third part builds on the insights derived from the analysis carried out above. It is especially aimed at providing ideas for an industrial ecological theory and practice that is recognisant of the need for an economic system conforming to the "type III" system characteristics, the only outcome yet of the effort to describe the anatomy of a sustainable system in the human realm. The task for Industrial Ecology appears to be to translate from the requirements for a sustainable system on the macro-level, the "type III" condition, to the individual characteristics of micro-level systems, on the production and consumption side. The design, implementation or change of these micro-level systems consequently has to be in line with the condition of sustainability of the overall system.

First of all, it has to be emphasised that Industrial Ecology at present is a discipline that is dominated by technical, supply-side oriented solutions. This is perhaps the reason why the discipline is dubbed "the science of sustainability", and industrial ecological processes are referred to as "operationalising" sustainability, as discussed in the first chapter. Changing our society to one that can fit in with the constraints of the Earth's biosphere is a process that cannot be undertaken by technological endeavours only. Sustainable development, if it is a science, is a social or political science as well. Industrial Ecology's current focus ignores the social process involved in sustainable development. It does not concern itself with issues of equity, even though these have ramifications for an overall sustainable human economy. Notwithstanding its goal of a "type III" system (or assuming that this goal can be attained without social changes), Industrial Ecology at present concentrates on the "low-hanging fruit" of integration between industrial manufacturers, which can be seen as merely pursuing eco-efficiency, as a measure that only concerns the supply or production side and leaves out the demand or consumption side entirely.

This might also be a reason why Industrial Ecology at the moment stays a peripheral and mostly theoretical discipline: the technological focus predominant in Industrial Ecology (viewed by its proponents as an unpolitical endeavour) does not encourage involvement of a larger variety of stakeholder groups. The supposedly all-embracing nature of Industrial Ecology, as expressed in the "type III" system goal, however, is not communicated by Industrial Ecology's advocates.

This doctoral thesis has been striving for portraying Industrial Ecology as a way forward for creating a sustainable human economy in the sense of aligning economic and social requirements with ecological constraints. If the "type III" system goal is taken seriously as a blueprint for a sustainable society, Industrial Ecology becomes a discipline with a political and social stance as well as a technological one: One of the major reasons for environmental degradation lies in the overall level of consumption in the industrialised societies. The crucial question consequently becomes the change of the demand side to meet requirements for ecological sustainability, and the integration of supply-side measures with those on the demand side. Without doubt, this constitutes the biggest challenge that business enterprise will face.

Chapter 6

Reconceptualising Industrial Ecology for compatibility with "type III" systems

1. Chapter introduction

Modifying Industrial Ecology in theory and practice is founded on three dimensions that are largely ignored in the present efforts of pursuing sustainable development in the corporate arena: the first is the requirement of ecological sustainability as the framework of orientation for the economic system. In the case of Industrial Ecology this means understanding the flows of matter and energy in natural systems and the consequences of recognising the limiting scale of global stocks, flows, and sinks for the scale and direction of human development. Thus, the present chapter aims to give practical recommendations for anchoring industrial ecological practice in the theory of a "type III" system, by proposing a system of indicators measuring cyclical behaviour in industrial production, and advocating the creation of industrial ecosystems that integrate production with consumption and recycling. This is suggested to be achieved by cycling all outputs, whether main products or by-products, after their use back into the production process. These outputs' energy content thus is the main component that has to be replenished so that output products and by-products can serve as inputs with the same quality as required for inputs coming from virgin resources.

The consequence of such a system of operation would be bringing production and consumption closer together. Up until now, the sphere of industrial production saw the consumption side only as markets that must be discovered, entered and exploited, as market share that must be increased. Communication happens in a mostly one-way fashion, from industry to consumers (via advertising). Environmental engagement has been confined to altering structures within the production system (for instance, end-of-pipe technology, energy efficiency measures, but also the supposedly "ecosystem" structures in current industrial ecological thinking and practice), but has not reached out to integrating the role of consumers vis-à-vis production, as the latter is thought to be the sphere of sovereignty of enterprises. Cycling of all outputs by taking them back directly, and in vast quantities from the consumption side, results in production and consumption becoming more closely associated with one another. One set of tools that is developed at the moment, reverse logistics, is a step into the right direction. The role and nature of demand, its stimulation and its environmental impact moves into a prominent position for creating and managing a sustainable human economy and "operationalising sustainable development", with both production and consumption contributing to the sustainability condition.

The second dimension is closely linked with the first: the implementation of an ecological tax reform is examined here as a support for complete cycling of outputs into inputs, with an emphasis on the local rather than the global scale. It is the recognition that striving for sustainable development constitutes a political process, which in fact is on a very basic level not so different from other economic agendas (e.g., the pursuit of free trade economics, or the prominence of the market concept), in that this process, as all political processes, inevitably involves political actors who exercise power in order to support the creation of a specific political climate of their choice. Economics, as was stated above, is not a pure science, but a political and social science: the attempts that have been made to make economic theory appear more rigid and conceptually close to some natural sciences can also be interpreted to reveal a specific political stance. As a consequence, government legislation is seen to play a vital role for creating a framework susceptible for business evolving towards sustainable development by taking the condition of ecological sustainability seriously.

The third dimension chosen for playing an important role for the creation of industrial ecological structures is the question of ownership and control of companies and their industrial facilities with respect to corporate efforts towards sustainability. The corporate structure of the companies participating in an industrial ecological network surely also needs to be responsive to and compatible with the aim of a more integrated system between producers and consumers.

Therefore, the structures of private and public limited companies will be contrasted with one another, resulting in the recommendation that industrial ecological structures, which bear in mind the "type III" condition, will be supported mainly by private limited or unlimited companies, as these are free to place emphasis not just on the short-term financial bottom line.

2. Integrating the production and consumption sides of economic activity - the litmus test for aspiring industrial ecosystems

As mentioned above (in the first chapter), one of the major activities of Industrial Ecology is devoted to the creation, development and management of industrial ecosystems. Taking its cue from relationships of participants within natural ecosystems, the industrial ecosystem approach proposes to replicate characteristics of these relationships in industrial organisation. The good dozen eco-industrial parks, mainly in the United States, aim to become the nuclei for making industrial ecological restructuring a more common activity.

The metaphor of the industrial ecosystem is certainly an apt one that attracts interest and conveys quite a simple concept. We have seen earlier, however, that the "cyclical activity" of industrial ecosystems is little more than an attempt at increasing the productivity of some non-renewable resource, coal, for instance. Industrial ecosystems still depend on a large input stream of virgin resources and they still produce a large stream of waste with their output.

In present attempts at industrial ecosystem, e.g., the industrial park at Kalundborg, Denmark, the by-products are fed into processes that do not require high quality inputs. Although this feeding into another production process (rather than emitting) is understood as "cycling" by industrial ecologists, one should label these so-called "cyclical" processes (used with the much vaunted "waste as food" metaphor) rather "cascading" processes of resource use (O'Rourke et al. 1996, cf. Figure 6.1).

Cascading occurs in instances where the virgin resource on its way through production processes towards becoming waste (which is to be disposed of) takes more steps than just the one that takes it straight from the resource state through one production process into the state of waste. The resource's inherent energy (and therefore, usefulness) is utilised and removed not just in this one step (as in traditional industrial activity), but in several successive steps, and is thus utilised to a much greater extent. The "waste" entering another production process "as food" does so only in a state of diminished quality. Cascading, however, becomes the most viable option with respect to energy production and use, as electricity generation results in waste output and heat - the waste outputs cannot be reconstituted to enter the same production process again, and the heat (waste energy) cannot be reconstituted in its usefulness at all. What can be done, though, is to use the energy generated from the material inputs as completely as possible. Today, the most promising scheme is coproduction of heat and power (CHP). Waste heat that has no use for electricity generation any more can still be used as process steam and for district heating purposes. Energy use, whether in human or in natural systems, always leads to the emission of waste heat, radiating into space. The most resource efficient use of energy would result in the emission of waste heat of the lowest grade possible, that is, the energy generated would be used in many energy cascading steps that remove its utility ("exergy", cf. O'Rourke et al. 1996) as completely as possible.

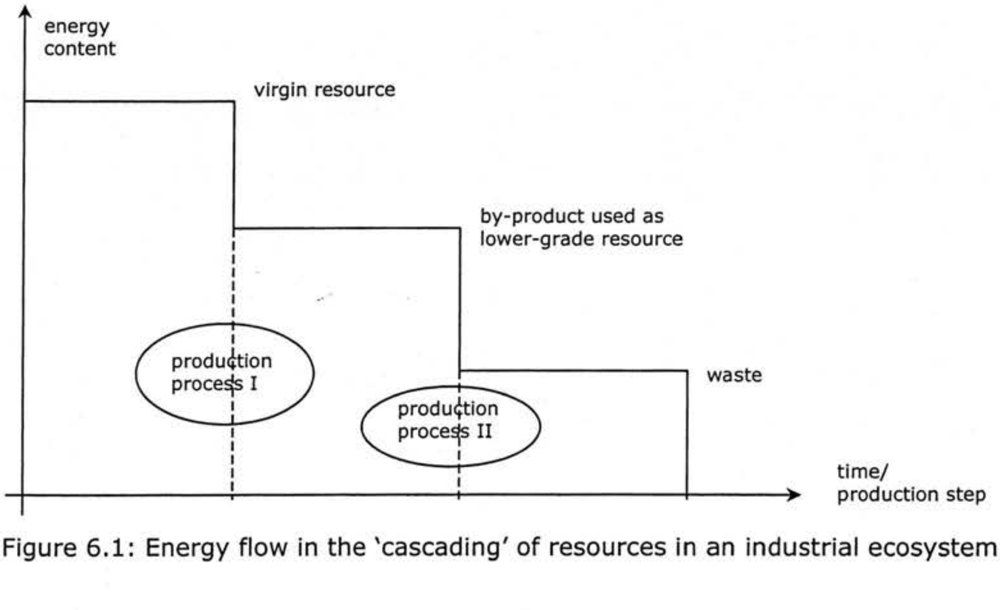

Figure 6.1: Energy flow in the 'cascading' of resources in an industrial ecosystem.

Owing to the high dependence on virgin resources as inputs and waste output, any industrial ecosystem at present can only be regarded as a "type I" system, perhaps at best as a first step towards the "type II" stage. Furthermore, these industrial ecosystems are "type I" systems that are isolated from one another, without the connections to other "type I" systems that would be found in the parallel system of the biosphere. In the latter, numerous subsystems with linear resource use patterns combine to form the one cyclical supersystem, the entirety of the biosphere that is dependent only on the influx of solar energy. The connections of linear, quasi-linear, or semi-cyclical processing units in the natural system with one another ensure the whole system's stability and longevity, thus rendering the latter a "type III" system. By nature of its goal of the "type III" system, Industrial Ecology is a comprehensive effort for cycling all outputs into becoming new inputs, looking down the entire chain of production and consumption. In its applications, however, Industrial Ecology as yet falls short of that goal.

Cycling is understood as looping by-products and wastes back into that production process from which they emerged, as resources of a quality on the same level as virgin input. This looping back must incorporate replenishment of energy, to enable the material to cross the threshold from wastes to resources. O'Rourke et al. (1996) call this replenishment "entropy cycling".

True cycling of all outputs into inputs (cf. Figure 6.2), while certainly being able to incorporate cascading (the use of resources in different states of quality), must be seen as an activity that is located at the boundary of an industrial ecosystem, for instance, in the form of exchanges between producers and consumers, especially from the latter to the former. Therefore, these structures are denoted as "integrated producers-consumers ecosystems" to distinguish them from industrial ecosystems in their present, production-centred, state.

Industrial ecosystem activity that remains at the cascading stage, on the other hand, is located in the centre of the industrial park, as several participants within the system pipe their by-products and wastes to one another. These participants are all producers of industrial goods and services - cascading thus does not cross the system boundary to include consumers, even though producers from several eco-industrial parks might exchange wastes and by-products. It is this crossing between the domains of producers and consumers - e.g., manufacturers and households -

that makes true cycling of resources stand out over cascading. Cycling thus incorporates the goal of the "type III" system, whereas cascading does not.

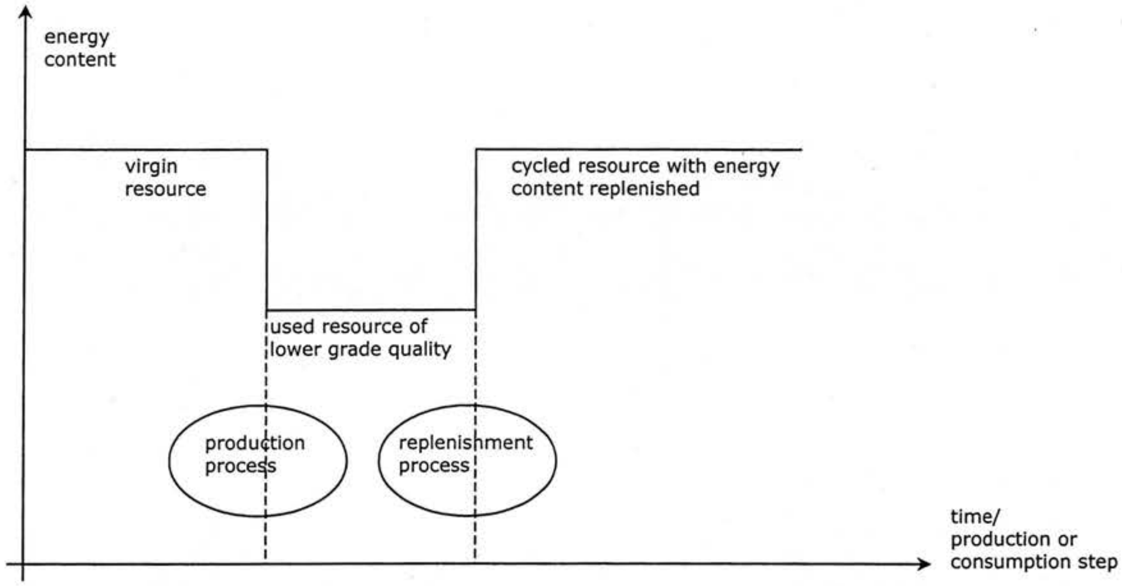

Figure 6.2: Energy replenishment in 'true cycling' of output into same-quality input.

The difference between the two can be illustrated with the example of a pulp mill: A Finnish pulp-producing company enters into a local waste exchange system, ensuring a more efficient use of its major resource, timber in different qualities. The timber is processed and some of the by-products and wastes are used locally for energy production and in the manufacturing of chemicals and other wood-based products. The timber is sourced from sustainably managed forests, where the felling rate does not exceed the growth rate. If the focus of analysis stays with this local system, we could make out cascading processes in the relationship of the pulp manufacturer with the power plant, a wood chip producer and a chemical plant. Cycling, however, would have to include all outputs from this relationship, the paper pulp in particular, which is the primary source of revenue. 90% of this paper pulp is exported to Germany, where it is marketed as coming from sustainably managed forests, and thus as a product with high environmental credentials. At this stage the pulp leaves the Finnish eco-industrial park. After its conversion into paper and related products in Germany and subsequent use, the paper waste is either landfilled, burnt or recycled to enter production processes as lower-grade resource, where it might be converted into toilet paper, for example. Only a small proportion of the paper waste that was derived from the original paper pulp from Finland reenters the cycle of quality paper production. For the overwhelming majority of this resource, we can thus observe a cascading relationship from high quality to lower quality, leaving the quality paper production process dependent on virgin resources. Cycling, on the other hand, would mean that the paper waste stays in the paper production process, just flipping between production on the supply side and consumption, the demand side. The difference between cascading and true cycling lies, as detailed below, in the energy expended to replenish the paper waste's quality, so that it can stay in the high quality paper production process and does not have to cascade down to enter e.g., the toilet paper production process. True cycling would make the production process less dependent on virgin resources, whereas cascading, as a linear process, cements the dependence on virgin resources at the high-quality end of the production process. In the case of Finnish timber as this virgin resource, this distinction between the two processes does not seem to pose too much of a difference or problem in environmental impact. If industrial ecosystems, however, are to become an integral part of restructuring industrial activity towards sustainable development, they will be more widespread and involve a whole host of industries. These will depend on virgin resources with a far higher environmental impact, for example, mined resources, leading to the distinction between cycling and mere cascading to become more pronounced.

Bearing in mind the distinction between cycling and cascading, this section proposes to take the "type III" condition much more seriously than has been done until now in applications of Industrial Ecology. This goal is thought to be approached by measuring one industrial ecosystem's dependence on virgin resources, and the overall cycling of all output.

Industrial ecological indicators proposed:
the percentage of output cycled
the percentage of input derived from cycled outputs

The first indicator, "How much of the industrial ecosystem's output and waste is cycled?", assessing the cycling of a percentage of all output back from the demand side, the end consumers, to their suppliers, represents a true "cradle-to-cradle" approach (which expresses Industrial Ecology's philosophy in its concepts and tools; in contrast to the more commonly known cradle-to-grave approach of product stewardship). It includes all outputs produced in the course of one good's manufacturing processes until that good is delivered to its end consumer, including the waste outputs of the transport used as well. If this question can be answered in a meaningful way (that is, with a high overall percentage score), only then can Industrial Ecology be seen as a feasible way for future economic organisation taking sustainable development seriously.

Industrial ecosystems could be expected to cycle all their outputs directly back into the same production processes, replenishing the waste's energy content, and thus creating value added. If global transport is factored in to a fairly realistic degree (cleaner transport), these outputs can be cycled back not into the same industrial ecosystem that produced the output, but into another industrial ecosystem, which in turn has some of its output cycled back elsewhere. For the latter situation, a standard occurrence today, we have to factor in both the environmental impact of transport, and remedies for it (e.g., carbon sinks), to obtain a zero-impact cycling loop.

The question "How much of one industrial ecosystem's input is derived from cycled sources?" examines the reverse process: an industrial ecosystem should measure the percentage of its inputs that is not derived from virgin resources, but instead from its own output cycling or, parallel to the above qualification of international trade, the cycling of other industrial ecosystems' output. Cycling back of industrial output in a meaningful way entails a closer relationship between producers, industrial manufacturers and service providers, and consumers, private households and public organisations: In order to obtain the resources deriving from their output and waste, producers need to create "reverse logistics" systems. These systems are increasingly employed by business enterprise to govern the channelling of waste from end consumers back to industrial producers.[45] Figures 6.3 and 6.4 provide an overall (and much simplified) view of producers, consumers and their

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[45] One small example, not necessarily connected with industrial ecosystem activity, is the "design for disassembly" strategy employed by the car manufacturer BMW to recycle a higher amount of the resources embodied in the cars produced.

environmental impacts in a current industrial ecosystem (Figure 6.3) and in an integrated producers-consumers ecosystem (Figure 6.4). The first figure depicts a slight decrease in the amount of virgin resources used and waste produced compared to the industrial output to consumers, whereas the second figure shows a much reduced dependence on both virgin resources and waste capacity, up to the point where both are of negligible scale. The figure will throw some light on the "entropy cycling" concept of O'Rourke et al. (1996).

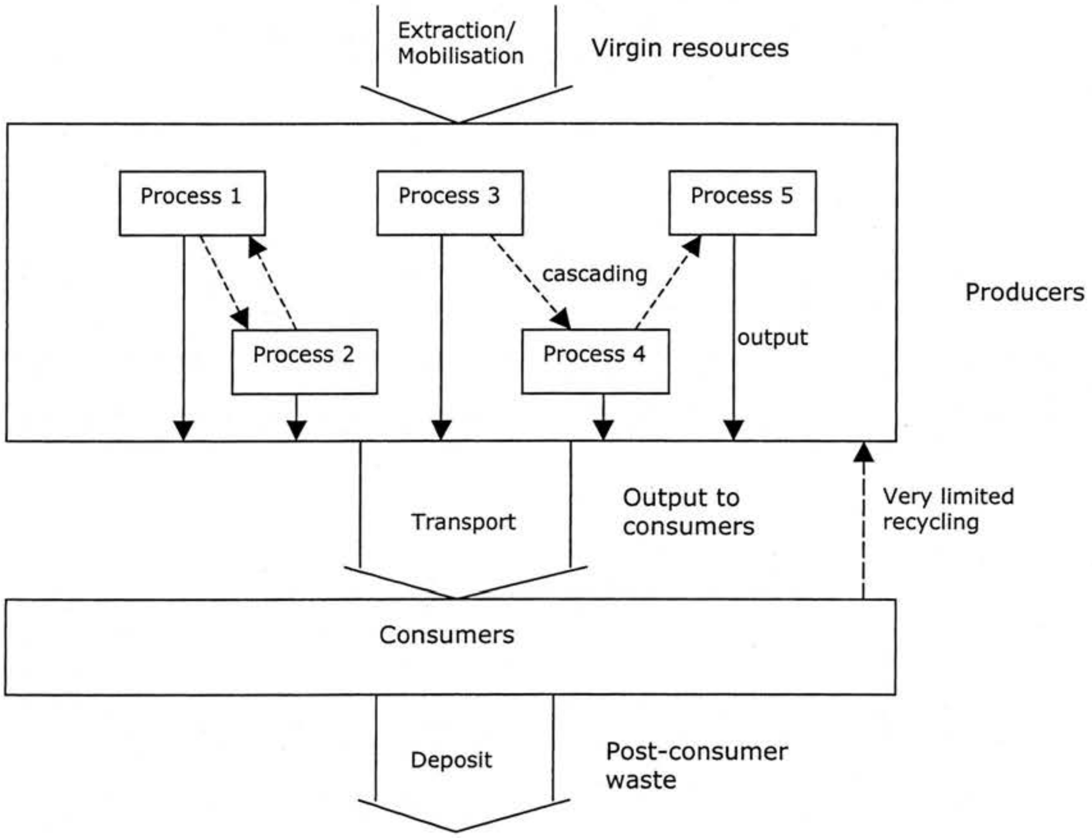

Figure 6.3: A perspective of waste cascading in current industrial ecosystems.

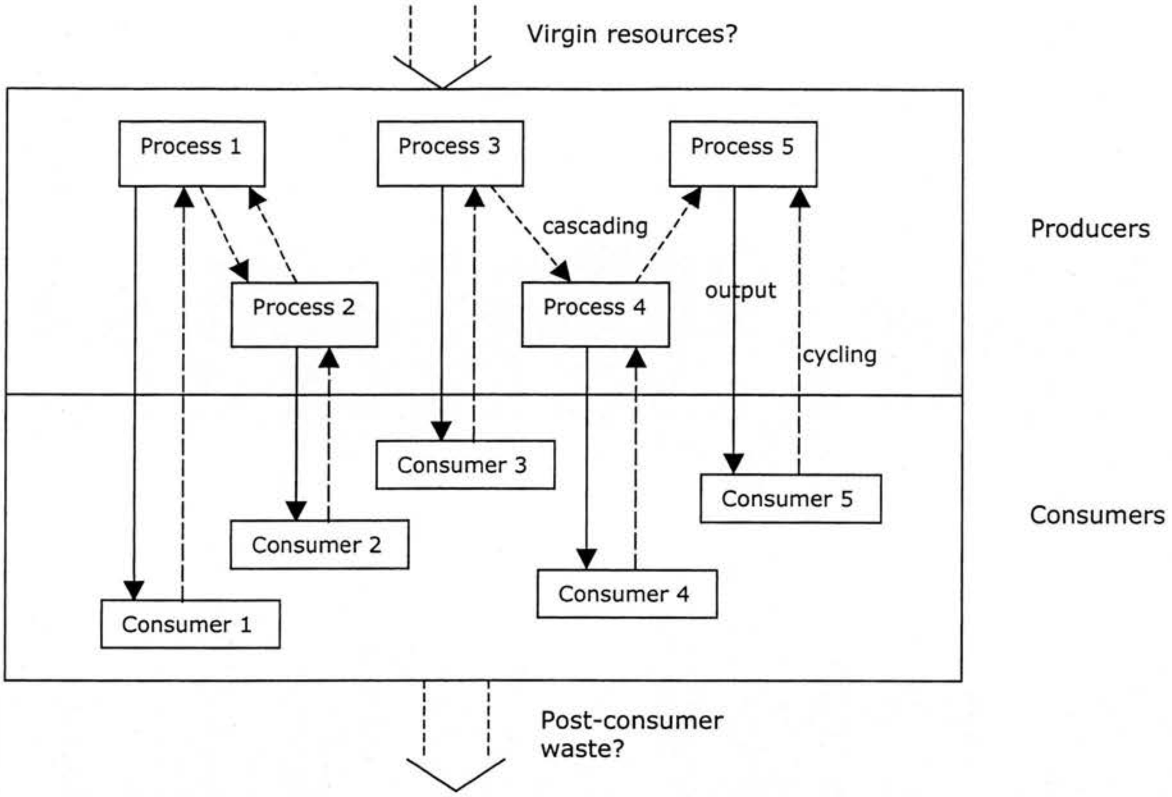

Figure 6.4: A perspective of cycling in an integrated producers-consumers ecosystem.

The assumption underlying the indicators proposed is that all industrial outputs, products, by-products and wastes will have to be subjected to tracking and accounting. Without material accounting and material flow analysis in and between industrial processes, cycling of output into input will not be possible to a meaningful extent, as these processes need to be coordinated for effectiveness. The effort of tracking and accounting, however, is very likely to be a major pressure on business enterprise, costly in time and financial resources, and thus a concept not expected to be embraced with enthusiasm by the business community. As discussed below for implementation of an ecological tax reform, this measure as well needs to be accompanied by appropriate government regulation, incentives and tax mechanisms in order to offset possible discrimination (and also the much-vaunted loss of international competitiveness) that might be brought about by this measure. The measures proposed, complete material flow accounting and the indicators for material cycling in industrial ecosystems, take their cue from input-output analysis, pioneered by Nobel laureate Wassily Leontief in the 1970s. Duchin (1992) took a first step in elaborating this analysis for environmental purposes, by incorporating effects of environmental protection measures. I/O analysis uses matrices of production relationships to obtain a national picture of economic activity and technological change. Critics of I/O analysis have contended, though, that the collection and arrangement of production data on a national level is a process too time consuming, cumbersome, rigid and static to incorporate change on a meaningful level. The sheer number and complexity of flows, they argue, defeats the purpose of analysis, as the data can only be handled retrospectively (data is at least five years old), so that recommendations for future developments cannot take the current *status quo* into account, affecting planning accuracy negatively.

It is proposed here that high data complexity, and related to it, the inability of handling data that are up to date, would not be so much of an issue if the system under analysis was not the entire economy any more, but a smaller subsystem, for example, an eco-industrial park. Input-output relationships of an industrial ecosystem would include the efficiency of industrial processes that transform materials into products, and also the inputs and outputs across the system boundary. If the industrial ecosystem comprises more than just the industrial production facilities that can be found in today's eco-industrial parks, one would observe a great proportion of material flows between producers and consumers within the ecosystem under analysis. The tools of complete material flow accounting will be effective especially in the more self-reliant bioregional systems discussed below.

At present, attempts at creating industrial ecosystems tend to revolve around power generation, mostly from fossil fuels, as in the Kalundborg industrial park. The "type III" goal, however, advocates the restructuring of *all* economic activity towards an overall circular nature of the economic system, with respect to resource use. If applications of Industrial Ecology are to be in line with this goal, industrial ecosystem structures need to incorporate all sectors of industry, and all sizes and types of enterprises. (The question of ownership structures in connection with the role of financial markets in the face of environmental and social aims is discussed below in the third section.) Industrial Ecology will be able to become a more viable method of achieving a sustainable economy only when a significant proportion of all post-consumer waste, together with intermediate wastes and emissions can be diverted from linear processes to be contained in cycles.

Resource cycling from outputs into inputs of the same quality as the virgin materials requires replenishment of their content of usable energy. In general, wastes are distinguished from resources by the fact that once pure ingredients are now mixed together to form less useful compound, and that their level of useful energy is much lower, if not exhausted. In order to separate waste compounds and replenish the individual resources' energy (mostly chemical energy), there must be a further expenditure of energy. This process in principle would happen in both cycling and cascading processes. The major distinction between the two lies in the amount of energy expended to revert wastes into usable resources: True cycling would require complete replenishment of the resources' usefulness, as they are looped back into the same input point, and therefore a high energy expenditure. Cascading, on the other hand, in order to render wastes usable for use in other processes that can be seen as "downstream" from an energy perspective, has a comparatively much reduced energy requirement. The cascaded wastes that serve as inputs in other processes do not make a significant contribution to reducing the sourcing of inputs from outside the system. It becomes clear that cascading is nothing more than increasing the productivity of virgin resources, but without the production processes becoming independent from virgin resources to a meaningful extent. A significant use of energy would have to be budgeted for if wastes were to revert to inputs that are of comparable quality to virgin resources, used in the same production processes.

The type of energy used in the replenishment processes of either cascading or cycling resources clearly has implications for the environmental impact of the whole process; would there be energy from non-renewable, renewable or continuous sources used? When Jacobs (1991) speaks of the cost of recycling, he touches on exactly this point: "The moral is simple: if we want to recycle more wastes, we have to use more energy" (p. 113). This traditionally has led to higher environmental degradation, for instance, CO_2 emissions from fossil fuels. Jacobs mentions the net contribution to pollution of recycling activities, thus possibly making recycling more a problem than a solution. According to Jacobs (1991), there exist two avenues for moving away from this situation; both these avenues are not mutually exclusive: Firstly, the throughput of the economy must be reduced. This could be achieved by utilising processes that do not require additional energy input, as is necessary in traditional recycling. Avoiding pollution is preferred to cleaning up after pollution has occurred. Economic activity today is strongly correlated to several indicators of pollution, e.g., CO_2 emissions. Thus, the proposition of throughput reduction contrasts sharply with the imperative of economic growth, as it is traditionally perceived. Increasing the growth rate of the economy in this way is directly coupled to the rate and speed of resources processed and waste produced, throughput in a linear system. The idea of reducing the throughput of the economy can be seen, however, as being parallel to a main characteristic from mature ecosystems, as discussed above in the third chapter: In the pioneering stage of ecosystem development, resources are utilised quickly resulting in high throughput rates in linear resource consumption patterns (food chains). In the climax or mature phase of a natural ecosystem, on the other hand, a maximum of biomass is sustained by a throughput rate that is much below that of a pioneering or developing ecosystem. This becomes possible as the mature system develops a complex network of many circular structures.

Increasing energy efficiency plays a role here as well: if reduction of throughput is set as the overarching goal, the pursuit of energy or eco-efficiency becomes a meaningful tool for attaining it. As was discussed in chapter 2, implementation of energy efficiency measures without a broader aim and framework leads to the opposite of the intended result - a decrease in the relative energy consumption per unit of output still leads to an absolute increase of energy used, via increased production and output.

The other method of avoiding the energy trap of cycling resources is the use of energy from continuous sources, chiefly solar energy in its direct (solar radiation) and indirect forms (hydropower, wind and wave energy). These sources are the only ones that have little or no pollution in use (cf. Jacobs 1991, p. 115), once the environmental impact of installing facilities for energy collection (e.g., solar panels) has been accounted for. This latter fact places continuous energy in a position very much apart from other sources of energy that require the burning or otherwise conversion of fuels (even from renewable resources), processes that inherently result in pollution and dissipation.

2.1. A sustainable economic system will resemble a climax ecosystem

From the discussions in this chapter and further above in previous parts, a pattern of organisation for sustainable economic activity emerges, sharing its basic characteristic of matter and energy processing with natural ecosystems.[46]

Before continuing, there is, however, the need to point out one important difference between the behaviour of human economic systems and that of natural ecosystems: The economic system is expected to be a perpetual and stable system for providing human beings with their basic or otherwise needs. Large fluctuations in its behaviour and structure, occurring often, would lead to severe negative consequences for human well-being, as they would disrupt patterns of economic activity, such as supply with the most basic necessities.

Contrary to this, all natural systems are part of the continuous dynamic pioneering-climax loop, where pioneering and climax system states supersede each other in the wake of external disturbances and reactions to them. This means that each climax system will be disturbed or even destroyed for a new pioneering system to develop, which then in turn will develop into a new climax state.

The economic system, subject to the limitations on resource and energy use set by the surrounding biosphere, therefore, needs to settle in the natural ecosystem equivalent of a perpetual climax state: there, it would not revert any more to a pioneering state, in which only a lower amount of biomass (in natural ecosystems; for the human system, human beings and their needs - carrying capacity - would be the closest approximation) can be supported on a given energy and resources budget. One could understand both the roots and the consequences of this reverting

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[46] The similarities exist in the circular nature of its processes with a continuous loop between producers (plants and other autotrophic organisms), consumers (all heterotrophic organisms), and recyclers (bacteria), all depending on the producers' ability to synthesise mineral resources and gases into organic molecules, driven by solar radiation. We cannot equate the producers and consumers of the natural system directly with those of the human economy, as industrial producers in the strict sense do not "produce" like autotrophic organisms do; industrial producers rather mobilise resources, by transforming them into a shape that makes them fit for consumption.

to a lower state in the human system as social upheavals, with often dramatic, and even violent outcomes. In order to be able to remain in a stabilised climax state, the human economic system cannot continue to grow in its use of natural resources: a system in climax state, by definition, is a non-growing system in a steady-state condition (cf. chapter 3). Moreover, continued growth in the use of natural resources in a "full world" scenario (Daly 1992) would prompt reactions from other systems, and these reactions, in turn, would impact on the human system, too. The impacts represent a disturbance on the human economic system, which, in the manner of any complex thermodynamic system, will react by reverting to a lower grade of organisation and efficiency, thereby coming closer again to a pioneering system state.

A sustainable economic system that would pertain to this perpetual climax state would assume characteristics of a more localised and self-reliant nature, only very rarely bringing in or getting out resources and products outside of its local or regional focus.[47] Some reasons for this claim would be the much reduced amount of transport and its environmental impact within those local or regional entities, and reduced duplication of economic efforts, as supply in a more localised economy can be much closer matched to demand (cf. section 2 of this chapter). Closer relationships between local social and economic actors in turn strengthen the whole system and make it more resilient against disturbances from outside.[48]

As discussed above in chapter 4, however, by advocating ecosystem-like structures one can very easily fall into the trap of imposing one's own mental constructs on the outside world. Trying to fashion economic activity "after the image of nature", which derived "from projecting onto nature what the author wanted to believe anyway" (Simmons 1993, quoted in Trudgill 2001) turns out to be an endeavour based on a tautology.

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[47] In current reality, the economic system is bound on a very different trajectory of development, of opening more and more local and regional units to global economic transactions (cf. the preceding chapter).

[48] For example, a new competitor arriving in a locality and threatening to extinguish currently active businesses. This would be more difficult, as the new entrant would not easily achieve the integrated relationships with other businesses and consumers that established ones have already engaged in.

The natural ecosystem analogy could be one of these constructs having exerted its thrall thoroughly in the discipline of Industrial Ecology.

It is Trudgill's assertion (Trudgill 2001) of improving the adaptability and flexibility of human systems in the face of limited predictability (rather than the harking back to supposedly sustainable living conditions of some societies in history, cf. Welford 1995) that can be taken as a justification for the proposal of a more regional and decentralised organisation that is more likely to contribute positively to the sustainability of human systems. As Faber et al. (1996) remind us in their essay on "surprise and ignorance", increasing predictability beyond a certain limit is inherently impossible, as there exists "irreducible ignorance", that is, future events that cannot be anticipated at all. Faber et al. discuss the attitude of "openness, creativity and flexibility" (p. 229) as an appropriate response. As a non-flexible measure in the energy sector, they mention the introduction of nuclear power plants.

Arthur's (1988, 1993) and Allen's (1996) research into the behaviour of complex systems, especially social and economic systems, call for the recognition of development trajectories and probability landscapes. "Lock-in" and increasing returns (instead of the diminishing returns of standard economic theory) of a predominant structure or organising principle occurs when it has reached a critical mass of support or adoption.[49] These standards, once they are centrally adopted, become the backbone of socio-economic organisation: their "hardwiring" renders them virtually impregnable to change. Therefore, policy-making for socio-economic organisation with sustainable development in mind needs to be aware of the pitfalls of standardisation and resulting centralisation of socio-economic activity.

Hence, it is smaller-scale and decentralised socio-economic structures that Trudgill (2001) may have had in mind when calling for an improvement in adaptability and flexibility of the structures of human society, as centralised operations are less flexible than decentralised ones - this is especially true in the areas of business enterprise in manufacturing, and energy production, as mentioned above.

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[49] Examples abound in industrial development, ranging from the "qwerty" keyboard to motorcar dominated transport infrastructure, centralised electricity generation from fossil fuels, and the emergence of the VHS video cassette standard in the early 1980s.

Borgström Hansson and Wackernagel (1999) discuss bioregional structures in socio-economic development under the strategy of re-embedding, arguing that the expansion of the human economy within the biosphere has become a phenomenon largely unnoticed. This is due, they point out, to the "disembedding" of human systems, by populations from their local ecosystems, helped by substitutability of resources and waste assimilation capacity.

Brunckhorst (2000), an ecological scientist, approaches this issue from the basis of the "biocultural landscape" as a defining concept. The reason for recognising and engaging in bioregional organisation, thereby "integrating human governance with ecological law" is, in his opinion, "an operationally pragmatic" one that is seen, similarly to Borgström and Wackernagel (1999), to match "functions and requirements of culture and society with ecological processes, services and functions" (p. 31).

To summarise, the concept of bioregional organisation has come to the fore as a pragmatic alternative for future infrastructure development. Avoiding a romantic and largely discredited picture of tribal societies living off the land in a sustainable manner (the fates of the Maya and the neolithical Indus culture disprove such a proposition), local and regional socio-economic organisation is resonant with Industrial Ecosystem structures that integrate producers and consumers into networks containing a very high degree of all resources needed in cycling loops.

3. Changing economies of scale – synergies between implementation of an ecological tax reform and development of industrial ecosystems

From a solely material perspective, the overall quantity and character of resource and energy use needs to be changed, but this cannot be achieved by technological development alone. As history has shown us, technological change leads to social and political change as well. Any new technology consequently needs to be contained in a social, political and economic context for evaluating its role with respect to bringing about sustainable development. It is also for this reason that sustainable development is built on the three themes of environmental quality, economic prosperity and social equity (Elkington's "triple bottom line"[50]).

The section's purpose is to draw attention to the potential long-term consequences of government policy-making for socio-economic organisation - here in the case of fiscal incentives in the example of an ecological tax reform helping to bring about wider societal changes in the form of restructuring into industrial ecosystems. This gradually increasing tax burden on fossil fuels (or alternatively, on all fuels resulting in CO_2 emissions) has the potential, owing to its timescale of more than a generation and its steadily increasing nature, to link together different corporate approaches to environmental pressures: Eco-efficiency, suspected to be nothing more than an elaborate smokescreen for carrying on with business-as-usual (cf. Welford 1998), will thus be transcended and give way to a different mode of organising production and consumption systems. Furthermore, an ecological tax reform can be seen as encouraging the notion of complete cycling, which was advocated in the previous section as the implementation of a "type III" condition for industrial ecosystems.

The section commences with a description of an ecological tax reform, its remit, and its direct effects on fuel consumed. The immediate costs and benefits of adopting an ecological tax reform are much discussed[51], including the question of the "double dividend"[52] (the benefits of both removing existing and inefficient tax distortions, and improving environmental quality), what is lacking in that discussion, however, is the long-term perspective for the development of an infrastructure with reduced environmental impact, which this section will address. In the following part the implications of a change in fuel consumption are discussed with respect to different time frames. The implications of that change in fuel consumption for industrial

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[50] cf. Elkington (1997).

[51] e.g. Weizsäcker & Jesinghaus (1992), Costanza et al (1998), Bach et al (1994).

[52] O'Riordan (1997) devotes five chapters of his book to the double dividend question, exposing its contentious nature. As it is not in the scope of this section to discuss this problematique in great detail, the interested reader is referred to the above publication. The author prefers the term "double leverage" which is used from here.

organisation will then be discussed with respect to different economies of scale to be found in the present industrial system (focusing on manufacturing) and in industrial ecosystems. The last part will consider the synergies between a long-term structural change and the effects of an ecological tax reform over such a time period.

3.1. The basic mechanisms of an ecological tax reform

An ecological tax reform comprises a bundle of measures that are aimed at restructuring the costs of economic activity, in particular industrial production. An important part of this proposed tax reform package is taken up by an energy tax that will place a higher tax burden on that energy use derived from fossil fuels (or from the fuel's CO_2 emissions in the case of renewable combustibles). Apart from this carbon tax, an ecological tax reform could include other measures of environmental taxation as well. Studies so far, however, have focused on taxes on fossil fuels, as they may have the biggest fiscal impact, the anticipation of which creates much controversy around a carbon tax. The ensuing discussion consequently will be solely concerned with a tax on fossil fuels as the main measure employed on the revenue side of an ecological tax reform.

As a compensation for the higher tax burden on fossil fuels, policy proposals stipulate that tax rates relating to value added, labour or corporate profits be reduced accordingly. This overall revenue neutrality is the reason why this tool is a tax reform, rather than merely an eco-tax. It is not intended to increase a government's tax revenues, but to create leverage for providing incentives for alternatives of fossil fuel use. However, the debate currently focuses on whether and how revenue can be shifted from one source of taxation to another, the implications being firstly that existing tax distortions would not be reduced, but moved and even exacerbated, and secondly that the government's hands would be tied by pre-assigning tax revenues to expenditures (earmarking). The supposed economic benefits of this shift in tax burden, the "double leverage", are assessed and valued with widely varying results in the ongoing discussion among policy-makers and academics. This article will only touch on that particular discussion where integrated transport systems are concerned.

Under an ecological tax reform, taxes on fossil fuels will be raised in a long-term and harmonious scenario, for example by 5% annually over the next 40 years.[53] This scenario provides stability for an estimation of future costs of energy use, a stability that is an incentive itself to engage in planning and implementing alternative ways of using energy.

As mentioned above, economic activity, if measured by turnover of the economy, is strongly linked to the consumption of energy[54], of which fossil fuels still make up the lion's share. If precisely that lion's share became the subject of gradually rising energy taxes, the nerve of economic activity in its present form could be hit: introduction of a carbon tax in one country would result in its products and services becoming more expensive and this therefore could lead to a loss in international competitiveness. In the absence of harmonisation across the European Union, for instance, any government wishing to introduce a carbon tax would be bound to support its domestic industries in other ways (e.g., subsidies)[55]. Furthermore, as a change in the tax system would lead to industrial and social change, such measures need to be introduced with a view to accommodate that change. The UK government was reminded of this relationship by the "fuel protests" in autumn 2000.

In order to have economic activity continue at least at present levels, if not grow, incentives have to be set to achieve delinking of that activity from fossil fuel use and CO_2 emissions. This is the aim of an ecological tax reform, and consequently, lowered rates of VAT, income tax, labour costs, and/or corporation tax would be those incentives. All of the aforementioned are part of an ecological tax reform's "double leverage": both the revenue and the expenditure side are integrated to shift tax burden towards undesirables (material and energy use, pollution), and away from economic desirables (employment, value added).

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[53] Weizsäcker & Jesinghaus (1992), p. 54.

[54] It is even suggested that instead of the delinking some researchers have observed, that energy throughput since the late 1980s has exceeded growth in GDP of some advanced economies - in other words, relinking has occurred (cf. de Bruyn and Opschoor 1997).

[55] Studies by Barker and Lewney (1991) and Wubben (1999) conclude that national competitiveness in general does not seem to become adversely affected by environmental regulation or increasing energy costs.

GDP could still be strongly correlated to the use of renewable energy with no pollution consequences (ultimately, solar power), or, instead of measuring material production and consumption, it could become an indicator for creating, handling and applying information.

3.2. Shifting transport away from the road and reducing its amount altogether

Examining the revenue side first, an ecological tax reform has two effects on fuel consumption: Rising prices for fossil fuels lead to a substitutional effect of these fuels being replaced by renewable ones (cf. Figure 6.5). This may result in some freight traffic on the roads being shifted to waterways and the rail, for example. For the time being there does not seem to be an alternative to the internal combustion engine for person transport or freight on the road in a large scale. The substitutional effect results in a change of the means of transport or the energy source used, but the overall quantity of transported goods would not necessarily be affected.

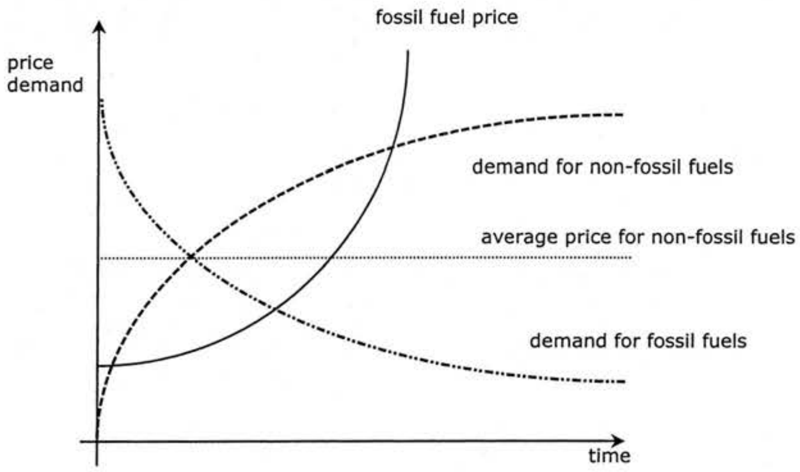

Figure 6.5: The substitutional effect of rising fossil fuel prices.

The second effect (cf. Figure 6.6) is a quantitative one: the ecological tax reform will provide economic incentives for decreasing overall transport costs (or countering an increase) by decreasing the demand for fossil fuels. This means either that fuel efficiency per ton transported would increase, or that the necessity of transport would have to be re-evaluated due to high fuel prices. That could mean, to mention an oft-quoted example, that there would not be any more bakery vans from

Edinburgh bound for London and vans from London with the same produce bound for Edinburgh passing each other on the motorway at York.

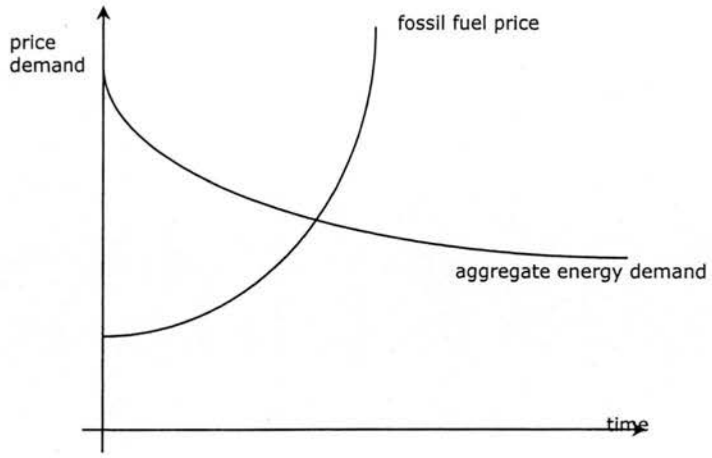

Figure 6.6: The quantitative effect of rising fossil fuel prices.

Both effects, the substitutional and the quantitative one, will occur at the same time, and they would be correlated in such a way that would make it very difficult to disentangle them from each other for analysis. For example, even if the substitution effect results in phasing out fossil fuels in favour of renewable ones, the overall cost of transport would be very likely to be higher due to the altogether higher niveau of fuel prices. Although renewable fuels would become more competitive, as prices of fossil fuels rise steadily, transport costs would take up a higher proportion of the overall costs of production and distribution. Price elasticities would result both in an increase of fuel efficiency and in a reduction in the quantity of goods transported, which would be sourced, produced, marketed and consumed more locally.

To summarise, the ecological tax reform will mainly result in two reactions in behaviour on the revenue side:

1. Where fossil fuel is necessary, it will be used with the highest efficiency possible. Consumption of fuel per tonne-kilometre (and person-kilometre) will decline, and transport will see a decrease in tonne-kilometres overall.
2. Where energy is necessary, it will not only be used with the highest efficiency, but also embodied in those energy carriers with the lowest global warming potential. These energy carriers only become more competitive compared to fossil fuels. As they do not become cheaper overall, they provide an incentive to reduce transport altogether as well.

These direct effects will give rise to indirect ones; for example, logistics systems with much improved transport efficiency. Furthermore, products and services with a high amount of embodied energy will be affected as well (e.g. recycling of metals increasing, energy-intensive virgin resource extraction decreasing).

In order to bring about the "double leverage" and also to render the ecological tax reform fiscally neutral, the expenditure side of it must be integrated with the revenue side and existing distortions diminished: Lowering taxes or offering subsidies to means of transport that are less fossil fuel intensive, modes of production and distribution that are less energy-intensive (including less transport and capital-intensive and more labour-intensive). An example for abolishing a tax distortion would be the reduction of VAT on energy saving technology.

3.3. Five different time frames

How do the quantitative and the qualitative effect of an ecological tax reform result in changes of economic activity over time? The question of predicting price elasticities becomes a more complex one if viewed from a longer-term perspective rather than a short-term one. In the following, the short, medium and long-term changes in fuel consumption are discussed which an ecological tax reform may bring about. After an outline of Weizsäcker and Jesinghaus's (Weizsäcker and Jesinghaus 1992) position that the discussion will use to build on, it will revolve in greater detail around structural changes in the period with the longest time frame. Both the quantitative and qualitative effects of the ecological tax reform on fuel consumption play an important role here. Long-term changes incorporate short-term changes in a development path, but for a specific long-term change to come about, the specific one of those short-term effects whose development path leads to the desired long-term effect has to be encouraged by the legislative framework: this is the reason why there is a need to elaborate long-term changes and to encourage the most desirable one by appropriate government regulation.

Change will always incur costs of reallocation. A cataclysmic change will simply be costlier to the entire economy than a gradual one. There is, however, something to be said for putting off change for as long as possible: inevitably, new structures will hardwire a specific use of energy. As technological progress continues, new and better ways of energy use may become available (breakthroughs in harvesting renewable energy, e.g. solar, wave, and geothermal power). It is of paramount importance, then, not to repeat the mistakes of the past, where the whole economy was built around one single source of energy, namely subsidised fossil fuels, and the resulting infrastructure was not expected to change anymore.

In the immediate time frame, the first of the five analysed, gradually rising fuel prices will mainly have a quantitative effect, as less fossil fuel will be consumed. Weizsäcker and Jesinghaus compared the effects of an ecological tax reform to the effects of the oil crisis in the late 1970s. This first period reflects the immediate future after prices rose, and quantitative effects then amounted to energy savings of 10-20%, where existing equipment was just used less.

The second period will give rise to cost-benefit-analyses of existing machines or vehicles not yet at the end of their use period, compared to the ones with the highest fuel efficiency currently available on the market, probably leading to first decommissions and new investment.

As the fossil fuel prices affected by the ecological tax reform will be transparent for a long time period, immediate investment decisions of the first and the second period will favour machines or vehicles that have a higher fuel efficiency, and that are already being marketed. These investment decisions only cover the replacement of machines or vehicles that have reached the end of their use periods.

In the third period, further rising fuel prices will provide a strong stimulant towards research into and development of types of machinery with much higher fuel efficiency.

From now on, the high level of fossil fuel prices will have effects on the systems level: in the fourth stage whole transport systems will be reviewed as to their fuel efficiency, and the development of systems that do not use fossil fuel any more will be favoured. Only in the fifth stage the underlying purpose of the entire transport system comes under scrutiny, as industrial, commercial and residential infrastructure will be newly planned. Forecasts include not only low-energy housing, but also areas with a mix of residential and industrial/commercial property, where persons transport may be by bicycle, even in sheltered bicycle lanes.

But there is more to this fifth stage than just the elimination of individual transport by fossil fuel powered cars, and this is where restructuring into industrial ecosystems fits in: Companies will move closer not only to their workforce (and vice versa), but also to their markets. Central warehousing by then will have become so expensive, that there will be a drive towards local production for local consumers. A further step involves companies' closeness to their suppliers and their resource base as well, where possible. The whole socio-economic system will aim towards a new balance where as little transport as possible is necessary for production, marketing, allocation and consumption of goods and services. It is particularly the latter, the service industry, that will see a higher growth rate than manufacturing, due to the fact that services, most of which embody a significantly lower proportion of processed materials, differ from manufactured goods, in that they are demanded and created locally. We can see from the envisaged fifth stage that the pursuit of eco-efficiency does not have to be a technological device that is employed for wrapping a green cloak around a grey core of business-as-usual.[56]

In order to understand the significant impact of an ecological tax reform, especially in its latter stages, on industrial organisation, the analysis has to take a look at the area where most fossil fuel is used: manufacturing and transport of goods. In the manufacturing industry and its related activities of resource extraction, processing, end-consumer sale, and possibly recycling, economies of scale in each of these characterise economic activity here.

The above discussion of economic development rests mainly on the increasing cost of fossil fuels, which is but one of the two sides of the ecological tax reform - the revenue side. Depending how the increased revenue is spent on the expenditure side, the leverage toward the desired development can be increased. Earmarking (hypothecation), however, while rendering the ecological tax reform more transparent, leads to problems once it is tied in with fiscal neutrality, which makes the tax reform more politically acceptable: The revenue side of the tax reform will most certainly show different dynamics than the expenditure side (e.g., reduction in VAT, employers' national insurance contributions, corporation tax). This situation can be solved by achieving fiscal neutrality not year after year, but within a larger timeframe, so that borrowing from or saving to this budget item becomes possible.

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[56] cf. Welford 1998.

3.4. High-risk, high benefits: current economies of scale in manufacturing

Building on the previous part, this chapter will present a brief outline of the predominant system of sourcing, manufacturing and distribution. These basic characteristics are seen to describe industrial production both on a national and on a global level. Insights into this system of industrial production from a systemic perspective will point towards the advantages and problems of system changes due to the adoption of an ecological tax reform.

Conventional industrial production in general is characterised by the following factors:

1. Mass manufacturing
2. Cheap transport based on an abundance of fossil fuels

The move of industrial producers towards global markets can be seen as prompted by the potential to increase sales and to produce on a larger scale. Initially, manufacturing companies were just trying to escape the narrow boundaries of regional or national markets and their competitors, and the markets outside their home turf were regarded as undiscovered land. This perception resulted in the first wave of globalisation: companies set up sales offices all over the world and stepped up production at home to cater for the increased demand abroad. However, nowadays, some fifty years later, the global market itself has become the chief arena for industrial production and distribution. Traditionally, the markets outside the national one depended on how the producer was faring selling his goods in the national arena. Now this relationship is inverted: Standard consumer goods have to be marketed successfully worldwide to be successful in domestic markets.

This scenario affects industrial production even further. The potential to serve a global market enables the producer to pursue economies of scale in sourcing, producing and distributing. Large-scale warehousing and transport have become essential requirements. Furthermore, the economies of mass production can support substantial outlays of research and development, resulting in and accelerating technological change. The aforementioned inversion of the relationship occurs; as noted earlier with global markets bearing down on national or regional ones, technological change, once accelerated by increasing R&D, becomes the driving force itself to which industrial producers have to adapt. Together with it, pressure and speed of competition accelerates, driving those producers out of the markets who cannot keep up with the rate of technological change. Although having beneficial effects, technological change can very often degenerate into giving rise to ever more sophisticated "techno-gizmos", developed mainly for marketing purposes to best the competition.

Economies of scale enabling costly R&D, together with ever more costly R&D (dictated by competitive pressure) requiring ever bigger economies of scale: this spiral describes the coevolving system leading to higher degrees of concentration in various manufacturing industries. Mergers and acquisitions, and hostile take-overs, a mass movement since the early 1980s, have been creating ever-bigger companies in a whole array of industries.

These companies' markets, due to increasing economies of scale in production and dissemination of global advertising, become more homogenous, so that companies can apply global market selection for devising marketing strategies for their target markets.

Homogenous markets can be served by standardised products. This is the reason why competitive battles for establishment of a market standard can have grave consequences for those companies whose products do not achieve a dominant position in the market. And in the present economic system, it is not only just the company in question losing a competitive battle: all the stakeholders associated with that company - investors, employees, customers, suppliers, local communities, local enterprise companies granting start-up aid - take a share in that loss.

The concept is not unchallenged: indeed, research into economies of scale of growing multinational corporations has found that the link between higher market share and profitability is only an intuitive one, but cannot be generally accepted as correct, as there are too many examples to the opposite: the classic tool for portfolio analysis, the "market share – market growth" matrix, created by the Boston Consultancy Group in 1969, has after a long and popular existence become sidelined, as its fundamental assumptions have been found flawed:

First, there is the observation that many businesses thrive as long as they are small. Once growth beyond a certain point is embraced, profits fall: traditionally, the response has been to advocate further growth in sales in order to claw back, presenting a classical lock-in situation (cf. Arthur 1993).

A simple example for the possible pitfalls of growth can be found in the computer industry, which at present is stratified into the "big five" computer manufacturers Compaq, Hewlett-Packard, IBM, Dell and Gateway with an international scope to their business, and the very large number of small ones with a national and regional scope. The reasons for the recent merger of Compaq with Hewlett-Packard and the troubles of Gateway are an illustration of the plight of the industry in the top tier at the moment - an assessment not shared by the smaller manufacturers that are supposed to be weaker financially and therefore less independent with respect to their decision-making.

Companies that grow beyond a certain point enter a different corporate environment and competitive situation: Bigger companies that serve bigger markets attract competition not only to their products, but to their financial assets as well. These are accessible via takeovers through the international financial markets, if the companies in question have a public limited legal entity.

These much sought after economies of scale and the resulting global competitive pressure, although under attack from academics and some practitioners, have become an entrenched perspective with some ideological leanings. They are pursued by the management of the majority of large business enterprises as a standard strategy.

Economies of scale in the current economic environment depend mainly on transport costs that do not reflect negative externalities of transport itself: thus concentration and centralisation of industrial processes becomes financially viable. The feasibility of large-scale transport subsidised by relatively cheap fossil fuels is bound to be re-evaluated under an ecological tax reform. How would a supposedly sustainable industrial system process resources and energy, compared to the system just described?

3.5. Different economies of scale in integrated producers-consumers ecosystems

A future sustainable system of industrial production might employ the same structure as natural ecosystems do: the most important characteristics of a natural ecosystem are symbiotic relationships on any level, from inside a single cell to an ecosystem-wide symbiosis between species (and possibly between different ecosystems as well, the result being the supersystem referred to as Gaia , cf. Lovelock 1989). It is symbiotic structures like these that need to be encouraged for restructuring into industrial ecosystems. Natural systems are the only sustainable systems known so far. What seems to make them sustainable is the absence of waste and the closed-loop structure between producers, consumers and recyclers, where nutrients are merely transformed and cycled between different species, and not used up. Nutrients are mainly used and cycled locally, so that there are no huge stockpiles of unwanted resources. Availability of nutrients strongly influences the level of biological activity, which is fuelled by solar energy captured by and embodied in biochemical molecules.

Restructuring of industrial systems in a similar fashion would lead to the creation of integrated networks of production and consumption between manufacturers and households, rather than linear input-process-output-waste relationships (cf. section 1). Such networks would emphasise local integration rather than globalisation, and their stable structures balancing competitive forces by symbiotic/cooperative ones. The ensuing, reformed socio-economic system produces very little waste and exploits virgin resources only to a low extent, and thus is self-reliant to a high extent. The high degree of local integration and a focus on the community would lead to a much higher transparency of markets (due to more direct and increased two-way communication) and thus to reduced risk, benefiting producers.[57]

Economies of scale in such a system would be markedly different from the ones sustained by subsidies on fuel prices. In the present system, economies of scale can

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[57] As was established in the first chapter, creation of industrial systems in the fashion of natural ecosystems, has had for the time being a technocratic ring about it. This thesis is built on the understanding of industrial ecosystems as incorporating households and other consumers of industrial products and services, thus going further than a traditional industrial production system that might exhibit chiefly a higher resource efficiency. Extending the natural ecosystem metaphor to all participants of the socio-economic system transcends merely technological change and embraces a social dimension, in a very similar way that Jackson and Roberts understand ecological modernisation as cultural politics (cf. Jackson and Roberts 1999). Both concepts are thus resonant with the three pillars of sustainable development, environmental quality, economic prosperity and social equity. It would probably help to distinguish "socio-economic ecosystems" (that embody the social and political perspective) from the industrial ecosystems with a more technological emphasis.

only be established after considerable financial outlays for initial R&D and competitive positioning towards control of that product's global market. In integrated producers-consumers ecosystems, "control", that is, an understanding of customer needs and access to the market, can be attained without corporate battles. Due to the focus on a smaller scale, an ecological niche approach for business might contribute towards easing the need for a global race for competitiveness. The lower risk in creating, accessing and serving a local market[58] is offset by lower returns, as economies of scale in manufacturing do not play a significant role. In their place, one will find economies of scope or efficiency with very much reduced wasting of corporate resources, financial and material ones, in industrial production. These economies of scope arise from synergy effects created by a higher integration of functions within producers, and a closer relationship of producers with their consumers. Companies in such an arrangement of close proximity can understand customers and their needs better, and consequently exploit the competitive advantage of a higher scope for product adaptation towards specific and local customer needs. Through this measure, the individual company and its surrounding ecosystem would be in a position to strengthen themselves against competition from far away, be it from national or international competitors. Looking across to natural ecosystems, one can find similar integrated organisation structures: in those ecosystems, there is a myriad of niches that are all occupied by highly adapted organisms. In a healthy system, these would not grow unchecked, so that they would be in danger to both become the one dominant species in the system and simultaneously destroy their own basis for existence and that of many other ecosystem participants. This relationship is one of negative feedback: organisms keep each other in check and thus let each other flourish at the same time.[59]

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[58] A local market here is understood to be a basic unit of aggregate demand for distribution of products and services, e.g., a city and its surroundings.

[59] There are worldwide only very few organisms that can be described as omnivores thriving on a wide range of foods and at the same time having no or hardly any natural enemy who keeps them in check. Humans are now the one exceptional species in this respect, overcoming limits both in their nutrient basis and in their reproduction. The point of the discipline of ecological economics has been to point out that human beings are not an exception to all other species: they are the ecosystem participants growing out of scale and thus being in danger to destroy the whole system.

Arguably, both approaches have the same expectancy value, the high-risk, high-return model of large-scale production and the low-risk, low-return one of an ecological niche[60]. An ecological tax reform will aid to establish limits to the scale of production, as the local market is easily served and the threshold of higher transport costs to penetrate markets further away has to be overcome. Those corporate resources devoted to pursuing economies of scale could instead go into increasing efficiency and more closed loops in production and consumption, or expansion by creating new local production facilities somewhere else.

Implementation of an ecological tax reform can play a valuable role in encouraging the complete cycling of outputs, and preferably so in a local fashion: companies would locate closer to their customers, the consumers - the benefit being that the costs of reallocation of materials would be much decreased. As one company's output nearly equals its input, it is facing less costs of market allocation and storing, and also decreased costs because of a better match in capacity, of local supply to local demand.

Overall, such systems will offer a higher degree of security for their participants with a much lower frequency of destabilisation. There would not be the danger of a global player pulling out, for economic and political reasons that are unrelated to the company's performance in that local market.

3.6. Why can an ecological tax reform yield a change in infrastructure where rising fuel prices of the oil crisis did not?

The crucial difference between measures to curb petrol consumption in the years of the oil crisis that Weizsäcker and Jesinghaus describe and an ecological tax reform is its long-term perspective and the fossil fuel prices rising in a transparent and predictable manner.

Whereas the oil crisis mainly prompted short-term reactions in government decision-making, that is, in the scale of 5-10 years, and the measures (car-free Sundays, more detailed information on cars' fuel efficiency etc.) were largely

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[60] There might be, however, a dilemma in the shape of the "Tragedy of the Commons" arising, when companies would be unwilling to shift their focus from a global to a local approach, for fear of vacating space that will be filled by their international competitors.

abandoned after fuel prices relaxed again, an ecological tax reform presents industrial producers and household consumers with a stable scenario for the next two or three decades, if not the next 50 years. Furthermore, the increased revenue for oil in the 1970s went to the oil companies, whereas the revenues of an ecological tax reform would be used to lower taxes on labour and value added.
This should be the main difference why Weizsäcker and Jesinghaus could only observe short to medium term solutions to the increase of fuel prices in the 70s[61], and not long-term solutions which could be expected under an ecological tax reform. They assumed long-term structural changes coming about when the potential of incremental adjustment had been exhausted, and a breakthrough was needed (cf. Figure 6.7).

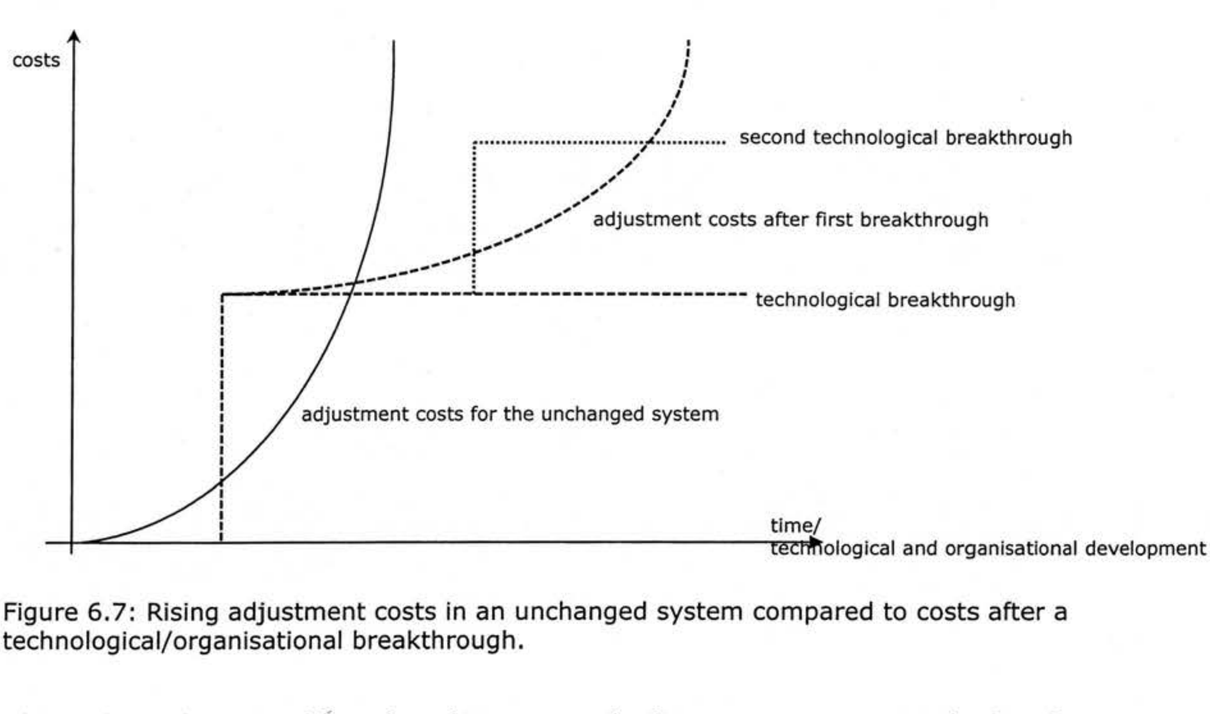

Figure 6.7: Rising adjustment costs in an unchanged system compared to costs after a technological/organisational breakthrough.

This ceiling of marginal benefits of incremental adjustment was not reached in the oil crisis. In the ecological tax reform's perspective of increasing fuel prices by 5% annually over the next 50 years, it would be much easier to plan and implement structural changes in a long-term perspective now, right from the beginning, as the

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[61] cf. also Neuburger 1992, who uses that point against the usefulness of an ecological tax reform, fails to realise the planning implications of a planned and harmonious rise in fossil fuel prices, and furthermore does not consider the leverage effect of the ecological tax reform's spending side, despite a statistical analysis of the demand of energy relative to its supply price.

factor under consideration, fossil fuel prices, is behaving in a stable way. In that sense, it should also be considered whether the tax would be rising steadily, or the price of the fuels. The former would still leave fuel prices open to fluctuations of world market prices and would reduce predictability of the fuel price scenario. The latter option, however, would yield the benefit of highly predictable fuel prices for consumers and industry, but fluctuations in the tax revenue, to accommodate changes in world market prices.

In any case, in the course of a predictable, ideally monotonous price rise, a ceiling of incremental adjustment will be reached and exceeded with certainty, which will make structural redesign a necessity. Hence, structural redesign would not have to be phased in only when that ceiling came closer, but can be taken on now.

The crucial point, however, is the "double leverage" of the connection of the ecological tax reform's revenue side with the expenditure side that will have more profound effects than the rising fuel prices of the oil crisis years, as the tax revenue will be used to make possible and assist in the wider changes needed for transition to a sustainable society.

3.7. An ecological tax reform facilitates long-term sustainability planning

In addition to the stable price scenario an ecological tax reform can provide, there are substantial financial advantages in employing a long-term perspective and subsequent planning early on:

Firstly, the earlier new components of infrastructure, allowing a decrease in fossil fuel consumption, will be implemented, the less expensive they will become to set up, as the whole system will not have developed as much lock-in as in later situations[62], for example become dependent on a specific technology. These costs have to be compared with the opportunity costs of doing nothing and leaving the system to itself: at the beginning the restructuring costs will be significantly higher than the marginal abatement/adjustment costs without structural changes. As time progresses, however, one would observe a sharp rising of adjustment costs as the ceiling draws nearer, whereas on the other hand the restructuring costs would either remain constant or even fall, as research will result in new achievements and

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[62] cf. Arthur (1993).

offer economies of scale, and implementation efforts devoted to the new structures will spread more widely.

Moreover, there are considerable financial benefits to be reaped from the much smoother transition from conventional to sustainable structures, as adaptation costs (due to a shallower learning curve and higher time reserves) would remain as low as possible.

Having said that, there is one argument in favour of "wait and see": Early efforts to restructure are more likely to be fraught with imperfections, as new infrastructures and technologies are implemented while still being tried and tested. Technology will move on and provide radically new and efficient solutions. Committing to the best available now could result in being locked in with that technology or that specific way of organisation, just in the same way Western economies are locked in the present system with its centralised infrastructure of manufacturing and energy production, dependent on subsidised transport. Countries benefiting from adapting their structures later than others and learning from experience elsewhere will certainly comprise some developing countries, but also countries at the periphery of the European Union such as Greece, Spain and Portugal.

This is true not only for the current socio-economic system, but also, and more importantly, for any newly emerging one. Technological development will not halt at a system that today would represent a major step towards sustainability. Hence, even the new infrastructure will have to be flexible enough to be adapted when better technical solutions become available. It certainly seems easier to adapt small-scale, decentralised structures in the fashion of industrial ecosystems than large-scale centralised ones.

4. Modes of corporate ownership and control, and their relationship to industrial ecosystem structures

Industrial ecosystem structures like those advocated in sections 1 and 2 of this chapter are characterised by close cooperative relationships of the participants with one another on a local and regional level, thereby eliminating much of the need for excessive long-haul transport, often resulting in oversupply and costly duplication of production.

Together with this change of strategy towards a more local and self-reliant perspective, there needs to be an appropriate corporate and organisational structure of the participating companies to go with that strategy. This recognition comes from the field of strategic management, where it has assumed a paramount position: the "structure - strategy" debate has kept the field occupied since its inception four decades ago (cf. Chandler 1962). The basic tenet of that debate holds that a business enterprise can only be in a position to execute a specific strategy successfully if it has in place appropriate structures for doing so. Industrial ecology has so far placed emphasis on the nature of relationships between companies with each other, and between companies, households and public agencies, but it has not contemplated their internal structures, and the possible changes that might have to accompany the change in external relationships towards a more integrated local economic system.

The most important structural element having an impact on the behaviour of a company that might be possibly engaging in industrial ecosystem behaviour is its legal and financial framework: who owns and controls this business, and what degree of strategic and financial independence does it enjoy?

The crucial factor playing a role in a company's legal and financial situation and impacting on its strategic outlook, in this researcher's opinion, is the public availability of their shares or no.

There are companies assuming limited liability whose shares are publicly available and traded on national or international stock exchanges (public limited companies), and those whose shares are not publicly available, as they are held by a small number of private individuals, very often the company's directors (private limited companies).

The question of corporate ownership impacting on corporate strategy has not received much attention in the number of academic fields that concern themselves with the behaviour of companies: Carmen and Lubelski (1997) consider this question an essential one that is ignored by the field of business ethics.

The case of the public limited company entering into local relationships will be considered first. Employed here is the Anglo-Saxon concept of a public limited company, which in theory is no different to its counterparts in other countries. In reality, the behaviour of a public limited company depends on the stance of its majority shareholders – in the case of the UK, these are large insurance companies and pension funds, and in the example of Germany, the major banks.

In Anglo-Saxon economies, public limited companies are bound to deliver the maximum shareholder value. These companies' fiduciary duty to their shareholders has been asserted in court case threats (e.g., the shareholders of the ice cream maker Ben & Jerry's, cf. Bey 2000). Insurance companies and investment funds, the large shareholders of Anglo-Saxon public limited companies, invest in shares because they expect a high return on their capital outlay in a short-term perspective, as money is free to flow worldwide towards the best investment opportunity nearly instantly. For German public limited companies the picture is slightly different: their largest shareholders are the major German banks, who hold a controlling interest and have representatives on the public limited companies' board of advisors. In contrast to Anglo-Saxon shareholders, these banks have a long-term interest in the companies they hold. The coalition of banks with large public limited companies thus renders the German corporate system closer to the South Korean *chaebols*, comprising large companies that form clusters of ownership.

In the case of Anglo-Saxon public limited companies, unfettered exposure to the short-term interests of the financial markets means that these companies are constrained in their choice of strategy towards options that are in line with that financial perspective. Returns on investment that are either too far in the future or that cannot be quantified are then a weak justification for substantial outlays of capital. In the United States in particular, corporate health is measured in quarter for quarter results, where profit warnings have an immediate impact on share prices. In Germany, the situation of longer-term stability for public limited companies has been starting to change in the wake of the takeover of Mannesmann by Vodafone Airtouch plc: the concept of shareholder value is beginning to take tentative roots in that country as well.

Companies in such a legal and financial situation do not in general make good candidates for local integrated structures such as industrial ecosystems. The latter require stability in the development of waste exchanges and integration of different enterprises towards the system level. This stability can be jeopardised easily by international public limited companies relocating their activities, as Scotland experienced when South-East Asian manufacturers pulled out following the economic crisis in that region in 1997 (cf. Talbot and Thomson 1998).

The concept of shareholder value is not necessarily concomitant with e.g., environmental considerations. Financial analysts and top management very often regard them as mutually exclusive: environmental legislation has been strongly lobbied against by public limited companies.

The example to the contrary of Interface Inc. is quite illustrative: Although a large multinational corporation, Interface is a privately owned company (cf. Lancaster et al. 1998), and sees itself in control over its activities. Therefore, it can set itself goals that are independent from the immediate requirements of the financial markets, enabling the company to pursue long-term strategies. For Interface, these strategies revolve around the company's transition towards a sustainable, and even restorative business (Talbot and Thomson 1998).

In summary, companies being floated on the stock exchange gain funds for expansion and pay for this by losing some control over their activities. Furthermore, and as a consequence from public limited ownership, these companies very often experience a power struggle between the shareholders as the owners, and the managers, who run the business.

In recent years, however, public limited companies and their shareholders have witnessed the emergence of another power source, which could be seen as a mitigating force breaking the logic of funds for control: a company's mismanagement of its stakeholder relations, relationships with people or groups of people that are in some way affected by that company's activities, was found to have an impact on its reputation and ultimately, its share price.

Public limited companies, therefore, can be observed to be subject to a host of (sometimes conflicting) forces that require a careful and diplomatic stance that corporate top management must employ. Korten (1995), and Goldsmith and Mander (2001) see these companies as footloose organisations both powerful and at the whim of the more powerful and elusive global capital, rendering them unable to engage in close local relationships.

The mode of ownership and corporate control that would be more in line with industrial organisation resembling natural ecosystems is ownership by a small

number of private individuals, holding shares of a company that are not easily transferable, as the example of Interface Inc. shows. Very often, these individuals are the company's directors, so that there are no potential conflicts between ownership (shareholders) and control (managers).
Suitability of such companies for integration into larger systems, though, must be qualified: very often, privately owned companies are subsidiaries that are largely or wholly owned by larger, and public limited, companies. In this case, the private company must be regarded as being run by the principles of the public company (e.g., Ben & Jerry's Homemade Icecream owned by Unilever). The latter type of corporation are forced to increase their profits continuously in line with the performance of the financial markets, whereas the former could be content at producing a healthy profit, or breaking even. Short-term viability of the public limited company, as speculative capital roams the globe for the best immediate investment, is contrasted with long-term survival and prosperity of the private company. This perspective has a profound effect on the company's stance on environmental issues, as Welford (1997) observes: environmental concerns can assume the position of ballast to be thrown overboard when the economic outlook for that company worsens. We can now see that it is public limited companies that would be more likely to react in such a way.

Although circa 90% of European enterprises are small businesses (cf. Korhonen 2000), their turnover constitutes only a small percentage of the total turnover of all European companies, which is produced mainly by public limited companies. Presently, there is a mismatch of predominant (in terms of turnover) legal structure to the potential for changing industrial organisation structures.

Smaller companies that are owned by larger ones face a related difficulty: their operations are integrated into the holding company's network. Their procurement and sales strategies cannot be conceived and conducted independently, and possibly locally. They are part of the network of supplier and buyer relationships of the holding company, making it impossible to create local links with other businesses and local consumers. Private companies that are not subsidiaries of larger public limited companies can be regarded as being more reliable for integrated network activities such as industrial ecosystems requiring a certain degree of stability for relationships of interdependence to emerge.

As a resume, one can state that Industrial Ecology today does not seem to be feasible for the majority of industrial systems. This is due to the lack of independence in terms of financial and strategic constraints that companies face when they are part of a larger corporate system, be it a large holding company or the global system of financial markets. Because of their reliance on independent private companies, principles of Industrial Ecology in today's economic and legislative climate can only be implemented in exceptional circumstances. The "system III" condition as a principle governing the creation of Industrial Ecology applications, however, stipulates the adoption of industrial ecosystem structures for the entirety of production and consumption relationships. In order to bring this strategy closer to fruition, the legal, financial and organisational structures of participating companies, and the structures of potential participators as well must be conducive to that goal.

5. Chapter conclusion:

Multiplying feedback loops for creating industry responsiveness to sustainable development

The mainstay of this chapter has been the recognition that industrial structures can be changed when these structures are open to change. This seemingly trivial assertion has come to the fore as an important factor both in the discussion of output recycling and sourcing inputs from cycled outputs, in the analysis of long-term changes under an ecological tax reform, and thirdly, in the relationships of privately and publicly owned companies with sustainable business practice. When opportunities for feedback processes on environmental performance are encouraged in industrial organisation, industrial structures can change towards a much reduced dependence on fossil fuels and virgin resources.

This development is not at all a new process, to be created and nurtured only today: It has always been present in industrial activity that needed to adapt to changing circumstances. The changing environment until now demanded updates in legislation and company strategy mainly in the financial arena: Until the "black Friday" 1929, publicly quoted companies were not obliged to publish financial results or have these certified. The stock market crash of that day prompted a change in legislation and communication, which amounted to a proliferation of feedback loops: A similar speculative investment bubble like the one of the late 1920s that led to the (inevitable) crash is not possible any more with the system of collecting and verifying financial information now securely in place. The mandatory submission and verification of corporate accounts enabled a clearer picture of a company's health and led to a more stable corporate investment environment. Of course, it is possible for a speculative situation to arise again - because of the absence of other data that are vital for judging a company's performance (direct and indirect subsidies for the airline industry, for instance).

It is argued here that in a similar way, the installation of feedback processes for environmental performance enables business enterprise to assess and communicate their own performance, and adapt their strategies and behaviour. These feedback loops that are part of the ecological tax reform proposal discussed here, and as well of the indicator idea for industrial ecosystem performance, overcome the current perception of the "either market liberalism or centrally planned economy" divide that pervades much of the reaction to proposals of increasing ecological awareness: within a legislative framework that maximises the feedback processes to economic agents, one can look forward to economic behaviour that is adapting itself to incorporate an environmental perspective as well. What cannot be overlooked in this process, however, is the importance of the legal framework for determining a company's strategy.

A handful of examples for increasing feedback processes from different areas include Weizsäcker's proposal (Weizsäcker et al. 1995) to locate companies' effluent pipes upstream of their water intake, prompting them to clean their waste discharge (one of many NIMBY - "not in my back yard" - situations). Here we can observe some degree of proximity to endeavours of environmental economic policy proposals that advocate environmental valuation: the backbone of establishing environmental valuation lies in the recognition that environmental costs have been externalised so far, and thus largely ignored - putting a price on them enables economic actors to internalise and thus consider the positive or negative effects on the biosphere of their activities[63].

Recent parallel developments in the field of strategic management include the prominence of the stakeholder approach, where large companies in their search for long-term survival and prosperity increasingly consider (either voluntarily or because they are forced to by stakeholder pressure) a much wider range of persons and opinions, ultimately, everyone affected by a company's decision-making (cf. e.g., Freeman 1984, Wheeler and Sillanpää 1999). The adoption of a stakeholder perspective has instigated major changes in companies' policy: these have to take into account multiple perspectives and cannot isolate themselves so easily from their surroundings. It can only be hoped that this process even has an influence on publicly owned companies that must place responsibility to the short-term interests of their shareholders (mostly unknown to the company and not loyal to it) above all other business considerations.

Taken to its logical conclusion, the process of proliferating feedback processes would entail blurring of the distinction between the "economic actor" and its "environment", not just in the ecological, but in a very general sense. With the introduction of more and more feedback processes, the boundary of the economic actor is extended until it includes and is included itself, in the wider system, which was formerly fenced off as "the environment" and referred to and used as resource container on the input side and waste dump on the output side in the predominant linear logic of economic activity. Thus one would find industrial ecological relationships at the forefront of integration between the economic and the ecological sphere, as advocated by ecological economists. The physical constraints of the natural system would be acknowledged, the biosphere recognised as the supersystem into which all economic activity is nested.

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[63] The problem with environmental valuation lies in the valuation technique used, and the absence of markets that determine prices. The proximity observed between environmental valuation and the proposition of increasing feedback loops is not intended to support environmental valuation, rather to state that there are many more ways of internalising hitherto external "costs" and "benefits".

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Conclusions and implications for further research work

1. Review of the thesis' findings

This thesis has concentrated on the assessment of the comparison of natural with social systems, as this comparison is at the heart of Industrial Ecology and its means for achieving sustainable development, the aim of a human economy that can flourish in perpetuity. The division of the thesis into three parts follows the idea of a sequence of exposition and stating of the problem to be investigated, its subsequent analysis, and finally, the recommendation of policy conducive to the results of the analysis. The second part of the thesis was conceived to become by far the largest owing to the interdisciplinary nature of the problem, an attempt at grounding Industrial Ecology in appropriate theory. The theoretical framework for industrial ecological work was perceived to require a foundation from the fields of ecological economics, thermodynamics and theoretical ecology, cognitive psychology, and business and economics.

Part I:

Developments in the field of Industrial Ecology and its current standing

The first part of the work had the purpose of reviewing the status quo of research and applications in Industrial Ecology and of pointing out problem areas in the understanding of this thesis, that is, the soundness of scientific enquiry in the field. The biggest problems observed was first the merely very vague idea of which domain actually was to be observed and researched into by industrial ecologists: the system of industrial production (manufacturing of goods and provision of services) or rather, the entirety of the human economy, that is, both the production and consumption sides of the economy. What is more, in case of the latter, both systems then would need to be observed in an integrated fashion, i.e., with feedback loops emerging from and connecting both. The second problem area of Industrial Ecology can be seen to be related to the first: in which way is industrial ecological work different from end-of-pipe technology or work devoted to increasing resource and energy efficiency? Industrial ecologists would argue that it is the compelling image of the ecosystem that provides for a more profound perspective of, for example, understanding and remedying scarcity of resources and waste assimilation capacity, biodiversity, and the effects of human development on biogeochemical cycles. How is that image of the ecosystem utilised for work in Industrial Ecology? It was argued in the above that industrial ecologists need to answer this question and take the answer as the foundation of their field. At the moment, the concept of the ecosystem itself is understood in Industrial Ecology only in a very superficial way: the network of plants ("producers"), animals ("consumers") and bacteria ("recyclers") that make up the multitude of biomass cycles in the biosphere. This cycle is then taken as the blueprint for an industrial organisation that is supposed to result in sustainable development ("eco-industrial parks", "industrial ecosystems", "industrial symbiosis"). In the chapters of the second part, this thesis has been concerned with exactly this question: what is there of "ecosystem behaviour" that can inform a sustainable development?

Part II: assessment of the scientific basis of Industrial Ecology

The second part of the thesis built up on the problems stated in the first and endeavoured to integrate Industrial Ecology with relevant neighbouring disciplines. The decision to call Industrial Ecology an application of ecological economic theory, treated in the second chapter of the thesis, was based on the recognition that there are ecological constraints facing socio-economic development: the finiteness of natural resources does not only apply to non-renewables, but also to renewable resources (like plants that can be harvested for food, fuel or materials) that require conservation, and continuous resources that, although not exhaustable, have an upper limit of providing benefits (e.g., solar radiation hitting the earth). More importantly, and more difficult to ascertain, there are limits to the waste assimilation capacity of the biogeosphere. Thus, the remit of ecological economics, living within the constraints set by the larger system of the biogeosphere, must become the remit of Industrial Ecology, as the socio-economic system is embedded in the biogeosphere. The most coherent concept of an economic system that exists as an embedded system within the surrounding biogeosphere and adheres to its constraints is Herman Daly's steady-state economy. In this chapter, the similarities between a steady-state economy and the aspired end state of industrial ecological work, the "type III" system that cycles all material resources and runs exclusively on solar energy are being made clear.

The third and fourth chapters, although each utilising a different focus on separate fields of the sciences that pertain to Industrial Ecology, unite to form the core of the thesis' argument. Here, Industrial Ecology's claim to understand industrial systems in terms of natural ones is substantiated. For this claim to become a valid part of Industrial Ecology's endeavour, it must be evaluated in two respects. Firstly, do natural and social systems actually share common behaviour or characteristics, so that one can actually be understood in the terms of the other? A comparison of two systems without characteristics that validly describe both would be little more than a play on words. The third chapter argues that there is indeed a common behaviour shared by natural and social systems: the tendency to resist forces that pull a complex system away from its temporary equilibrium. Reaction to these forces would consist of the emergence of structures of higher complexity than there were before the pull away from the equilibrium occurred. The chapter established that this characteristic is shared by all complex systems, be they living or non-living. The capacity to degrade energy and dissipate gradients of temperature and pressure is this common feature of both natural and social systems, and it is this capacity that is the driving force underneath all systems organisation. Thus, in order to compare natural with social systems, industrial ecologists need to understand and evaluate the energy-degrading capacity of those systems. The superior facility of degrading energy of living systems compared to non-living ones has first been a boon for enhancing stability of the non-living systems that surround the former. With the emergence of *homo sapiens sapiens* and the species' ability to degrade not only flows of energy, but also stocks of biomass that had left the cycles of producers, consumers and recyclers (e.g., fossil fuels such as coal and oil), this boon turned into a problem that is now threatening the survival not just of the species, but of a large part of the living systems currently making up the biosphere. Ecological sustainability thus means the change in socio-economic systems away from exploiting stocks of resources and energy towards tapping flows. A linear fashion of utilisation (resource extraction – transformation – waste disposal) then gives way to a cyclical treatment of resources, powered by an underlying linear flux of continuous energy. The tapping of flows in the biogeosphere raises the question of the maximal size of an economic activity that does not impact negatively on the biochemical cycles it participates in.

The fourth chapter, starting from the basis laid in the third, of a comparability of activities in both natural and social systems, evaluates the mechanism of the comparison carried out in the field of Industrial Ecology, the "natural ecosystems analogy". First, it was established that the use of analogy, of metaphor in general, is widespread in the sciences and needs to be both acknowledged and assessed for its quality. Economics emerges as the first testing ground for the diagnosis of the metaphorical character of its theory and underlying assumptions. Far from being mere ornaments of speech, metaphors (and analogies as part of that family) are found to structure thought, both scientific or otherwise, in a fundamental way, so much so that the difference between the literal and the figurative must now be seen as artificial and impossible to draw. Industrial Ecology, thus, needs to recognise metaphor use in its work, too, and to assess the quality of the metaphors utilised. Metaphor use can be understood as a translation of system properties from one system to another, even unrelated one. The tool of structure-mapping from the field of cognitive psychology is concerned with evaluating the quality of that mapping. As a result of this chapter's application of structure-mapping to the "natural ecosystem analogy" of Industrial Ecology, several recommendations emerge: First, the socio-economic system under observation in Industrial Ecology must be the entirety of the human economy, not just the sub-system of industrial manufacturers and service providers. Thus, one of the problem areas highlighted in the first chapter, the correct system under observation, is presented with a solution. Second, the mapping exercise results in the discarding of species relationships in the food chains of natural systems as the blueprint for industrial ecological organisation. Charting relationships between producers, consumers and recyclers in natural systems is now being revealed as not a meaningful activity in itself. This is due to the recognition of the energy degradation work as the fundamental purpose of living systems that underlies these relationships and supersedes them as the proper base of analysis for understanding behaviour of natural systems for informing work in Industrial Ecology: food chains are merely the expression of underlying energy-degrading relationships. The structure-mapping tool is found to be a good vehicle for quality control of industrial ecological treatment of, for example, natural systems characteristics that are assumed to hold in industrial ecosystems, too.

The second part's fifth chapter is utilised in a support function, flanking together with the second chapter the core of the thesis, the third and fourth chapters. Where the second chapter sets out the type of economic system that Industrial Ecology adopts as its foundation, but makes only implicit reference to, the fifth chapter is taken up with juxtaposing the latter with the realities of international trade and resource use and the role, power and constraints of business enterprises in today's economic environment. Furthermore, the argument is presented that it is the attainment of changes in consumption patterns in the industrialised world that will provide the biggest step towards, and at the same time the biggest challenge for, a more sustainable use of material resources and energy. Thus Industrial Ecology's focus merely on industrial production, that is manufacturing of goods and provision of services, is found to be misplaced without an understanding of what the causes for this mobilisation of resources and use of energy are in the satisfaction of consumers' needs. As a last point, the environmental impacts of competitive activity between business enterprises deserve to be taken seriously as well: the mobilisation of resources and use of energy resulting in products and services brought to the markets and satisfying needs of consumers ought to be assessed in the efficiency of market allocation bridging supply and demand, production and consumption. Market allocation at present is responsible itself for environmental impact: creation of demand, obsolescence of products, oversupply to the market - all are results of competitive activities employed by business enterprises. The intensity of competition, though not directly quantifiable, is found to have increased, and thus the role market allocation plays for creating or reducing environmental impacts must come under scrutiny.

This second part of the thesis serves as a call for a wider understanding of what constitutes Industrial Ecology, in the chapters on complex systems behaviour, the role of metaphor for understanding systems under analysis and the comparison of Industrial Ecology's aspirations with the present system of economic activity. The contexts of discovery, mostly associated with the "natural ecosystem analogy" and pertaining to the creative, but not evaluative element of the generation of scientific theory, and the context of justification, as argued here, the commonality of behaviour between natural and social systems in their developing complex structures for the purpose of degrading energy, need to be recognised and distinguished from one another by scientists who concern themselves with an Industrial Ecology as a proper science. An application of the "natural ecosystems analogy" is possible only when the thermodynamic characteristics of the natural and the social systems that are being compared are taken into account.

The field of Industrial Ecology emerges thus as a much more complex and interdisciplinary endeavour than might have been imagined by its founders and the majority of its proponents. The fashioning of cyclical "type III" systems requires a much broader focus than the one on industrial production and eco-industrial parks made up from business enterprises.

Part III: an Industrial Ecology reconceptualised

This last part of the thesis takes its cue from the results of the second part's analyses: the understanding of Industrial Ecology as an effort with a much wider focus than an engineering one calls for a reform or a reconceptualisation of Industrial Ecology's central tenets, research projects and applications (parallel to Pier Vellinga's conception of the three-layered architecture of scientific endeavour as "intuitions and beliefs" leading to "derivate concepts and principles" that in turn provide a foundation for and inform applications, as discussed in the first chapter. This hierarchical division into three layers provided the impetus at the outset of this research work).

The sixth chapter, comprising the entirety of the third part's work, is thus concerned with three perspectives of integration for industrial ecological endeavour: first, as stipulated already in the second part, the three parts of economic activity, production, allocation and consumption need to be considered together in order to enable truly cyclical (in terms of use of material resources) socio-economic processes to emerge. The supposedly cyclical arrangement of processes in industrial ecological case studies is revealed as a linear arrangement with increased efficiency of resource extraction. True cycling of resources is shown to involve replenishing of their content of useful energy, reverting the material back from the status of a waste to a useful resource. Recognition of this cyclicality requires the provision of much higher amounts of available energy that can be used to replenish the materials' energy contents. Clearly, this energy has to come from renewable or continuous sources lest it compounds the negative environmental impact of using those materials.

Related to the latter issue of energy provision is the recommendation that a reconceptualised Industrial Ecology needs to occupy a position on policy-making for restructuring towards a society that uses resources and energy less wastefully. It is proposed here that an ecological tax reform constitutes a very coherent approach to that end. The latter's long-term consequences have not been discussed or informed the process of political decision-making – this chapter attempts to link long-term replacing of infrastructure in the wake of an ecological tax reform with the creation of more localised and more cyclical economic activities.

The third issue discussed in this chapter concerns the responsiveness of business enterprises to a more long-term outlook on successful business activity. It is argued here that the concept of the public limited company today might be in need of amendment, as the dynamics of financial markets are not conducive to that longer-term perspective.

In sum, all the issues brought forward in this chapter touch on the proliferation of feedback possibilities for informing private enterprise and postulate an active role for public administration to provide incentives for restructuring infrastructure and economic activity to a less environmentally damaging behaviour pattern, and even truly cyclical uses of material resources. An Industrial Ecology taking to heart these issues can be regarded as aligning properly its applications to its professed aspirations, the concept of a "type III" system.

2. General Conclusions

From this work it emerges that the aspiration of Industrial Ecology, "learning from nature", in order to attain an ecologically sustainable way of social and economic development, is a very complex undertaking. In order to provide an answer to the problems of which structures in natural systems can be taken as blueprints for socio-economic organization and the limits of the similarity between the two systems, the natural and the social, this doctoral project needed to traverse and integrate insights from the disciplines of ecological economics, thermodynamics, ecology, linguistics, and business and organisation theory for attempting to establish how learning from nature could occur successfully, that is, truly contribute to the understanding and pursuit of sustainable development. It was felt from a critical review of existing work in Industrial Ecology that the danger of a superficial inquiry into the characteristics of and relationships between natural and social systems was not a remote one. Thus, the prospect is real that aiming for a sustainable economic system with the help of ill-founded applications might actually bring about the contrary: in this way, the impetus for a change in behaviour that is needed for re-embedding the human socio-economic system as a subsystem into the surrounding biosphere can be blunted and the present state of largely unrestrained consumption of natural resources and sink capacity upheld. Industrial Ecology can be saved from that fate, if the discipline is prompted to take into account the underlying dynamics of all complex systems, natural and social, and to translate these into economic organisation in a fashion that is more profound than undertaken by the present attempts.

In so doing, employing a positivist or empiricist approach to understanding natural systems and relating this understanding to human decision-making, as this doctoral project might suggest, is not of much better help. Even a more profound analysis, as is advocated in this thesis, will have to acknowledge limits to the understanding of the dynamic behaviour of complex systems. These occur due to the inherent impossibility to model a whole system by participants inside the system, as Gödel's theorem showed. Faber's comments on "irreducible ignorance" need to be heeded for the development of appropriate applications: the limits of carrying capacity of the biosphere represent a system constraint that is unknowable in its extent and its dynamic. At this point the "science of sustainability", as Industrial Ecology likes to style itself, must fail, and the principle that emerges is to err on the side of caution when approaching a ceiling of carrying capacity locally, regionally or globally. Examples for such an approach must include the definition of critical natural resources. In that respect, one of the main points of the doctoral thesis, calling for the recognition of the importance of consumption of economic goods and services and its reduction in absolute terms, can be regarded as sympathetic, or at least not contradictory, to that *caveat*. In the sense that contemporary economic theory is regarded as a technical discipline, as it strives to understand the mechanics of economic exchange and to establish a rational utility maximising perspective that it imputes to human behaviour, it is part of a doctrine that holds that technological progress will offer a solution to the problem of making the planet Earth increasingly uninhabitable for human beings and other species. Apart from ignoring absolute limits to this understanding as mentioned above, a temporal perspective is also not taken into account: once a supposed absolute understanding of the biosphere as a constraint might be achieved, time might not be on our hands anymore to find a solution to adapt human society accordingly.

The technical slant of a scientific inquiry into the nature and consequences of human development thus needs to be balanced by a social one, furthermore, the precautionary principle needs to be embraced by all applications of Industrial Ecology. The social perspective includes education to raise awareness and sensitiveness to the fragile nature of the biosphere in the face of unrelenting human impact, and to address the root of economic consumption and remedy its pathological and nature-destroying side. This endeavour will most certainly entail the evaluation and reorganisation of all models of decision-making, up to democratic institutions and the role of the nation-state and international political and economic integration. Again, the issue of time available for effecting this change of mind comes to the fore.

3. Perspectives for further research work

Beyond the basic theoretical understanding of Industrial Ecology as the changing behaviour of economic actors towards sustainable development, there is a need for more applied research projects that would have to investigate the development trajectories of change in business organisations and local communities that aspire to embrace Industrial Ecology as an important path towards sustainable development:

1. Research into organisational change for inter-company cooperation and regional integration

On the scale of the business organisation, it would be important to understand better the organisational change required for companies willing to engage in IE activities. Beyond the generic, which was attempted in this project, there is a need for specific inquiries into awareness raising toward and implementing the external focus for integrated activities that Industrial Ecology requires. Thus, applied projects would concentrate on the creation of regional environmental management activities (in the sense of the region as being a part of the national dimension) that go beyond supply-side integration in the manner of the Kalundborg system and would slowly lead to a regional economy in which industrial producers and consumers are much closer to each other, not just in geographical terms, but also in their awareness of each other's needs and the constraints of the local ecological system. The "Urban Mines" project in West Yorkshire is a first effort in that vein. As proposed in the sixth chapter, such an effort should comprise a measurement of dependence of a local or regional economic system on external flows for resources provision and waste disposal, together with measures for improving the ratio of locally produced and consumed goods to those that are not.

2. Research on policies that encourage local and regional organisation without conflicting with international trade arrangements

Strengthening a local and regional focus on production and consumption, and thus, on resource procurement and waste disposal within a more narrowly confined economic area, will probably lead to a conflict with national and international interests, expressed mainly by companies and some political actors who would argue that a local arrangement to economic activity might favour local enterprises and then might discriminate against their international competitors. Consequently, research into policy proposals would be required that would consider and evaluate those policy measures enabling business and consumers' behaviour that do not openly conflict with international economic interests, as laid down by GATT/WTO negotiations.

3. Research into implementation of an ecological tax reform and consequences for Industrial Ecology

Implementation problems in Germany, the first country to discuss and commit itself to an ecological tax reform, show that introduction of the measure might lead to some profound social and economic changes, with some actors perceiving beneficial effects, while others do not. More research into the benefits of an ecological tax reform for corporations would be required in order to make the policy proposal more widely acceptable, and crucially, gain the support of important stakeholders. At the moment, the German government has only committed itself to two steps of raising taxes on fossil fuels within 5 years. Although this might be for the reason of economic assessment of the tax's consequences, political reasoning does not seem to allow more, when the opposition is intent on reversing even this very cautious first step. While lecturing on the subject, the author has come across the standard response to ecological taxation: "what about the implications for jobs?" Among the general public and business commenters, particularly in the German economy that is characterised by high labour costs, the spectre of job losses looms large and serves as an outlet for fears about the future. It thus has to be taken seriously, so that it cannot present a psychological obstacle (or as a tool for a rearguard action for proponents of a business-as-usual approach) to attaining sustainable development, the latter being a proposal that should be regarded as securing, not destroying welfare for society as a whole. In that light, the policy proposal of Robert Ayres, "reverse substitution of labour for capital" should be given serious attention in research and policy-making.

4. Research into reverse logistics networks for industrial ecological organisation

For industrial ecological organisation, the development and assessment of reverse logistics systems ("design for disassembly") will be becoming an area of increasing interest for financial gains and organisational implication. Although some research has been carried out, the link of reverse logistics with Industrial Ecology has not been made. There might be major synergy gains and sources of financial value to be found in closing supply-demand loops, via creating inverse distribution channels that return products after their use to the manufacturer in as high a quality as possible. An increasing integration of such networks would encourage a local focus of production and consumption on the one hand, and on the other, a more labour-intensive production, as disassembly and recycling at present are labour-intensive processes.

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CHANGING ECONOMIES OF SCALE – SYNERGIES BETWEEN IMPLEMENTATION OF AN ECOLOGICAL TAX REFORM AND DEVELOPMENT OF INDUSTRIAL ECOSYSTEMS

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In this paper an investigation is presented into the long-term effects of an ecological tax reform. Exploring time frames of different length, the paper considers the reform's effects on manufacturing systems, especially on economies of scale. Industrial ecology, a framework for restructuring into industrial ecosystems, is one attempt at transforming the socio-economic system for sustainability. The paper points out the synergetic effects an ecological tax reform has with those restructuring efforts for sustainable industry and society. For that purpose, the economies of scale in the current linear production system and those found in the closed-loop circular structures of industrial ecosystems are compared, and the paper is concluded by a discussion of opportunity costs of implementation of an ecological tax reform and industrial ecological restructuring.

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INTRODUCTION

Environmental change towards a more sustainable society does not come about from the market place alone, nor can it be prescribed by government decision-making – the democratic process stipulates that it needs to be agreed upon by all stakeholders. Recognizing their role and responsibility for setting the appropriate framework that can be utilized by these stakeholders, governments have at their disposal the following tools to assist in bringing about a sustainable socio-economic system: fiscal incentives, environmental regulation and targeted public investment. Although there is the contention that taxation/charges are more economically efficient than environmental regulation taken in isolation, it is the integration of the three that achieves a coherent political–economic climate and system to foster progress towards sustainable development. The focus in this paper is on fiscal incentives, and an ecological tax reform as the cornerstone.

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From a solely material perspective, the overall quantity and manner of resource and energy use needs to be changed, but this cannot be achieved by technological development alone. As history has shown us, technological change leads to social and political change as well. Any new technology then needs to be contained in a social, political and economic context for evaluating its role with respect to bringing about sustainable development. It is also for this reason that sustainable development is built on the three themes of environmental quality, economic prosperity and social equity (Elkington's 'triple bottom line', cf. Elkington, 1997).

Applications have centred on the discussion and evaluation of several different approaches for policy-making, which are aimed at changing the way enterprises, households and public agencies use resources and energy, and how they can use them more effectively and efficiently. These approaches can be grouped into three categories.

The first, waste minimization and curbing of emissions into air, water and soil by filter technologies etc can be summarized under the wide umbrella of environmental management programmes.

The second category employs a more strategic approach, which is concerned with increasing technical efficiency in the use of material and resources, proposing a technological revolution with at least a fourfold efficiency rise[1].

The third approach compares industrial systems to natural ecosystems, which are being seen as the only examples of sustainable systems so far, and which according to that approach should be emulated by economic development. Following from that school of thought, the creation of industrial ecosystems calls for fundamental and long-term changes in the way our society is organized with respect to factors such as production, consumption, work, leisure and education. This approach is not centred on the individual firm or economic unit only, but seeks to make visible the connections between different economic actors and integrate them into a system, the industrial ecosystem. The changes this approach might result in will be both institutional/infrastructural and cultural, in line with the environmental, economic and social dimensions of sustainable development[2].

These three approaches, of course, do not have to be seen as mutually exclusive: Although a socio-economic system restructured for sustainability can be seen as the goal, and the industrial ecosystems approach the biggest step towards that, the private and public sectors usually start out with environmental management programmes. It is, however, the savings potential of the efficiency approach that would provide financial incentives and thereby balance the costly and therefore unpopular end-of-pipe approach of environmental management systems. Pursuing these incentives makes sense to business organizations, and it is this financial bottom line on which eco-industrial restructuring is based, too. Ultimately, it could be envisaged not only that industrial ecosystems will be super-efficient, but that they will also make use of latest filter technology and waste minimization programmes (if only for the purpose of gathering most efficiently those wastes that will be reverted into resources again).

The paper's purpose is to draw attention to the potential long-term consequences of government policy-making for socio-economic organization – here in the case of fiscal incentives in the example of an ecological tax reform helping to bring about wider societal changes in the form of restructuring into industrial ecosystems.

This gradually increasing tax burden on fossil fuels (or, alternatively, on all fuels resulting in CO_2 emissions) has the potential, owing to its timescale of more than a generation and its steadily increasing nature, to link together different corporate approaches to environmental pressures: eco-efficiency, suspected to be nothing more than an elaborate

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[1] The main proponents of this approach are von Weizsäcker *et al.* (1997).

[2] For a general introduction to the concept, cf. Tibbs (1992). Further developments in that research field, however, mainly focus on the technological aspects of industrial ecology and the production/supply side of the economy, neglecting integration with the demand side, and thus failing to contribute to a sustainable socio-economic *system*.

smokescreen for carrying on with business as usual (cf. Welford, 1998), will thus be transcended and give way to a different mode of organizing production and consumption systems.

We shall commence with the description of an ecological tax reform, its remit and its direct effects on fuel consumed. The immediate costs and benefits of adopting an ecological tax reform are much discussed (see e.g. von Weizsäcker and Jesinghaus, 1992; Costanza *et al.*, 1998; Bach *et al.*, 1994), including the question of the 'double dividend'[3] (the benefits of both removing existing and inefficient tax distortions, and improving environmental quality); what is lacking in this discussion, however, is the long-term perspective for the development of an infrastructure with reduced environmental impact, which this paper will address. In the following part the implications of a change in fuel consumption are discussed with respect to different time frames. The implications of that change in fuel consumption for industrial organization will then be discussed with respect to different economies of scale to be found in the present industrial system (focusing on manufacturing) and in industrial ecosystems. The last part will consider the synergies between a long-term structural change and the effects of an ecological tax reform over such a time period.

THE BASIC MECHANISMS OF THE ECOLOGICAL TAX REFORM

An ecological tax reform comprises a bundle of measures that is aimed at restructuring the costs of economic activity, in particular industrial production.

An important part of this proposed tax reform package is taken up by an energy tax that will place a higher tax burden on that energy use derived from fossil fuels (or from the fuel's CO_2 emissions in the case of renewable combustibles). Apart from this carbon tax, an ecological tax reform could include other measures of environmental taxation as well. Studies so far, however, have focused on taxes on fossil fuels, as they may have the biggest fiscal impact, the anticipation of which creates much controversy around a carbon tax. The ensuing discussion consequently will be solely concerned with a tax on fossil fuels as the main measure employed on the revenue side of an ecological tax reform.

As a compensation for the higher tax burden on fossil fuels, policy proposals stipulate that tax rates relating to value added, labour or corporate profits be reduced accordingly. This overall revenue neutrality is the reason why this tool is a tax reform, rather than merely an eco-tax. It is not intended to increase a government's tax revenues, but to create a leverage for providing incentives for alternatives of fossil fuel use. However, the debate currently focuses on whether and how revenue can be shifted from one source of taxation to another, the implications being firstly that existing tax distortions would not be reduced, but moved and even exacerbated, and secondly that the government's hands would be tied by pre-assigning tax revenues to expenditures (earmarking). The supposed economic benefits of this shift in tax burden, the 'double leverage', are assessed and valued with widely varying results in the ongoing discussion among policy-makers and academics. This article will only touch on that particular discussion where integrated transport systems are concerned.

Under an ecological tax reform, taxes on fossil fuels will be raised in a long-term and harmonious scenario, for example by 5% annually over the next 40 years (von Weizsäcker and Jesinghaus, 1992, p. 54). This scenario provides stability for an estimation of future costs of energy use, a stability that is an incentive itself to engage in planning and implementing alternative ways of using energy.

As mentioned above, economic activity, if measured by turnover of the economy, is strongly linked to the consumption of

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[3] O'Riordan (1997) devotes five chapters of his book to the double-dividend question, exposing its contentious nature. As it is not the space of this paper to discuss this problematic in great detail, the interested reader is referred to the above publication. The present author prefers the term 'double leverage', which is used from here.

energy,[4] of which fossil fuels still make up the lion's share. If precisely that lion's share became the subject of gradually rising energy taxes, the nerve of economic activity in its present form could be hit: introduction of a carbon tax in one country would result in its products and services becoming more expensive and this therefore could lead to a loss in international competitiveness. In the absence of harmonization across the European Union, for instance, any government wishing to introduce a carbon tax would be bound to support its domestic industries in other ways (e.g., subsidies)[5]. Furthermore, as a change in the tax system would lead to industrial and social change, such measures need to be introduced with a view to accommodating that change. The UK government was reminded of this relationship by the 'fuel protests' in autumn 2000.

In order to have economic activity continue at least at present levels, if not grow, incentives have to be set to achieve delinking of that activity from fossil fuel use and CO_2 emissions. This is the aim of an ecological tax reform, and, consequently, lowered rates of VAT, income tax, labour costs and/or corporation tax would be those incentives. All of the aforementioned are part of an ecological tax reform's 'double leverage': both the revenue and the expenditure side are integrated to shift tax burden towards undesirables (material and energy use, pollution) and away from economic desirables (employment, value added).

GDP could still be strongly correlated to the use of renewable energy with no pollution consequences (ultimately, solar power), or, instead of measuring material production and consumption, it could become an indicator for creating, handling and applying information.

SHIFTING TRANSPORT AWAY FROM THE ROAD AND REDUCING ITS AMOUNT ALTOGETHER

Examining the revenue side first, an ecological tax reform has two effects on fuel consumption: rising prices for fossil fuels lead to a substitutional effect of these fuels being replaced by renewable ones (cf. Figure 1). This may result in some freight traffic on the roads being shifted to waterways and the rail, for example. For the time being there does not seem to be an alternative to the internal combustion engine for person transport or freight on the road on a large scale. The substitutional effect results in a change of the means of transport or the energy source used, but the overall quantity of transported goods would not necessarily be affected.

The second effect (cf. Figure 2) is a quantitative one: the ecological tax reform will provide economic incentives for decreasing overall transport costs (or countering an increase) by decreasing the demand for fossil fuels. This means either that fuel efficiency per ton transported would increase, or that the necessity of transport would have to be re-evaluated due to high fuel prices. This could mean, to mention an often quoted example, that there would not be any more bakery vans from Edinburgh bound for London and vans from London with the same produce bound for Edinburgh passing each other on the motorway at York.

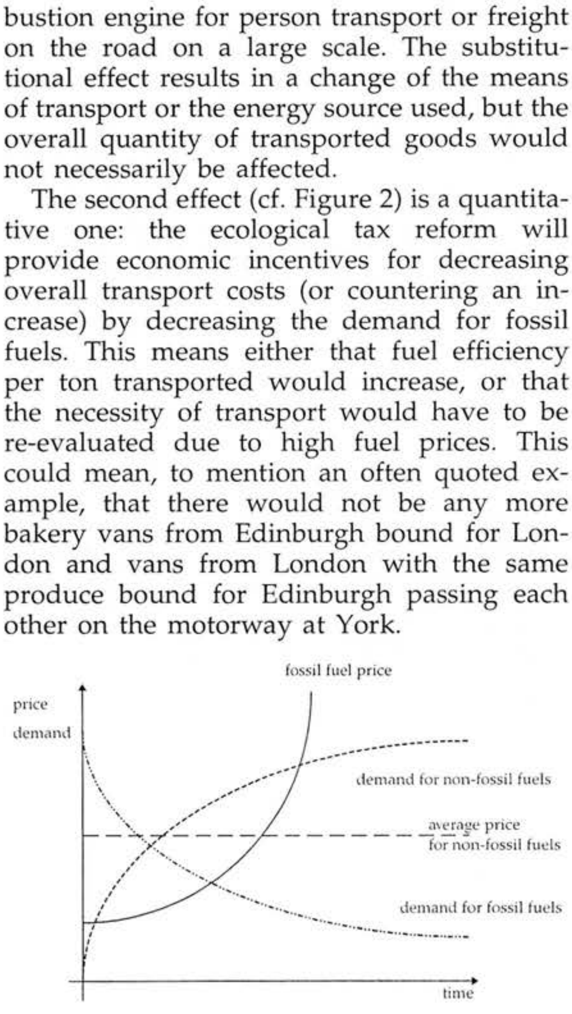

Figure 1. The substitutional effect of rising fossil fuel prices.

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[4] It is even suggested that, instead of the delinking some researchers have observed, energy throughput since the late 1980s has exceeded growth in GDP of some advanced economies – in other words, relinking has occurred (cf. de Bruyn and Opschoor, 1997).

[5] Studies by Barker and Lewney (1991) and Wubben (1999) conclude that national competitiveness in general does not seem to become adversely affected by environmental regulation or increasing energy costs.

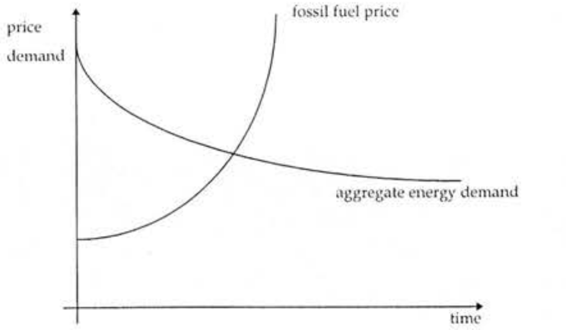

Figure 2. The quantitative effect of rising fossil fuel prices.

Both effects, the substitutional and the quantitative one, will occur at the same time, and they would be correlated in a way that would make it very difficult to disentangle them from each other for analysis. For example, even if the substitution effect results in phasing out fossil fuels in favour of renewable ones, the overall cost of transport would be very likely to be higher due to the altogether higher level of fuel prices. Although renewable fuels would become more competitive, as prices of fossil fuels rise steadily, transport costs would take up a higher proportion of the overall costs of production and distribution. Price elasticities would result both in an increase of fuel efficiency and in a reduction in the quantity of goods transported, which would be sourced, produced, marketed and consumed more locally.

To summarize, the ecological tax reform will mainly result in two reactions in behaviour on the revenue side.

1. Where fossil fuel is necessary, it will be used with the highest efficiency possible. Consumption of fuel per tonne kilometre (and person kilometre) will decline, and transport will see a decrease in tonne kilometres overall.
2. Where energy is necessary, it will not only be used with the highest efficiency, but also embodied in those energy carriers with the lowest global warming potential. These energy carriers only become more competitive compared to fossil fuels. As they do not become cheaper overall, they provide an incentive to reduce transport altogether as well.

These direct effects will give rise to indirect ones: for example, logistics systems with much improved transport efficiency. Furthermore, products and services with a high amount of embodied energy will be affected as well (e.g. recycling of metals increasing, energy-intensive virgin resource extraction decreasing).

In order to bring about the 'double leverage' and also to render the ecological tax reform fiscally neutral, its expenditure side must be integrated with the revenue side and existing distortions diminished: lowering taxes or offering subsidies to means of transport that are less fossil fuel intensive, modes of production and distribution that are less energy-intensive (including less transport and capital-intensive and more labour-intensive). An example for abolishing a tax distortion would be the reduction of VAT on energy saving technology.

FIVE DIFFERENT TIME FRAMES

How do the quantitative and the qualitative effect of an ecological tax reform result in changes of economic activity over time? The question of predicting price elasticities becomes a more complex one if viewed from a longer-term perspective rather than a short-term one. In the following, the short-, medium- and long-term changes in fuel consumption that an ecological tax reform may bring about are discussed. After an outline of the position of von Weizsäcker and Jesinghaus (1992) that the discussion will use to build on, it will revolve in greater detail around structural changes in the period with the longest time frame. Both the quantitative and qualitative effects of the ecological tax reform on fuel consumption play an important role here. Long-term changes incorporate short-term changes in a development path, but for a specific long-term change to come about the specific one of those short-term effects whose development path leads to the desired long-term effect has to be encouraged by the legislative framework: this is the reason why there is a need to elaborate long-term changes and to encourage the most desirable one by appropriate government regulation.

Change will always incur costs of reallocation. A cataclysmic change will simply be costlier to the entire economy than a gradual one. There is, however, something to be said for putting off change for as long as possible: inevitably, new structures will hardwire a specific use of energy. As technological progress continues, new and better ways of energy use may become available (breakthroughs in harvesting renewable energy, e.g. solar, wave and geothermal power). It is of paramount importance, then, not to repeat the mistakes of the past, where the whole economy was built around one single source of energy, namely subsidized fossil fuels, and the resulting infrastructure was not expected to change any more.

In the immediate time frame, the first of the five analysed, gradually rising fuel prices will mainly have a quantitative effect, as less fossil fuel will be consumed. von Weizsäcker and Jesinghaus compared the effects of an ecological tax reform to the effects of the oil crisis in the late 1970s. This first period reflects the immediate future after prices rose, and quantitative effects then amounted to energy savings of 10–20%, where existing equipment was just used less.

The second period will give rise to cost–benefit analyses of existing machines or vehicles not yet at the end of their use period, compared to those with the highest fuel efficiency currently available on the market, probably leading to first decommissions and new investment.

As the fossil fuel prices affected by the ecological tax reform will be transparent for a long time period, immediate investment decisions of the first and the second period will favour machines or vehicles that have a higher fuel efficiency, and that are already being marketed. These investment decisions only cover the replacement of machines or vehicles that have reached the end of their use periods.

In the third period, further rising fuel prices will provide a strong stimulant towards research into and development of types of machinery with much higher fuel efficiency.

From here on, the high level of fossil fuel prices will have effects on the systems level: in the fourth stage whole transport systems will be reviewed as to their fuel efficiency, and the development of systems that no longer use fossil fuel will be favoured. Only in the fifth stage does the underlying purpose of the entire transport system come under scrutiny, as industrial, commercial and residential infrastructure will be newly planned. Forecasts include not only low-energy housing, but also areas with a mix of residential and industrial/commercial property, where persons transport might be by bicycle, even in sheltered bicycle lanes.

But there is more to this fifth stage than just the elimination of individual transport by fossil fuel powered cars, and this is where restructuring into industrial ecosystems fits in: Companies will move closer not only to their workforce (and vice versa), but also to their markets. Central warehousing by then will have become so expensive that there will be a drive towards local production for local consumers. A further step involves companies' closeness to their suppliers and their resource base as well, where possible. The whole socio-economic system will aim towards a new balance where as little transport as possible is necessary for production, marketing, allocation and consumption of goods and services. It is particularly the latter, the service industry, that will see a higher growth rate than manufacturing, due to the fact that services, most of which embody a significantly lower proportion of processed materials, differ from manufactured goods in that they are demanded and created locally. We can see from the envisaged fifth stage that the pursuit of eco-efficiency does not have to be a technological device that is employed for wrapping a green cloak around a grey core of business as usual (cf. Welford, 1998).

In order to understand the significant impact of an ecological tax reform, especially in its latter stages, on industrial organization, the analysis has to take a look at the area where most fossil fuel is used: manufacturing and transport of goods. In the manufacturing industry and its related activities of resource extraction, processing, end-consumer sale and possibly recycling, economies of scale in each of these characterize economic activity here.

The above discussion of economic development rests mainly on the increasing cost of fossil fuels, which is but one of the two sides of the ecological tax reform – the revenue side. Depending how the increased revenue is spent on the expenditure side, the leverage toward the desired development can be increased. Earmarking (hypothecation), however, while rendering the ecological tax reform more transparent, leads to problems once it is tied in with fiscal neutrality, which makes the tax reform more politically acceptable: The revenue side of the tax reform will most certainly show different dynamics than the expenditure side (e.g. reduction in VAT, employers' national insurance contributions, corporation tax). This situation can be solved by achieving fiscal neutrality, not year after year, but within a larger timeframe, so that borrowing from or saving to this budget item becomes possible.

HIGH-RISK, HIGH BENEFITS: CURRENT ECONOMIES OF SCALE IN MANUFACTURING

Discussed in more detail elsewhere[6], this paper will present a brief outline of the predominant system of sourcing, manufacturing and distribution. These basic characteristics are seen to describe industrial production both on a national and on a global level. Insights into this system of industrial production from a systemic perspective will point towards the advantages and problems of system changes due to the adoption of an ecological tax reform.

Conventional industrial production in general is characterized by the following factors:

1. mass manufacturing and
2. cheap transport based on an abundance of fossil fuels.

The move of industrial producers towards global markets can be seen as prompted by the potential to increase sales and to produce on a larger scale. Initially, manufacturing companies were just trying to escape the narrow boundaries of regional or national markets and their competitors, and the markets outside their home turf were regarded as undiscovered land. This perception resulted in the first wave of globalization: companies set up sales offices all over the world and stepped up production at home to cater for the increased demand abroad. However, nowadays, some 50 years later, the global market itself has become the chief arena for industrial production and distribution. Traditionally, the markets outside the national one depended on how the producer was faring selling his goods in the national arena. Now this relationship is inverted: standard consumer goods have to be marketed successfully worldwide to be successful in domestic markets.

This scenario affects industrial production even further. The potential to serve a global market enables the producer to pursue economies of scale in sourcing, producing and distributing. Large-scale warehousing and transport have become essential requirements. Furthermore, the economies of mass production can support substantial outlays of research and development, resulting in and accelerating technological change. The aforementioned inversion of the relationship occurs; as noted earlier with global markets bearing down on national or regional ones, technological change, once accelerated by increasing R&D, becomes the driving force itself to which industrial producers have to adapt. Together with it, pressure and speed of competition accelerates, driving those producers who cannot keep up with the rate of technological change out of the markets. Although having beneficial effects, technological change can very often degenerate into giving rise to ever more sophisticated 'techno-gizmos', developed mainly for marketing purposes to best the competition.

Economies of scale enabling costly R&D, together with ever more costly R&D (dictated

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[6] Bey C. The Ecological Impact of Market Allocation – Reforming Industrial Ecology's 'Integrated' Production Systems, PhD thesis at the University of Edinburgh.

by competitive pressure) requiring ever bigger economies of scale: this spiral describes the co-evolving system leading to higher degrees of concentration in various manufacturing industries. Mergers and acquisitions or hostile take-overs, a mass movement since the early 1980s, have been creating ever-bigger companies in a whole array of industries.

These companies' markets, due to increasing economies of scale in production and dissemination of global advertising, become more homogenous, so that companies can apply global market selection for devising marketing strategies for their target markets.

Homogenous markets can be served by standardized products. This is the reason why competitive battles for establishment of a market standard can have grave consequences for those companies whose products do not achieve a dominant position in the market. Moreover, in the present economic system, it is not only just the company in question losing a competitive battle: all the stakeholders associated with that company – investors, employees, customers, suppliers, local communities, local enterprise companies granting start-up aid – take a share in that loss.

These much sought after economies of scale and the resulting global competitive pressure depend mainly on transport costs that do not reflect negative externalities of transport itself to make concentration and centralization of industrial processes viable. The feasibility of large-scale transport subsidized by relatively cheap fossil fuels is bound to be re-evaluated under an ecological tax reform. How would a supposedly sustainable industrial system process resources and energy, compared to the system just described?

DIFFERENT ECONOMIES OF SCALE IN INDUSTRIAL ECOSYSTEMS

A future sustainable system of industrial production might employ the same structure as natural ecosystems do: the most important characteristics of a natural ecosystem are symbiotic structures on any level, from inside a single cell to an ecosystem-wide symbiosis between species. It is symbiotic structures like these that have to be encouraged for restructuring into industrial ecosystems. Natural systems are the only sustainable systems known so far. What seems to make them sustainable is the absence of waste and the closed-loop structure between producers, consumers and recyclers, where nutrients are merely transformed and cycled between different species, and not used up. Nutrients are mainly used and cycled locally, so that there are no huge stockpiles of unwanted resources. Availability of nutrients strongly influences the level of biological activity, which is fuelled by solar energy captured by and embodied in biochemical molecules.

Restructuring of industrial systems in a similar fashion would lead to the creation of integrated networks of production and consumption between manufacturers and households, rather than linear input–process–output–waste relationships. Such networks would emphasize local integration rather than globalization, and their stable structures balancing competitive forces by symbiotic/cooperative ones. The ensuing, reformed socio-economic system produces very little waste and exploits virgin resources only to a low extent, and thus is self-reliant to a high extent. The high degree of local integration and a focus on the community would lead to a much higher transparency of markets (due to more direct and increased two-way communication) and thus to reduced risk, benefiting producers[7].

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[7] Creation of industrial systems in the fashion of natural ecosystems, however, has had for the time being a technocratic ring about it, as briefly mentioned above. For the purpose of this paper, industrial ecosystems are understood to incorporate households and other consumers of industrial products and services, thus going further than a traditional industrial production system that might exhibit chiefly a higher resource efficiency. Extending the natural ecosystem metaphor to all participants of the socio-economic system transcends merely technological change and embraces a social dimension, in a very similar way that Jackson and Roberts understand ecological modernization as cultural politics (cf. Jackson and Roberts, 1999). Both concepts are thus resonant with the three pillars of sustainable development, environmental quality, economic prosperity and social equity. It would probably help to distinguish 'socio-economic ecosystems' (that embody the social and political perspective) from the industrial ecosystems that are thought of as being a solely technological initiative.

Economies of scale in such a system would be markedly different from those sustained by subsidies on fuel prices. In the present system, economies of scale can only be established after considerable financial outlays for initial R&D and competitive positioning towards control of that product's global market. In industrial ecosystems, 'control', that is, an understanding of customer needs and access to the market, can be attained without corporate battles. Due to the smaller focus, an ecological niche approach for business might contribute towards easing the need for a global race for competitiveness. The lower risk in creating, accessing and serving a local market[8] is offset by lower returns, as economies of scale in manufacturing do not play a significant role. In their place, one will find economies of efficiency with very much reduced wasting of corporate resources, financial and material ones, in industrial production. Arguably, both approaches have the same expectancy value, the high-risk, high-return model of large-scale production and the low-risk, low-return one of an ecological niche[9]. An ecological tax reform will help to establish limits to the scale of production, as the local market is easily served and the threshold of higher transport costs to penetrate markets further away has to be overcome. Those corporate resources devoted to pursuing economies of scale could instead go into increasing efficiency and more closed loops in production and consumption, or expansion by creating new local production facilities somewhere else. Overall, such systems will offer a higher degree of security for their participants with a much lower frequency of destabilization. There would not be the danger of a global player pulling out, for economic and political reasons that are unrelated to the company's performance in that local market.

WHY CAN AN ECOLOGICAL TAX REFORM YIELD A CHANGE IN INFRASTRUCTURE WHERE RISING FUEL PRICES OF THE OIL CRISIS DID NOT?

The crucial difference between measures to curb petrol consumption in the years of the oil crisis that von Weizsäcker and Jesinghaus describe and an ecological tax reform is its long-term perspective and the fossil fuel prices rising in a transparent and predictable manner.

Whereas the oil crisis mainly prompted short-term reactions in government decision-making, that is, on the scale of 5–10 years, and the measures (car-free Sundays, more detailed information on cars' fuel efficiency etc) were largely abandoned after fuel prices relaxed again, an ecological tax reform presents industrial producers and household consumers with a stable scenario for the next two or three decades, if not the next 50 years. Furthermore, the increased revenue for oil in the 1970s went to the oil companies, whereas the revenues of an ecological tax reform would be used to lower taxes on labour and value added.

This must be the main reason why von Weizsäcker and Jesinghaus could only observe short- to medium-term solutions to the increase of fuel prices in the 1970s[10], and not long-term solutions, which could be expected under an ecological tax reform. They assumed long-term structural changes coming about when the potential of incremental adjustment had been exhausted, and a breakthrough was needed (cf. Figure 3).

This ceiling of marginal benefits of incremental adjustment was not reached in the oil crisis. In the ecological tax reform's perspective of increasing fuel prices by 5% annually over the next 50 years, it would be much

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[8] A local market here is understood to be a basic unit of aggregate demand for distribution of products and services, e.g., a city and its surroundings.

[9] There might be, however, a dilemma in the shape of the 'Tragedy of the Commons' arising, when companies would be unwilling to shift their focus from a global to a local approach, for fear of vacating space that will be filled by their international competitors.

[10] cf. also Neuburger (1992), who uses that point against the usefulness of an ecological tax reform, fails to realise the planning implications of a planned and harmonious rise in fossil fuel prices, and furthermore does not consider the leverage effect of the ecological tax reform's spending side, despite a statistical analysis of the demand of energy relative to its supply price.

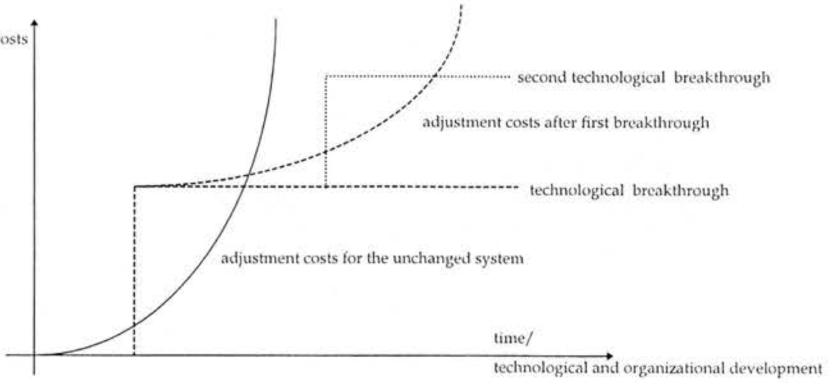

Figure 3. Rising adjustment costs in an unchanged system compared to costs after a technological/organizational breakthrough.

easier to plan and implement structural changes in a long-term perspective now, right from the beginning, as the factor under consideration, fossil fuel prices, is behaving in a stable way. In that sense, it should also be considered whether the tax would be rising steadily, or the price of the fuels. The former would still leave fuel prices open to fluctuations of world market prices and would reduce predictability of the fuel price scenario. The latter option, however, would yield the benefit of highly predictable fuel prices for consumers and industry, but fluctuations in the tax revenue, to accommodate changes in world market prices.

In any case, in the course of a predictable, ideally monotonic price rise, a ceiling of incremental adjustment will be reached and exceeded with certainty, which will make structural redesign a necessity. Hence, structural redesign would not have to be phased in only when that ceiling came closer, but could be taken on now.

The crucial point, however, is the 'double leverage' of the connection of the revenue side and the expenditure side of the ecological tax reform, which will have more profound effects than the rising fuel prices of the oil crisis years, as the tax revenue will be used to make possible and assist in the wider changes needed for transition to a sustainable society.

CONCLUSION: AN ECOLOGICAL TAX REFORM FACILITATES LONG-TERM SUSTAINABILITY PLANNING

In addition to the stable price scenario an ecological tax reform can provide, there are substantial financial advantages in employing a long-term perspective and subsequent planning early on.

Firstly, the earlier new components of infrastructure, allowing a decrease in fossil fuel consumption, are implemented, the less expensive they will become to set up, as the whole system will not have developed as much lock-in as in later situations[11], for example becoming dependent on a specific technology. These costs have to be compared with the opportunity costs of doing nothing and leaving the system to itself: at the beginning the restructuring costs will be significantly higher than the marginal abatement/adjustment costs without structural changes. As time progresses, however, one would observe a sharp rising of adjustment costs as the ceiling draws nearer, whereas on the other hand the restructuring costs would either remain constant or even fall, as research will result in new achievements

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[11] For a discussion on increasing returns and development path dependence in economic systems, cf. Arthur (1993).

and offer economies of scale, and implementation efforts devoted to the new structures will spread more widely.

Moreover, there are considerable financial benefits to be reaped from the much smoother transition from conventional to sustainable structures, as adaptation costs (due to a shallower learning curve and higher time reserves) would remain as low as possible.

Having said that, there is one argument in favour of 'wait and see': Early efforts to restructure are more likely to be fraught with imperfections, as new infrastructures and technologies are implemented while still being tried and tested. Technology will move on and provide radically new and efficient solutions. Committing to the best available now could result in being locked in with that technology or that specific way of organization, just in the same way as Western economies are locked in the present system with its centralized infrastructure of manufacturing and energy production, dependent on subsidized transport. Countries benefiting from adapting their structures later than others and learning from experience elsewhere will certainly comprise some developing countries, but also countries at the periphery of the European Union such as Greece, Spain and Portugal.

This is true not only for the current socioeconomic system, but also, and more importantly, for any newly emerging one. Technological development will not halt at a system that today would represent a major step towards sustainability. Hence, even the new infrastructure will have to be flexible enough to be adapted when better technical solutions become available. It certainly seems easier to adapt small-scale, decentralized structures in the fashion of industrial ecosystems than large-scale centralized ones.

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