
Industrial ecology: a critical review

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Abstract: Scientists, policy-makers, and the general public are becoming increasingly aware of environmental damage associated with the large and growing material through-put required in modern industrial society. One approach emerging in response to these concerns is called Industrial Ecology (IE). IE signals a shift from 'end-of-pipe' pollution control methods towards holistic strategies for prevention and planning of more environmentally sound industrial development. However, the broad umbrella of IE currently houses a diverse group of scholars, consultants, and environmentalists, who range in scope from those advocating incremental changes in existing systems, to some promoting a total transformation of industrial activity. This article presents a critical review of the existing US literature on IE. We introduce and critique IE's primary concepts, and analyse weaknesses and gaps in IE's conceptual framework. We also discuss the needs and potential for advancing IE concepts and projects in the future.

Keywords: design for environment, environmental policy, industrial ecology.

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1 Introduction

Industrial activities are increasingly in confrontation with ecological systems. Continued natural resource exploitation and environmental impacts of resource use and pollution are cause for concern around the world. One broad approach emerging in response to these concerns is called Industrial Ecology (IE). IE offers important goals and organizing principles for reforming industry, providing concepts that are gradually being embraced by leaders in industry, academia, and government agencies.

IE signals a shift from 'end-of-pipe' pollution control methods towards strategies for more comprehensive prevention and planning of environmentally sound industrial development. IE is advanced as a holistic approach to redesigning industrial activities. However, the broad umbrella of IE currently houses a diverse group of scholars, managers, engineers, consultants, and policy-analysts who range in scope from those advocating minor incremental changes in existing systems, to some promoting a total transformation of industrial systems.

This article presents a critical review of the existing US literature on IE. We first introduce IE's primary concepts: modelling industrial systems on ecological principles, closed material cycles, waste exchanges, and design for environment. We discuss where and how the literature differs in interpreting the basic concepts of IE. We then analyse the omissions and weaknesses in IE's conceptual framework. Finally, we discuss directions and potentials for advancing Industrial Ecology concepts and projects in the future.

2 Characterizing industrial ecology

Industrial Ecology is currently a broad umbrella of concepts rather than a unified theoretical construct. As such, it is described and presented in different ways by different authors. Based on the authors' perspectives on the current state of industry and the environment, IE can become either an incremental extension of efficiency improvements underway in industry, or a radical new paradigm that must be embraced if we are to save the planet from the impacts of industrial development.* Similar to 'sustainable development', IE is vague and broad enough to serve as the catchword for many different arguments. This ambiguity, of course, has benefits as it may lead more people to accept IE as a valuable concept. It also has pitfalls, however, as any movement or discipline lacking clarity of goals, objectives, and specific strategies is likely to founder.

In this Section, we shall characterize IE concepts by briefly analysing definitions, origins of IE thinking, and interpretations of how to apply IE in practice. IE is defined in very broad terms, which range from normative arguments to simple statements of efficiency and logic. The basic concept underlying most of IE is the idea of modelling industrial systems on natural ecosystems. However, even this fundamental concept is interpreted widely by the community of IE enthusiasts. A list of definitions serves to highlight the breadth of interpretations.

2.1 Definitions

Frosch and Gallopoulos (1990), two of the earliest US proponents of IE, explain that 'the traditional model of industrial activity – in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of – should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process...serve as the raw material for another process'. For Frosch and Gallopoulos (1992, p.290), IE serves as 'a better system for the coordination of technology, industrial processes, and consumer behaviour.'

* We discuss IE within a narrow view of industrial activity, analysing its relevance primarily to manufacturing operations.

Graedel and Allenby (1995, p.9), in the first textbook on IE, assert that, 'Industrial Ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.'

IE is described as an information-driven field in which the advances of the 'information revolution' can be harnessed for improving the environmental performance of industry. Frosch and Uenohara (1994, p.2) explain that 'Industrial ecology provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems. To optimize resource use (and to minimize waste flows back to the environment), managers need a better understanding of the metabolism (use and transformation) of materials and energy in industrial ecosystems, better information about potential waste sources and uses, and improved mechanisms (markets, incentives, and regulatory structures) that encourage systems optimization of materials and energy use.'

Using ambiguous terms to define IE, Allenby (1992) writes that 'industrial ecology may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely – given continued economic, cultural, and technological evolution.' Lowe (1993) similarly argues that 'Industrial Ecology is a foundation for creating sustainable industry in a sustainable society', employing a 'whole systems approach to design and management of the industrial system in the context of local ecosystems and the global biosphere.'

Socolow argues that 'Industrial ecology is a metaphor for looking at our civilization', which provides perspectives on long-term habitability, global scope, the overwhelming of natural systems, vulnerability, mass-flow analysis, and centrality of the firm and the farm (Socolow *et al.*, 1994, p.3). For Socolow, as for many other proponents of IE, the perspectives of IE 'add up to "new thinking".'

Tibbs (1992) and Ehrenfeld (1994) have laid out what they consider the basic components of IE, which we shall discuss in more detail below. Ehrenfeld's list (based on Tibbs, 1992) of the seven components of IE (Ehrenfeld, 1994, p.16) is useful as a base for discussing which concepts different authors accept or consider critical to IE. This list includes: (1) improving metabolic pathways for materials use and industrial processes; (2) creating loop-closing industrial practices; (3) dematerializing industrial output; (4) systematizing patterns of energy use; (5) balancing industrial input and output to natural ecosystem capacity; (6) aligning policy to conform with long-term industrial system evolution; and (7) creating new action-coordinating structures, communicative linkages, and information.

2.2 *Origins*

As the definitions show, Industrial Ecology has come to represent a broad set of concepts, tools, analogies, and visions for carrying out organized changes in industrial systems. The

origins of IE are based in many fields and past trends in environmental and industrial movements. What IE claims to offer are connections among different fields or systems of thinking – bringing systems thinking in ecology together with systems engineering (for design of products and processes) and economics.

Much of the terminology of IE comes out of ecological sciences and systems analysis. The ecosystem analogy is at the centre of most papers on IE, where proponents discuss modelling the development and behaviour of industrial systems on patterns of natural ecosystem evolution. Common aspects of ecosystems that are discussed include closed materials cycles, evolutionary principles, resiliency of systems, and dynamic feedback. Some authors also extol the linkages between cooperation and competition in ecosystems.

These concepts and constructs are by no means new. Barry Commoner in his seminal book, *The Closing Circle* (1971), argued for the relationships between modern industrial activity and ecology, laying out the 'laws' of ecology as they relate to current human activities. Commoner argued in 1971 that 'if we are to survive economically as well as biologically, industry, agriculture, and transportation will have to meet the inescapable demands of the ecosystem' (p.282). These ecosystem demands include 'essentially complete containment and reclamation of wastes...essentially complete recycling of all reusable metal, glass, and paper products; [and] ecologically sound planning to govern land use'. Commoner goes on to assert that 'present productive technologies need to be redesigned to conform as closely as possible to ecological requirements', (p.283), a very IE-sounding prescription.

On the industrial planning side, Europeans led a movement for 'low-waste' and 'non-waste' technologies in the 1970s. At a conference on non-waste technology, Royston (United Nations, 1978, p.39) argued for 'technology based on the conceptualization of the total system of raw material supply-production-consumption-disposal and recycling, viewed in an integrated and a systemic fashion so that no waste occurs'. Schmitt-Tegge (United Nations, 1978, p.53) describes non-waste technology in terms almost synonymous with IE – using materials and energy more economically, reducing pollution, increasing re-use and recycling of materials within production, and extending the life of products. Royston noted in 1978 that the strategy discussed by many IE proponents in the 1990s of 'producing a useful by-product instead of an environmentally degrading waste product is not new'. Fischer (United Nations, 1978, p.669) describes environmental programmes sponsored by the German government in the early 1970s, which included the goal of 'improved use of raw materials' through use of by-products, decreased material intensity, reduced production losses, and increased product lifetime.

A number of IE authors trace the term 'industrial ecology' to a programme sponsored by the Japanese Ministry of International Trade and Industry (MITI) in 1971 (Watanabe, 1994) which promoted 'principles of industry-ecology', such as recognizing system boundaries for industrial activities, understanding industry-environment interactions, recognizing redundancies and response relationships in systems, and developing mechanisms of control over human activities to promote ecological equilibrium.

Another component of the IE literature comes directly from analysis of 'industrial metabolism', and in particular work done by Ayers (1989, 1991). Industrial metabolism focuses on analysis of materials stocks and flows, and potentials for reducing materials and energy dissipation in the environment. Ayers work on tracking materials flows and promoting increased recovery/reconditioning/reuse/recycling is often cited as a cornerstone of actually implementing IE.

2.3 Interpretations

While there are a number of basic components of IE that all authors mention, there is a wide spectrum of interpretations of IE's goals and strategies. At one end of the spectrum are people who look to IE as an incremental approach to dealing with environmental problems, focusing largely on efficiency improvements. At the opposite end are those who see IE as the basis for a major transformation of industrial society, and a goal to strive for.

As with any new trend or buzzword, some individuals are attempting to co-opt IE so that it comes to mean nothing more than the status quo. For example, Linden (1994), in an argument for continued use of fossil fuels, writes 'from an industrial ecology viewpoint, it appears that the global energy system, while contributing a large share of dissipative material flows in the biosphere, also has sufficient flexibility and technology development potential to keep its environmental impact within acceptable bounds'. Linden represents a group of technological optimists who see IE as a means of better planning and technology development that will help solve many of the current environmental problems that planning and technology have created. In an attack on scientists and environmentalists who are concerned with global warming, Linden supports IE as one tool in 'the task of managing the transition to a sustainable global energy system that can satisfy human needs over the indefinite future with minimal environmental impact', and will help *avoid* the 'need to curtail greenhouse emissions from fossil fuel use beyond the sizeable reductions inherent in the pursuit of least-cost energy service strategies' (Linden, 1994, p.57).

Even more questionable are representatives of resource extraction industries who argue for re-thinking IE to make what they have always done seem part of IE. Chiaro and Joklik (1994, p.1) argue that industries such as coal mining can meet the goals of IE if you 'view the extractive industry as its own system, minimizing the amount of energy and resources that go into extracting the commodities in question and minimizing the amount of waste products that are created in the production of the raw materials'. By drawing the IE box small enough, anything it seems can be an optimized industrial ecosystem. These IE proponents assert that what is needed to develop IE concepts in their industries is for the government to advance a 'more voluntary, incentive-driven approach' (Chiaro and Joklik, 1994, p.6), which will help industry to be more creative and proactive. This, however, has been viewed by some environmentalists as a rationale for weakening environmental regulations.

A small group of writers see IE as a concept that primarily serves to assist their industry or organization to make money. (This view is problematic for a number of reasons but primarily – for the purposes of this paper – because it serves to further cloud the basic concept of IE.) Torrens and Yeager (1994) use IE as a means to argue for 'environmentally beneficial use of electrotechnologies in other sectors of the economy', which is exactly the goal of the electric power industry and the Electric Power Research Institute (EPRI) for which they work. After discussing IE and the electric power sector, the authors surmise that 'electricity can play a vital role in achieving economic growth and sustainability without sacrificing environmental quality', and we are further informed that 'the benefits of technological innovation made possible by electricity' will be the basis for sustainable development around the world (1994, p.25), a point that is no doubt more comforting for the power industry than for people concerned with ecological sustainability.

Several general trends in thinking have emerged among those authors who are discussing IE in a substantive way. The first focuses IE on single company changes in production processes to prevent pollution, increase energy efficiency and improve recycling and recovery, as well as improve efficiency of production. This brand of IE stresses re-designing industrial products and processes to meet environmental goals.

Within this framework, pollution prevention – a well-established industrial-environmental strategy – is presented as the key to IE. Patel (1992) describes IE as a 'cradle-to-grave production philosophy, except that in an ideal circumstance there is no grave'. Patel's six elements of IE all relate to process and product changes within an individual firm, from just-in-time delivery systems that reduce inventory and waste of hazardous inputs, to engineering controls to assure robust processes. Design for Environment (which we discuss in detail below) is sometimes described as a pollution prevention tool for product designers to improve product and process designs with respect to their environmental impacts while simultaneously increasing profits (Paton, 1994). Product stewardship and corporate product responsibility programmes relate to efforts to take greater responsibility for the full life-cycle impacts of products (Dillon, 1994, p.203).

As Frosch and Gallopoulos assert, 'the industrial ecosystems approach to manufacturing begins with individual process optimization'. Process optimization is interpreted as the core of environmental protection; the more efficient use of materials, energy, and capital will reduce environmental impacts. However, they do acknowledge that single company activities will not solve all environmental problems, and thus the 'ideal industrial ecosystem...requires the integration and coordination of industrial processes and subsystems to closely resemble the functioning of biological ecosystems' (Frosch and Gallopoulos, 1992, p.288).

This need for subsystem integration and coordination leads to calls for 'closing loops' and expanding systems of waste exchanges. Material closure is extended beyond material reuse and recycling within firms, to 'closed-loop systems', in which the system boundaries are defined much more broadly. Allen (1994) argues that it is possible to think of 'wastes as raw materials' and that 'extensive waste trading could significantly reduce the quantity of waste requiring disposal'. Tibbs and Lowe (and almost every other IE proponent) portray Kalundborg, Denmark, as a model of waste exchanges between firms, where wastes from one factory are piped and used in a nearby industry.

Although the implementation of IE is rather limited, several authors have argued that IE is central to 'sustainable development' (see Ehrenfeld, Lowe, Allenby, Socolow). These authors advance goals of bringing industrial development into balance with natural and social systems, integrating human and 'natural' systems by design. IE is thus placed as part of a paradigm shift. Lowe and others describe IE as critical to the 'goal of industrial transformation...[and] fundamental system-wide change in a longer time frame' (Lowe, 1993). Tibbs notes that 'the ultimate driver of the global environmental crisis is industrialization, which means significant, systemic industrial change will be unavoidable if society is to eliminate the root causes of environmental damage' (Tibbs, 1991, p.1).

As we shall discuss in more detail below, a large gulf separates descriptions of what IE can be, and specific examples and strategies for implementing IE. We believe that IE is an important (although still emerging) framework of goals and strategies for reforming industry. We shall thus describe and constructively critique IE on three levels in the following section: specific strategies for implementation; the disconnect between strategies and goals; and omissions and weaknesses in current constructs.

3 Strategies and tools

Early contributors to IE have sought to provide broad strategies as well as specific tools to bridge the gap between process-specific waste prevention activities and broader visions of sustainable industrial practice. Many of the tools suggested are based on the idea of achieving what Graedel and his co-authors call a 'systems-oriented' approach to product and policy design (Graedel *et al.*, 1993, p.18). Depending on how a 'systems-oriented' approach is interpreted, these techniques generally support one of two strategies: (1) the provision of information that will allow broader environmental consequences to be incorporated into the decision-making process at levels ranging from policy to product design (i.e. 'getting the information right'), and (2) the monetary incorporation of externalities that prevent the market from properly coordinating material flows (i.e. 'getting the prices right'). In this section, we shall characterize these two strategies and address methodological weaknesses in several of the tools that are advanced.

3.1 *Getting the information right*

The first interpretation of achieving a systems-oriented approach stresses the need for designers to consider the broader environmental implications of their decisions. The underlying premise is that industry needs more information about the environmental implications of their activities, and that by better analysing production it will be possible to re-design products and processes to save money and protect the environment. Emphasis in IE is placed on achieving a 'holistic approach' (Frosch and Gallopoulos, 1990, p.107) to product design by using what Lowe calls 'analytic and modelling tools' (1993, p.73) to incorporate a wide range of environmental concerns into the design process. Several specific tools for analysing systems-level issues have been discussed in the IE literature: Design for Environment (DFE) and its counterpart Life Cycle Assessment (LCA), Industrial Metabolism (IM), Input-Output (IO) models from the field of structural economics, and 'Ecofeedback'. We shall focus our critique on DFE and 'Ecofeedback' analyses as they are strongly emphasized (and promoted) in the IE literature and both possess several important methodological weaknesses.

3.1.1 *Design for Environment*

To improve on current design techniques that fail to consider broad environmental implications of products (and the processes that create them), several authors – but especially Allenby and Graedel – have supported the implementation of DFE as a means to 'integrate decision making across all environmental impacts of a product' (Lowe, 1993, p.80). According to Allenby, 'The idea behind DFE is to ensure that all relevant and ascertainable environmental considerations and constraints are integrated into a firm's product realization (design) process' (Allenby, 1994b, p.139). In practice, Graedel and Allenby have suggested that DFE would involve the use of matrices to qualitatively account for a wide range of environmental impacts corresponding to various stages of a product's life cycle. Such matrices could then be used to compare the broad environmental implications of various process and product options (Graedel and Allenby, 1995).

The benefits of this approach have been highly touted throughout the IE literature as a way not only to design environmentally preferable products, but also to increase inter-

firm coordination of materials use (through waste exchanges) and to cause favourable shifts in industrial material and energy use patterns. Allenby asserts that 'in the short term, Design for Environment is the means by which the still vague precepts of industrial ecology can in fact begin to be implemented in the real world today' (Allenby, 1994a, p.26).

For at least two reasons, these expectations appear to overestimate strongly DFE's ability to improve the environmental performance of products. Firstly, it is doubtful that massive (and costly) data requirements would yield *decisive* information about any product more complicated than a Styrofoam cup (Hocking, 1991). Any effort to consider 'all the potential environmental implications of [a] product or process' (Allenby and Fullerton, 1991-92, p.55) would generate a barrage of formidable tradeoffs between uncertain and widely disparate outcomes that must ultimately be reduced to social value judgements (Allenby, 1994a, p.28). Which, for example, is worse: localized air emissions that impair worker health or global emissions that may harm future generations? Allenby's suggestion of using an 'unambiguous, if general risk prioritization' (1994a, p.28) and an international 'materials database system' to allow materials choices to objectively 'reflect broad social consensus' (1994a, p.27) seems highly problematic. Conflicts regarding environmental justice, international equity, and the incomparability of disparate situations will severely limit our ability to distinguish benefit from harm and therefore limit DFE's ability to provide unambiguous prescriptions for product or process 'improvement'.

Secondly, although these analyses have been proposed as a way to help companies see the 'bigger picture', it is likely that industry will become enmeshed in complicated trade-offs regarding minute aspects of complicated products and miss entirely the need for fundamental changes in broader technological infrastructures. A team of design engineers may struggle for months over whether it is environmentally 'preferable' to use an aluminum or a plastic radiator-cap, while more fundamental questions about the sustainability of the gasoline-powered automobile are never raised. Although smaller changes in product and process design can certainly be helpful, efforts to design 'for the environment' risk losing sight of the forest for the trees.

3.1.2 'Ecofeedback'

Lowe and Tibbs have also suggested that industries use 'Ecofeedback' systems to support the 'adjustment of [industrial] operations in response to real time information about current environmental conditions' (Lowe, 1995, p.13). Although our ability to observe subtle changes in natural ecosystems continues to expand, the idea of using 'real time information about environmental conditions' (Tibbs, 1992, p.10) as a basis for regulating industrial emissions is at best an exaggeration of current monitoring abilities that detracts from the credibility of the IE literature, and at worst a reckless assertion that belies the complexity of the Earth's ecosystems. It should be clear that the consequences of today's emissions cannot always be observed today - the destruction of the ozone layer resulting from CFC emissions being one obvious example.

Even more problematic, however, is that environmental feedback systems are techniques for implementing an approach to waste reduction that focuses on 'managing the interface between industry and the natural environment', and obtaining a 'detailed understanding of ecosystem assimilative capacity and recovery times' (Tibbs, 1992, p10). Frosch and Uenohara even suggest the need to 'restore and improve the assimilative

capacity of the environment' (Richardson and Fullerton, 1994, p.3). Although the meaning of 'restoring' and 'improving' assimilative capacity is not defined, an ecosystem's capacity for waste can be increased only through the implementation of waste treatment and dispersion strategies or waste accommodation strategies (such as adding lime to lakes in an effort to increase their acid buffering capacity). These are the very strategies IE is trying to overcome. Implicit in these approaches is the *acceptance* of emission rates that do not exceed estimated assimilative capacities. Aside from the extraordinary difficulty (and subjectivity) that plagues even sincere efforts to estimate an ecosystem's 'capacity' for waste, these end-of-pipe strategies miss entirely IE's emphasis on preventive approaches to reducing material throughput.

3.2 *Getting the prices right*

A different approach to achieving 'systems-oriented' product and policy design seeks to supply information indirectly by incorporating environmental externalities into market prices. In this approach, the market is seen as an existing – but flawed – tool for coordinating decisions along economic principles of efficiency. The issue becomes not whether we can develop sufficient analyses to incorporate system-wide considerations into decision making, but whether 'the normal economic mechanism will fail to coordinate the interconnected system...' (Nordhaus, 1992, p.843). From this point of view, we simply need to ensure that the market can properly coordinate decisions by correcting market flaws that skew price signals.

Strategies for correcting market failures fall broadly into two categories: removing barriers that prevent private industry from responding to existing price signals, and addressing market externalities that lead to incorrect price signals. In the first category, several regulatory and legal constraints such as liability clauses and regulations that ostensibly prevent corporations from pursuing existing (economic or value-based) incentives to reduce waste are addressed (Allen, 1993; Frosch, 1994; Weinberg, *et al.*, 1994). Other problems, such as organizational and information deficiencies that distort market signals, have received far less attention in the IE literature.

In the second category, nearly every paper written on IE has proposed the use of Pigovian taxes on virgin raw materials or market-based policies such as tradeable permits to incorporate environmental externalities into prices. Frosch, for instance, argues that we need to 'internalize environmental costs' (1992, p.802), Ayers states that 'new economic incentives – e.g. higher prices or taxes on undesirable activities – are needed' (1991, p.21), Nordhaus asserts that '[externality pricing can turn] the economy into the economic equivalent of a closed ecological system' (1992, p.850), and Tibbs claims that 'probably the primary policy concern [for IE] is the resolution of the extensive debate in recent years about the need to reflect the real costs of environmental degradation in market pricing' (1992, p.16). Policy tools for incorporating the 'real cost of environmental degradation' have been a part of IE since Frosch and Gallopoulos first suggested the use of 'fees and taxes for pollution' that could 'if suitably set...be an effective means for manufacturers to incorporate societal costs of pollution and waste into their cost accounting systems' (Frosch and Gallopoulos, 1990, p.107).

Unfortunately, the enthusiastic and usually cursory promotion of pricing strategies paints a false picture of 'newness' and 'simplicity' over problematic policy tools that have been the focus of heated debate for decades. The first of several important problems

with 'getting the prices right' is the dilemma of placing monetary value on things such as environmental aesthetics or biodiversity that cannot be monetarily valued. Nordhaus, in a paper explaining the benefits of pricing strategies, acknowledges 'the practical difficulties that arise in implementing externality pricing' (1992, p.850). Formidable barriers would seem a more appropriate term. Graedel and Allenby explain that 'numerous valuation problems make cost/benefit analyses difficult: how to identify and properly quantify social costs; how to treat moral and ethical considerations; how to make decisions when data on impacts are so sparse and uncertain' (1995, p.87). This strategy also neglects the realities of the globalizing world economy and the associated barriers to the effectiveness of pricing strategies. Efforts to monetarily incorporate environmental externalities in today's world market could, for example, lead to international outsourcing or be interpreted as a barrier to free trade. As Schnaiberg argues, in a number of ways "'getting the prices right" flies in the face of a transnationally-competitive market system...' (1994, p.12).

4 Disconnect between strategies and goals

In this section, we introduce a second layer of critique by asking whether the strategies discussed above – notwithstanding the methodological weaknesses of their constituent tools – are constructed on accurate perceptions of the principal barriers to achieving IE's goals and hence whether their successful execution would indeed help advance these goals. As discussed in the beginning of this critique, defining IE's goals is problematic in itself because different people have expressed widely different interpretations of what these goals are. Nevertheless, among those advancing the stronger, transformative interpretations of IE, two broad goals are generally advanced: first, achieving closed material cycles; and second, realizing a fundamental paradigm shift in our thinking about industry–environment relations.

4.1 Closing the loop

The first of IE's two broad goals is to establish near-closed material cycles analogous to those found in natural ecosystems. According to Lowe, 'The *ultimate* goal of industrial ecology is bringing the industrial system as close as possible to being a closed-loop system with near complete recycling of all materials' (1993, p.75, emphasis added). Ayers argues further that 'unless the product cycle and the materials cycle are (very nearly) closed, the [industrial] system as a whole will continue to be unsustainable' (1991, p.21). A crucial test for IE, therefore, is to determine whether the successful implementation of the market and information strategies discussed in the previous section would advance – or at least not inhibit – this urgent goal. We begin with the market.

Notwithstanding the formidable task of pricing the unpriceable, 'getting the prices right' could indeed advance IE's first goal. The reasoning underlying this strategy is straightforward: private industry is in the business of maximizing profits. Incorrect price signals that fail to incorporate environmental externalities misdirect these efforts, making cleaner industrial practice less profitable. It follows directly that industry will respond favourably to market strategies that make it more profitable to be less polluting. The two assumptions underlying this reasoning – that private industry will reduce its waste if doing so will increase its profits, and that the prices of raw materials and energy seldom

reflect the environmental externalities associated with their production – are widely accepted. Incorrect price signals are not, however, the *only* problem that skews decision-making in private industry. Significant organizational and information deficiencies that can impede industry's ability to respond even to correct price signals need to be addressed as well. Nevertheless, *if* the methodological constraints could be overcome – 'a very big if!' as Nordhaus admits (1992, p.850) – economic incentives, such as virgin material or pollution taxes, would indeed help close material cycles.

Unfortunately, the extent to which 'getting the information right' will support the goal of achieving material closure, is more limited. Certainly, 'Ecofeedback' will not help advance this goal, because it focuses on managing open material flows. In addition, DFE may not advance the closure of material cycles, because it appears to address the wrong problem. DFE seeks to provide industry with the analyses and procedures necessary to incorporate 'systems-oriented' information into the design of environmentally preferable products. The problem this strategy addresses, therefore, is a perceived inability on the part of the design engineer to incorporate broader environmental considerations into product design. This strategy however ignores a larger question: *if* the necessary analyses were made available, *why* would they be used? Although some authors have mentioned that regulatory policies, such as mandatory product take-back or labelling programme, would be required to encourage DFE, the proposed policies – and the means by which they would encourage (or enforce) DFE – are not well described (Allenby, 1994a, 1994b; Graedel and Allenby, 1995). The IE literature delineates procedural aspects and potential benefits of systems-oriented procedures, such as DFE, but mostly assumes – wrongly we believe – that industries will have financial or value-based motivation to use these analyses. We look initially at two avenues of financial incentives that have been suggested.

First, Allenby (and others) proposed that companies might adopt systems-oriented strategies in order to satisfy a growing demand for 'green products' (Allenby, 1994b, p.140). This proposal is typical of the off-hand approach to social issues in the IE literature. Since the 1980s, researchers have been pointing out the limitations of green marketing (Plant and Plant, 1991). Furthermore, even if demand for greener products were strong, a company would not need to realize meaningful changes in its product design to bolster a 'green' image. The second avenue of financial incentive is more plausible but still problematic. Several authors, such as Paton, suggest that DFE could be used to produce 'environmentally responsible products [that] provide a measurable source of competitive advantage and business success by: contributing to revenues profits and growth...' (Paton, 1995, p.350). Graedel and Allenby similarly argue that companies should view these approaches as 'strategic to the firm in the same sense as competitive or economic considerations' (Graedel and Allenby, 1995, p.311). In these arguments, DFE is interpreted as a design-oriented pollution prevention strategy that could provide novel approaches to reduce wastes and increase profits.

This interpretation seems to miss the stated point of DFE. Although industry-wide pollution prevention activities have clearly demonstrated that environmental improvements in plant operations can indeed be profitable, the systems-oriented analyses described in the IE literature seek to go beyond the single factory perspective of traditional P2 activities and optimize environmental variables that lie beyond the realm of environmental stressors that the individual firm is traditionally responsible for. Indeed, the whole thrust of industrial ecology is to move 'beyond individual company or plant

boundaries to seek improvements in performance of larger systems' (Lowe, 1993, p.76). At this 'larger systems' level, the pollution prevention *pays* ideology does not apply. It is by no means certain that efforts to optimize environmental performance beyond the realm of an individual firm – and hence the realm of an individual firm's financial liability – would increase profits.

The other motivation suggested for DFE – aside from direct regulatory intervention in the design process – is based on environmental *values*. Indeed, Tibbs has proposed that information tools, such as DFE, may be adopted out of value-based motivation. Tibbs proposes that the emergence of a new environmental paradigm – what he calls 'corporate environmentalism' (Tibbs, 1992, p.7) – will motivate companies to 'accept the environmental imperative and willingly assume the mantle of environmental leadership' (Tibbs, 1992, p.8). Current trends in industry, however, seem to contradict this claim. As Schnaiberg indicates, '... it is hard to accept Tibbs' view that corporations are "greening" in the face of...growing indebtedness ... the threat of [hostile] take over ... "downsizing" ... "outsourcing" ... and globalizing trade' (Schnaiberg, 1994, p.12). Although a wide variety of economic, regulatory, and even value-based motivations have driven many industries to clean up their act, the IE literature provides only anecdotal evidence that these actions are based on 'greening' corporating agendas.

In addition, even if value-based decision-making were on the rise, it would lead to optimization of 'beyond the factory' variables only if value-based decision-making could sway price-based decision-making. Although value certainly outweighs profit in specific instances, it is nevertheless doubtful that value-based decision-making will play a significant role in realizing IE's broad 'goal of industrial transformation' (Lowe, 1993, p.73). Allenby describes the corporate dilemma well: '... private firms, especially in the United States, legally are only supposed to worry about making money. They are not supposed to set values for the country or act altruistically against their financial interests, no matter what the gain to society as a whole ...'. Although publicly held firms are indeed expected to maximize returns on their stockholders' investments, Allenby is correct to add that 'in practice, this [legal requirement] is somewhat blurred' (Allenby, 1994a, p.28). But beyond the latitude provided by this blurriness, corporations predominantly follow the market signals they receive. Even if value-based decision-making were becoming more important, it is unlikely that this blurriness would provide room for significant improvement in product design.

4.2 *Realizing a paradigm shift*

IE's second goal is to bring about a paradigm shift in relations between industry and the environment. This goal goes beyond measurable reductions in material throughput and focuses instead on the ways we perceive industries and their interactions with the natural ecosystems that ultimately support them. Several authors have emphasized the importance of cultural and cognitive changes if IE is to bring about 'fundamental system-wide change' (Lowe, 1993, p.73). Graedel and Allenby note that 'Technology alone cannot achieve the transformation we envision; it must work within the societal system to move closer to that goal' (Graedel and Allenby, 1995, p.338). They also emphasize that 'the fundamental point is that over time, implementation of industrial ecology and migration toward sustainable development will involve significant and difficult cultural, religious, political and social change' (Graedel and Allenby, 1995, p.33). Although the exact nature of this paradigm shift is not clearly expressed in the IE literature, it

nevertheless has important implications for the form and intention of IE. These authors are suggesting that IE means more than just closing material cycles; IE encompasses changes in the way we think. Unfortunately, the strategies proposed thus far do little to advance this second goal and in some instances may even impede it.

Following the arguments presented above, it should be clear that 'Ecofeedback' will not advance IE's second goal, because it encourages both the acceptance of open material flows that don't exceed an ecosystem's 'capacity' and an 'end-of-pipe treatment and dispersion' philosophy of waste management. It is also unlikely that DFE will advance IE's second goal. We have argued above that industry will not have the motivation to implement changes in product design based on information that does not conform to 'pollution prevention pays' criteria. In addition, even if DFE procedures were adopted, efforts to account for the broad environmental implications of a single component of an inherently dirty technology will not necessarily give rise to questioning the fundamental sustainability of the technology. Nevertheless, encouraging engineers to think about the broader implications of product design – even if the focus of the analyses is misplaced – would be better than relying solely on market strategies that may indirectly discourage this type of thinking.

Efforts to adjust market signals by incorporating the costs of environmental externalities are seeking not to change the way we think but rather to improve the coordination of price-based decision-making *without* the need to change the way we think. As Ausubel indicates, 'The challenge [for market strategies] is to bring into compatibility the possibly conflicting decentralized decisions, ideally *without the necessity for the individual or even institutions to bear in mind the logic of the whole system*' (1992, p.882, emphasis added). Market strategies will not – and indeed cannot – help to advance IE's second goal of realizing deeper learning. Indeed, they could inhibit it. Getting the prices right will give industry the incentive to be less polluting *and* to be less concerned about the environmental consequences of their actions. This dilemma, however, reflects deeper conflicts in capitalist economics and is not easily resolved. As Robert Heilbroner writes, a 'serious objection [to economic-driven behaviour] is that a general subordination of action to market forces demotes progress itself from a consciously intended social aim to an unintended consequence of action, thereby robbing it of moral content' (Heilbroner, 1993, cited in Ehrenfeld, 1994, p.8). Resolving this conflict would require fundamental changes in our system of economics that most proponents of IE would oppose.

5 Implementing industrial ecology?

In an effort to substantiate the principles of IE, the literature offers numerous case studies that ostensibly demonstrate their implementation. Some examples such as the industrial metabolism of platinum and iron do indeed exemplify the beginnings of cyclical material flows (Frosch and Gallopoulos, 1990). However, many of the examples intended to show how industrial practice can change to conform to IE principles consist of technical or operational modifications for reducing waste streams directly associated with individual processes (see Frosch, 1994; Jelinski, 1992; Frosch and Gallopoulos, 1990). Although these efforts certainly help to reduce material throughput, they do not capture the inter-industry, systems-oriented approach to waste reduction that ostensibly separates IE from

current pollution prevention activities. In addition, the few examples of inter-industry coordination that are offered – such as the 'industrial ecosystem' in Kalundborg, Denmark (Lowe, 1993; Tibbs, 1992) or the ARCO refinery in Los Angeles (Frosch and Gallopoulos, 1990) rely mostly on cascading high entropy wastes into higher entropy feedstocks, a practice which can reduce material throughput but does not conform with – and indeed may even inhibit – IE's goal of achieving closed material cycles. In this section, we shall discuss the extent to which these two (ostensible) forms of implementing IE – pollution prevention and material cascading – advance IE's principles.

5.1 Pollution prevention

Pollution prevention (P2) is often discussed as a component or example of IE practices, involving 'the use of materials, processes, or practices that reduce or eliminate the creation of pollutants or wastes at the source. It includes practices that reduce the use of hazardous materials, energy, water, or other resources and practices that protect natural resources through conservation or more efficient use' (EPA, 1990). P2 has been applied almost exclusively at the factory level through the use of waste audits, pollution prevention plans, technical assistance programmes that provide information on cleaner processes, information clearinghouses, and research into alternative production methods or product designs (Freeman *et al.*, 1992). IE proponents use examples of P2, such as the replacement of CFCs or no-clean soldering techniques, to show that IE is being implemented.

The underlying premise of the P2 movement is that industry needs more information on the inefficiencies of current production methods, and that by better analysing production it will be possible to re-design products and processes to save money and protect the environment. Further, by pointing out the economics of preventing pollution, it is assumed that industry will choose to do the economically rational thing and reduce wastes. P2, however, has been only partly successful in bringing about changes in industrial practices, and many examples remain of changes that are rational from a P2 perspective, but which firms have chosen not to implement.

Hirschorn and Oldenburg (1988, 1991) have examined barriers to the implementation of P2 and note that 'non-technical factors include: competing production priorities, belief that legally required pollution control is good enough, lack of management support to allocate people's time and capital for waste reduction, lack of rewards for successful waste reduction, accounting systems which do not allocate total environmental costs to production profit centers, incomplete data on the exact sources and amounts of environmental wastes, and the difficulty of simultaneously spending resources on regulatory compliance and waste reduction'. The experiences of P2 should serve as lessons for successful implementation of IE strategies, and show that simply providing information on 'cleaner' or more efficient production processes does not guarantee change will occur in industry.

5.2 Cascading wastes

Although the idea of using the waste of one industrial process as feedstock for another can certainly help reduce (or at least slow the growth of) dissipative material throughput, two important drawbacks – the lack of 'entropy cycling' and the risk of increased 'stiffness' in technological infrastructures – have not been addressed. We shall begin our discussion of these drawbacks by briefly developing the concept of 'entropy cycling'.

As Ayers has indicated, our current industrial system 'starts with high quality materials (fossil fuels, ores) extracted from the earth, and returns them to nature in degraded form' (Ayers, 1994, p.25). From a thermodynamic viewpoint, this predominantly open or linear flow of materials through the economy can be conceptualized in terms of the entropy changes that materials undergo as they are converted from virgin resource into waste. In broad terms, this flow can be depicted as a two-step process. In the first step, high entropy resources, such as mineral and metal ores, are refined into low entropy, primary materials. In the second step, these primary materials are consumed through a wide variety of uses and eventually returned to the environment as high entropy industrial or post-consumer wastes. The direction of entropy change in the consumption stage mirrors that of the refining stage.* Thus, to create a 'closed' material cycle, the first step of the linear flow model must be replaced with an analogous waste recovery step that refines high entropy wastes back into low entropy raw – or 'recovered' – materials. Material cycling therefore requires 'entropy cycling'.

The need for closed entropy cycles in the establishment of closed material cycles is expressed indirectly in both Jelinski's inclusion of a 'waste processor' (1992, p.794) in his four-node model of a closed, 'Type III' industrial ecosystem (Jelinski, 1992, p.793); and in Frosch's acknowledgement of the 'negentropy' (1994, p.66) necessary to recover materials from waste streams. The importance of entropy cycling is not, however, reflected in the popular idea of using direct waste exchanges that allow waste streams of some industrial processes to be used as feedstocks for others. Frosch has called this type of waste exchange 'cascading', because materials figuratively cascade from high entropy waste streams to higher entropy – or 'degraded' – feedstocks elsewhere in the economy (Frosch, 1992, p.801). Several authors have misinterpreted the idea of industrial waste exchanges as a technique for closing material cycles. Ehrenfeld states that 'The [material] loop is closed by routing waste materials (and energy) from the source of those wastes to other entities that use them as feedstocks' (1994, p.18). Lowe, in describing the material cascades that join several industries in Kalundborg, Denmark, praises the 'web of recycling and re-use' that has been established (Lowe, 1995, p.16).

Although waste cascading offsets the demand for other virgin resources, it is important to realize that material cycling can be achieved only by returning wastes to their refined (low entropy) state. Entropy losses do not need to be entirely recovered in only one cycle, and the recycled material need not be used for the same product in each cycle, but all entropy increases must eventually be compensated for. Thus, although cascading material exchanges will certainly reduce rates of material throughput, they are still 'open', non-cyclical flows and therefore do not '...demonstrate that industrial ecology's principles can work' as Edington suggested (1995, p.32). The IE literature needs to emphasize that shifting toward closed material cycles will require not just discovering higher entropy sinks for existing waste streams but also investing in separation and reprocessing technologies that refine wastes (by 'consuming' energy – or more precisely exergy) and return them to the economy as low entropy feedstocks (Brodyansky *et al.*, 1994).

* Although the total change in entropy associated with any real (irreversible) process must be positive, here we are addressing only changes in the entropy of materials. The entropy of a material may be reduced, but doing so requires the 'consumption' of energy – or more precisely exergy – and will produce a larger increase in the entropy of the surroundings associated with an expulsion of lower quality energy (Brodyanski, *et al.*, 1994; Lewis and Randall, 1961).

Our second concern about direct – or cascading – industrial waste exchanges is the strong possibility that increased interdependencies among disparate technologies will 'stiffen' industrial infrastructures and impede process innovation. This stiffness can be problematic – especially if it causes 'sub-optimal choices to get "locked in" by widespread adoption' (Ayers, 1994, p.36). Consider Frosch and Gallopoulos' following description of a successful industrial ecosystem:

In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process – whether they are spent catalysts from petroleum refining, fly and bottom ash from [coal fired] electric power generation or discarded plastic containers from consumer products – serve as the raw material for another process (1990, p.98).

Although 'optimizing' waste cascades from coal-fired power plants and oil refineries would certainly offset other sources of material throughput, it would also reinforce our dependence on highly dissipative energy sources that are *by themselves* largely responsible for many of the environmental crises that confront us. Can coal-fired power plants and oil refineries be part of an 'optimized' industrial ecosystem? Only if 'optimized' is narrowly defined. Indeed, the creation of 'complex food webs between companies and industries' (Tibbs, 1992, p.9) leads to a puzzling dilemma: efforts to 'minimize' material throughput by designing processes around existing waste streams (or designing waste streams for specific process needs) may 'minimize' waste from the existing technological infrastructure at the cost of entrenching 'sub-optimal', dirty technologies, and thereby impede a transition to more sustainable industrial practice – the very goal that IE alleges to promote.

6 Omissions and weaknesses

Efforts to realize IE's vision of sustainable industrial practice are thwarted not only by methodological deficiencies in IE's tools and broader dissonance between strategies and goals, but also by the omission of several aspects of our consumption predicament. Several important forms of material dissipation and the energy implications of closing material cycles both receive only passing attention. In addition, the IE literature reveals severe weaknesses in its analysis of social issues. In this section, we shall address these oversights as they relate to each of IE's two goals.

6.1 Resource dissipation: missing the target

Although nearly every form of dissipative material throughput is addressed at some point in the IE literature, the relative emphases placed on various forms of dissipation do not appear to reflect their relative significance. The material throughput addressed in the IE literature is primarily non-fugitive, non-dilute, point source, industrial wastes and non-dissipative consumer products. Not surprisingly, these are exactly the types of emission that can be reduced with the battery of tools put forth in the IE literature (i.e. changes that do not require fundamental shifts in consumption patterns).

As Ayers indicates, 'the problem, in brief, is that wastes associated with dissipative consumption (of energy and goods) now exceed waste emissions from manufacturing processes *per se* by a considerable margin in most advanced economies...intermediate goods manufacturing processes could be absolutely emission-free without having much

beneficial impact on overall environmental loadings' (1991, pp.6,7). The IE literature seldom addresses larger shifts in material use patterns that would be required to address material throughput associated with the use of dissipative products such as pesticides, fertilizers, decorative and protective coatings, lubricants, adhesives, inks, and friction-bearing surfaces such as brake pads or tyres that serve their purpose through irretrievable dissipation. Even more disturbing, the massive and highly dissipative point and non-point source emissions resulting from the combustion of fossil fuels receives only passing mention. We agree with Piasecki that 'the number [one] problem facing the field of industrial ecology in the 1990s will be securing safe, clean, abundant alternatives to fossil fuels' (Piasecki, 1992, p.875). The reluctance to address the use of fossil fuels reflects larger weaknesses in IE's handling of energy issues.

6.2 Energy matters

Although IE's goal of material closure is based on the model of material flows in natural ecosystems, it is rather odd that energy flows in natural ecosystems are largely neglected. In an introductory text on ecology, Kormondy writes that '...a one-way flow of energy constitutes one of the most important if not the cardinal principle of the ecosystem' (1969, p.17). If energy flows – not material flows – are 'one of the most important' principles of a natural ecosystem, then IE should place at least equal emphasis on energy flows and how they change as ecosystems evolve. Although the energy flows in an evolving ecosystem may seem more abstract than the material flows, they provide IE with at least two important analogies. First, in a closed material cycle – whether 'natural' or industrial – the flow of energy must remain open; energy cannot be 'cycled'. Because closing material cycles cannot eliminate the energy requirements of material provision, clean and non-dissipative sources of energy would be crucial even in a hypothetical closed-loop economy where all products and industrial wastes were recycled. Consequently, the importance of switching to renewable energy sources should receive far greater emphasis in the IE framework.

Secondly, the evolution of natural ecosystems from open material flows to closed material cycles is paralleled by significant changes in energy consumption patterns. Likewise, a shift in raw material processing activities from the virgin materials processing sector to a growing materials separation and reprocessing sector will produce dramatic shifts in energy demand. On the one hand, recycling post-consumer wastes, such as aluminum cans, yields large energy savings that are widely proclaimed among proponents of recycling but rarely addressed in the IE literature. On the other hand, recycling chemicals – such as solvents – from dilute industrial waste streams, may result in net energy costs. The IE literature focuses almost exclusively on reducing open material flows and scarcely considers the associated shifts in energy flows.

6.3 Social implications and impediments

IE's dominant approaches to closing material cycles involve changing product design to reduce material intensity, and returning wastes to the economy as products. Although these are important steps towards achieving closed material cycles, without addressing the social and economic forces driving consumerism and growing rates of product throughput, IE will end up chasing its tail. At best, it appears that IE's emphasis on reducing material content and material throughput will create a highly efficient 'closed-

loop', throw-away society. In one notable exception, Stahel and Jackson (1993) have addressed the importance of increasing product longevity and emphasizing product service over product ownership. Most papers on IE, however, seem to accept growing rates of product throughput as our 'modus operandi' and address the economic and social forces driving it only in passing if at all. This omission reflects a broader weakness in IE's analysis of socio-economic issues.

To move beyond purely technical questions, or even beyond closing materials cycles for specific industries, broader analyses of the social implications and impediments to IE is required. In general, the proponents of IE have chosen to ignore issues associated with bringing about an industrial restructuring under existing political and economic conditions. Those that do address social and political issues often gloss over them with simplistic calls for unleashing the invisible hand of the market, or reforming regulatory structures.

Although the idea of 'win-win' solutions for environmental problems is attractive, we would propose that current industrial-environmental problems (which IE is meant to address) will not be averted by simply promoting greater rationalization of industrial decisions, or more efficient market transactions. Other issues related to industrial restructuring need to be analysed and reformed.

The role of the market in industrial development is one example of IE's weak analysis of socio-economic issues. Few IE proponents ask the simple question of whether anything in the market system (aside from it not being sufficiently 'free' or comprehensive) may be causing industrial-environmental problems. Instead, most assume the market is part of the solution to problems, that via the profit motive, the environment can be protected and 'sustainable industrial development' can be advanced. This assumption may be correct; however, no evidence is presented to show causal relationships between levels of market freedom for instance, and implementation of IE. As Schnaiberg (1994) has argued, there are likely to be limitations to the promotion of IE concepts purely through capitalistic market structures, and furthermore, some functions of the market may be part of the problem and thus need to be regulated. If nothing else, the status quo will certainly place limitations on changes in industrial actions.

Government and industry leaders in the US have for many years resisted efforts aimed at formulating and promoting 'industrial policy'. The accepted thinking in the US is that the market alone should 'coordinate' industrial decisions. From this perspective, it is argued that individual firms have little control over what they produce but instead simply respond to consumer demands. Graedel and Allenby (1995, p.63) for instance, assert that 'all industrial activity is a response to society's needs and wants'. With demand for products exogenously established, producers are left only with the latitude to alter production methods.

IE proponents essentially accept the concept of consumer sovereignty, and advance IE only to serve the limited flexibility of constrained producers. This naive assessment discounts the power of a multi-billion dollar advertising industry that works to create and sustain 'latent demands' for products that consumers previously didn't know they needed. Is there no feedback from industrial activity to consumer decisions? Is there no need for reducing or shifting demand for certain products? These questions receive only passing comment in the IE literature.

IE proponents focus their socio-political analyses on reforming regulatory structures that act as barriers to the implementation of IE (Gertler, Frosch, Lowe). The Resource Conservation and Recovery Act (RCRA) is singled out in particular as an impediment to

waste exchange. Best Available Technology (BAT) standards are also criticized for their tendency to lock in end-of-pipe technologies and to deter process innovation. However, criticizing the EPA or policies that seem to impede IE does little to advance a path for actually moving IE forward. Few of the proponents of EI have analysed the difficult changes necessary in regulatory structures, and the balancing of regulations for waste management (such as RCRA) with the desire to promote greater symbiosis in the industrial economy. Ehrenfeld's (1994) work on product policy stands out as a single example of clear policy analysis related to IE implementation.

Any economic or industrial restructuring, no matter what its purpose, will confront barriers and entrenched interests that try to restrict its success. As Schnaiberg notes, '...despite their apparent interest in sustainable development, most treadmill actors are likely to offer substantial resistance to the actual policies that will promote genuinely sustainable development, except for those firms whose near-term profitability can be directly tied to such policies' (Schnaiberg, 1994, p.2). The prescriptive parts of the IE literature generally ignore institutional inertia and the basics of organizational behaviour that serve to block or slow change. Again, the attitude of the authors is simply that better information or better pricing will create a rationale that overpowers all existing interests.

Finally, IE's relationship to global economic changes and trends toward global production networks is left only to the imagination. As seems clear to most observers, the world is moving beyond 'Fordist' systems of mass production. Flexible, agile, and even virtual corporations are the new buzzwords of production. Production networks are constantly changing, resulting in changes in suppliers of raw materials, locations of factories, and product lines. How does IE, and in particular the vision of linking the wastes from one factory to the inputs for another, fit into these new operating parameters? As with a number of other issues, the IE literature has yet to address the realities of current global production systems (Kenney and Florida, 1993; Sklair, 1991).

7 Conclusions: the future of IE

Industrial Ecology offers an important set of goals and organizing principles for reforming industrial activities to reduce their adverse environmental impacts. The IE framework begins to fill a current void for analysing industrial-environmental problems and for designing solutions to growing resource constraints and degradation of environmental quality. It is quite clear that industry, government, and public organizations need tools for better analysis and planning of environmental issues. However, although it has the potential to provide these tools, IE is currently mired in its own ambiguity and weaknesses. As we have discussed, the five main critiques of IE are that: (1) it is poorly defined; (2) tools have methodological weaknesses; (3) strategies often don't support goals; (4) implementation to date does not reflect ideas expressed in the literature; and (5) technical analysis of energy issues and socio-political analysis of means to transform industry are extremely limited. We shall summarize these briefly and then propose steps to move beyond these impediments.

Early efforts to delineate IE have produced a wide variety of strategies and tools for achieving disparate visions of sustainable industrial development. IE, as a field, is in an inclusive phase where few authors have ventured to say what IE is *not*, thus leaving the field very broad and vague. If its scope is not clarified, IE may succumb to the sort of ambiguity that has plagued the concept of sustainable development (Lélé, 1991).

The market strategies touted in the IE literature are problematic policy options that have been the subject of debate for decades. The cursory and overly optimistic treatment of market tools, such as Pigovian taxes, does not aid their advancement and simply avoids the difficult conflict between market approaches and IE's ostensible goal of changing the way in which we think about industry-environment interactions. The IE literature also supports the development and implementation of new design tools and procedures, such as DFE. Although any improvement in the environmental performance of industrial processes and products is desirable, it remains unclear whether industry has sufficient motivation to broadly implement DFE and whether these design tools could produce unambiguous guidance even if they were used. In addition, our growing ability to estimate the broad environmental implications of minute changes in industrial practice seems to be leading many IE proponents in the wrong direction: larger questions about the sustainability of technological infrastructures (such as a transportation system that remains largely dependent on gasoline-powered automobiles) risk being buried under a barrage of complicated yet *relatively* unimportant design tradeoffs (plastic versus aluminium radiator caps).

Efforts to cite existing examples of IE implementation fail to capture the central ideas expressed in the literature. Several process-level modifications that reduce pollution and increase profits are described. Although 'pollution prevention' activities will certainly help to advance IE, these projects do not capture the systems-level approach that separates IE from the already large body of P2 literature. Where examples of systems-level efforts are cited (such as the 'industrial ecosystem' in Kalundborg), the ability of cascading waste exchanges to reduce material throughput is extolled whereas the importance of closing entropy cycles and the potential for 'stiffening' industrial infrastructures and thereby entrenching inherently dirty technologies are largely neglected.

Although energy flows are central to the operation and evolution of natural ecosystems, the IE literature seeks analogy only to the increasingly cyclical *material* flows of maturing ecosystems. Accordingly, the energy implications of closing material cycles and the importance of renewable energy sources receive only passing mention. IE also desperately needs to be fortified with serious social analysis regarding the impediments to changing current industrial practices. Whereas authors from within private industry may accept that industry should be left alone with the market to solve industrial-environmental problems, few citizens or environmental groups are likely to accept this strategy. Ultimately, many of the issues addressed in the IE literature boil down to value judgments that society must address. As we have mentioned, many of the concepts with IE are not new. None the less, the IE literature fails to examine the lessons of 1970s and 1980s attempts to reform industry. We are sceptical that simple changes in information or market structures will overcome the barriers that impeded past efforts. Society at large increasingly shares this scepticism. Environmental organizations, for example, have not embraced IE, partly owing to their distrust of technological solutions to technologically created problems. These concerns must be addressed if IE is to be accepted beyond the realm of industry environmental managers.

7.1 *Moving forward*

Our conclusion after critically reviewing the literature is that IE can be advanced on several levels, from incremental changes to more transformative efforts. On all levels it

will be necessary to expand debate and research. We would propose a three-stage approach to moving IE forward. First, focusing and refining existing IE concepts. Second, experimenting with the implementation of IE concepts. Third, creating mechanisms for discussion and debate regarding the transformation of industrial activity that includes a broad range of actors and interested parties.

The first level of work focuses on strengthening existing tools and strategies for implementing IE. A critical reading of IE leaves the impression that efforts to incorporate more information into product design and incrementally adjust market signals will not move society appreciably towards sustainable industrial development. We feel, none the less, that it will be valuable to attempt to refine IE tools.

Design tools such as DFE *can* help to reduce industry's burden on the environment and should be cautiously advanced. We must, however, acknowledge their limitations: although new approaches to design can realize incremental reductions in the environmental burden of products and processes, DFE will not advance the larger technological and cultural shifts in industrial practice that we believe are necessary to achieve IE's broader goals. The developers of DFE must strive to avoid three crucial pitfalls: linking DFE with unrealistic goals, pouring resources into relatively unimportant detail, and incrementally improving (and thereby entrenching) inherently dirty technologies when cleaner alternatives are available.

More rigorous consideration of the thermodynamic implications of closing material cycles is also needed. The almost complete omission of energy issues – and especially the importance of advancing renewable energy sources to reduce dissipative material throughput – greatly detracts from IE's strength and credibility. Finally, unrealistic and misleading concepts, such as Ecofeedback, do more to thwart IE than advance it and should be vigorously discarded. Along these lines, IE proponents should begin the process of determining what IE is not: that is, to discard vague, overly optimistic and even corrupt conceptions of the field. IE's vision and goals should be debated openly and vigorously. This will serve to focus the concepts and to separate those interested in transformative changes from those interested in putting a new face on the status quo.

The second level of work should help to turn theories and visions into implementable projects. We believe that it will be necessary to experiment with (and study) the implementation of IE concepts initially on a small scale. A role for government may be the promotion and assessment of IE concepts in projects such as 'brownfield' re-development efforts, eco-parks, and regional industrial metabolism studies. Actual implementation efforts should be monitored closely in the coming years as IE projects are begun. Research should focus on the following questions: What role did economic motivation, government policies and the local community have in the formation of existing 'industrial ecosystems', such as the one found in Kalundborg, Denmark, and the eco-park projects in Brownsville, Texas, and Baltimore, Maryland? To what extent have existing eco-park projects reduced material throughput and material dissipation, and what have been the resulting changes in energy demand and energy efficiency? To what extent has the formation of existing industrial ecosystems reduced the flexibility of process innovation? Finally, what are the primary barriers inhibiting the expansion and replication of these projects?

Smaller research projects and feasibility studies on implementing IE in different settings will also be important to advancing the concepts.

The implementation of IE concepts at the firm level is more problematic. If IE is to be

successful it must move from incremental change (and simple pollution prevention) to a more fundamental re-thinking and re-design of products and processes. We, however, are sceptical that a critical re-thinking of industrial practices will come from industry until pressures for change are much stronger. These pressures would include economic incentives and disincentives, legal pressures, and social input into industrial decision-making. It is clear that society must first embrace IE concepts if this sort of social pressure is to be generated to push for changes in industrial-environmental relations.

This brings us to the third level of work. IE's acceptance by the public and environmental organizations will require the development of mechanisms of social input into decisions about the restructuring of industry. As we have alluded to throughout this paper, many of the underlying decisions necessary for the promotion of IE (and DFE and LCA more narrowly) are based on social value judgements. We agree with Schnaiberg that 'we need more socially, economically, and politically integrated ways to observe, assess, and resist the institutions of the treadmill, if we are to be able to initiate and maintain a trajectory of sustainable development' (Schnaiberg, 1994, p.3). IE will not be successful if industry alone embraces its concepts and techniques. Rather, it will be necessary to create social institutions and mechanisms that serve to foster the goal of balancing industrial activity, the environment, and equity concerns. Our belief is that this type of balance is more likely to occur at the local level, where citizens have vested interests in balancing industrial activities with environmental quality.

As we approach the 21st century, a paradigm shift will be required for industry and the environment to move toward balance. This shift will require a re-thinking of more than just waste flows, pollution taxes, and information databases. It will require a change in values, in mechanisms of control over technology, and in the functioning of the economy. 'Sustainable industrial development' represents a critical goal towards which industry, government, and the public should strive. However, this goal will remain ever elusive unless concrete steps are taken to evolve IE gradually towards implementable solutions to industrial-environmental problems.

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