ELSEVIER

PII: S0959-6526(97)00003-6

J. Cleaner Prod. Vol. 5, No. 1-2, pp. 1-10, 1997

Printed in Great Britain
0959-6526/97 $17.00 + 0.00

Industrial ecology: an historical view

S. Erkman

Industrial Maturation Multiplier, P.O. Box 474, 1211 Geneva 12, Switzerland

A new perspective on the industrial system

Industrial ecology? A surprising, intriguing expression that immediately draws our attention. The spontaneous reaction is that 'industrial ecology' is a contradiction in terms, something of an oxymoron, like 'obscure clarity' or 'burning ice'.

Why this reflex? Probably because we are used to considering the industrial system as separate from the biosphere, with factories and cities on one side and nature on the other, the problem consisting of trying to minimize the impact of the industrial system on what is 'outside' of it: its surroundings, the 'environment'. As early as the 1950s, this end-of-pipe angle was the one adopted by ecologists, whose first serious studies focused on the consequences of the various forms of pollution on nature. In this perspective on the industrial system, factories as such remained outside of the field of research.

Industrial ecology explores the opposite assumption: the industrial system can be seen as a certain kind of ecosystem. After all, the industrial system, just as natural ecosystems, can be described as a particular distribution of materials, energy, and information flows. Furthermore, the entire industrial system relies on resources and services provided by the biosphere, from which it cannot be dissociated.

Industrial ecology has been manifest intuitively for a very long time. In the course of the past 30 years the several attempts made in that direction have usually been rather fruitless, except in Japan. The expression re-emerged in the early 1990s, at first among a number of industrial engineers connected with the National Academy of Engineering in the USA[1-5].

Today the concept is progressing with unprecedented vigour. In the past 3 years, the expression 'industrial ecology' has begun to spread in a number of academic and business circles, with the beginning of a perceptible buzzword effect. Thus, in order to avoid any confusion, I would like to specify in this introductory paper what is meant by 'industrial metabolism' and 'industrial ecology'.

'Industrial metabolism' is the whole of the materials and energy flows going through the industrial system. It is studied through an essentially analytical and descriptive approach (basically an application of materials-balance principle), aimed at understanding the circulation of the materials and energy flows linked to human activity, from their initial extraction to their inevitable reintegration, sooner or later, into the overall biogeochemical cycles.

Industrial ecology goes further. The idea is first to understand how the industrial system works, how it is regulated, and its interaction with the biosphere; then, on the basis of what we know about ecosystems, to determine how it could be restructured to make it compatible with the way natural ecosystems function.

As yet, there is no standard definition of industrial ecology, and a number of authors do not make a clear difference between industrial metabolism and industrial ecology. The distinction, however, makes sense not only from a methodological point of view, but also in a historical perspective: the 'industrial metabolism' analogy was in use during the 1980s, especially in relation to the pioneering work of Robert U. Ayres, first in the USA[6-8], then at IIASA (Laxenburg, Austria) with William Stigliani and colleagues[9-14], and more recently at INSEAD (Fontainebleau, France)[15-18]. At about the same time, the metabolic metaphor was pursued independently by Peter Baccini, Paul Brunner and their colleagues at the Swiss Federal Institute of Technology (ETHZ)[19,20]. In parallel, it should be recalled that there is a long tradition of organic metaphors in the history of evolutionary economics and urbanism (urban ecology)[21,22].

Raymond Côté, at Dalhousie University (Halifax, Nova Scotia), compiled a number of definitions from the early literature on industrial ecology[23]. However, whatever the definitions may be, all authors more or less agree on at least three key elements of the industrial ecology/metabolism perspective:

1. It is a systemic, comprehensive, integrated view of all the components of the industrial economy and their relations with the biosphere.
2. It emphasizes the biophysical substratum of human activities, i.e. the complex patterns of material flows within and outside the industrial system, in contrast

with current approaches which mostly consider the economy in terms of abstract monetary units, or alternatively energy flows.

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

An operational approach to sustainability

It is probably no coincidence that the ideas involved in industrial ecology have recently reappeared among industrial engineers, who are accustomed to solving practical problems, given that industrial ecology makes it possible to provide concrete answers to a crucial question that arose out of the big UN conferences that culminated with the Rio Summit in June 1992, namely: How can the concept of sustainable development be made operational in an economically feasible way? Industrial ecology represents precisely one of the paths that could provide real solutions. In fact, it is already more than a smart theoretical idea: the 'industrial symbiosis' that has evolved during the last three decades in the small city of Kalundborg, in Denmark, offers the best evidence that such an approach can be very practical and economically viable[24,25].

Industrial ecology emerges at a time when it is becoming increasingly clear that the traditional depollution approach (end-of-pipe) is insufficient. Several companies have for many years experimented with pollution prevention strategies, but these have thus far been relatively isolated, often very publicized, cases involving a few big companies that can afford to test methods such as life cycle analysis, total quality management, design for environment, etc.[26,27]

Moreover, approaches such as pollution prevention and cleaner production also have their limits. Most industrial activities necessarily generate wastes or by-products. It is impossible to make cheese, for instance, without having the part of the milk that is not used become 'waste' or a 'by-product'. Finally, the pollution prevention and cleaner production approaches still think in terms of preventing and reducing 'wastes', and thus, to a certain extent, share a perspective similar to the end-of-pipe philosophy. By contrast, in certain cases, the industrial ecology approach would even consider to increase the production of a particular 'waste', in the absence of a cleaner production viable alternative, if this would allow this 'waste' to become a marketable (by-)product.

The point is, therefore, to integrate end-of-pipe approaches and prevention methods into a broader perspective, to which they should be subordinated. This is precisely the perspective intended by industrial ecology and industrial metabolism.

Industrial ecology: earlier attempts

There is little doubt that the concept of industrial ecology existed well before the expression, which began to appear sporadically in the literature of the 1970s. As usual, on certain occasions, the same expression does not refer to the same concept: it describes the regional economic environment of companies[28,29] or it is used as a 'green' slogan by some industrial lobbies in reaction to the creation of the US Environmental Protection Agency [30].

However, the concept of industrial ecosystems is clearly present although not explicitly named in the writings of systems ecologists such as Odum, Margalef, and Hall[31–33]. In fact, and not surprisingly, systems ecologists studying biogeochemical cycles had for a very long time the intuition of the industrial system as a subsystem of the biosphere[34,35]. However, this line of thought has never been actively investigated, with the notable exception of agroecosystems, whereas the recent industrial ecology perspective acknowledges the existence of a wide range of industrial ecosystems with varying degrees and patterns of interactions with the biosphere, from certain kinds of almost 'natural' agroecosystems[36] to the supremely artificial ecosystems, like space ships[37–40].

What might be one of the earliest occurrences of the expression 'industrial ecosystem' (in accordance with today's concept) can be found in a paper by the late well-known American geochemist, Preston Cloud. This paper was presented at the 1977 Annual Meeting of the German Geological Association[41]. Interestingly, it is dedicated to Nicholas Georgescu-Roegen, the pioneer of bioeconomics who on many occasions has insisted on the importance of matter and material flows in the human economy in a thermodynamic perspective[42–48], and has also extensively written on technological dynamics[49–52].

Several attempts to launch this new field have been made in the last couple of decades, with very limited success. Charles Hall[53], an ecologist at New York State University, began to teach the concept of industrial ecosystems and publish articles on it in the early 1980s, without getting any response[53]. At about the same period, in Paris, another academic, Jacques Vigneron, independently launched the notion of industrial ecology, without, until very recently, awakening any real interest on his side either[54].

The industrial ecology concept was indisputably in its very early stages of development in the mid-1970s, in the context of the flurry of intellectual activity that marked the early years of the United Nations Environment Program (UNEP). Set up following the 1972 UN Conference on Human Environment in Stockholm, UNEP had as its first director Maurice Strong, who is presently a special adviser to the president of the World Bank. One of his close collaborators at the time was none other than Robert Frosch, who was to make a decisive contribution to the revival of the concept of industrial ecology thanks to an article published in 1989 in the monthly magazine *Scientific American*.

A similar intellectual atmosphere was also prevailing around the same period in other circles, like the United Nations Industrial Development Organization (UNIDO) and the United Nations Economic Commission for Europe (ECE). For example, many papers presented during an international seminar organized by the ECE in 1976 on what was called at that time 'non-waste technology and production' disseminated ideas similar to those discussed today in the cleaner production and industrial ecology literature[55]. Another example: Nelson Nemerow, who has been active in the industrial waste treatment field in the USA for more than 50 years, acknowledges in a recent book a brainstorming session with Alex Anderson of UNIDO in Vienna during the early 1970s, at which time the idea of 'environmentally balanced industrial complexes' in the perspective of zero pollution was born[56]. Very similar ideas were discussed by Ted Taylor, a nuclear physicist turned environmentalist, and Charles Humpstone, a lawyer, in a book published in New York at around the same time[57]. In fact, Ted Taylor had created in 1967 the International Research and Technology Corporation, a company devoted to the development of these concepts, of which he was the president and Robert Ayres the vice president. Other examples of similar thinking could be provided[58,59], including in Russia, where a Department of Industrial Ecology has been in operation for a decade at the Mendeleiev Institute of Chemical Technology[60–63]. Two earlier attempts, however, deserve to be mentioned in some detail here: the Belgium ecosystem research, and the ground-breaking work carried out in Japan.

The Belgium ecosystem

In 1983, a collective work called *L'Ecosystème Belgique. Essai d'Écologie Industrielle* was published in Brussels by the Centre de Recherche et d'Information Socio-politiques, an independent research centre associated with progressive circles in Belgium[64]. The book summarizes the thinking of a half-dozen intellectuals linked to the left-wing socialist movement. Inspired by 'The Limits to Growth' (the Meadows report to the Club of Rome), and especially by the 'Letter' of Sicco Mansholt (Common Market Commissioner), this small group sought to fill a gap that prevailed in standard, including left-wing, economic thinking. The small group comprised six persons from different fields (biologists, chemists, economists), who accomplished this work outside of their everyday occupations. Their idea was to produce an overview of the Belgian economy on the basis of industrial production statistics, but to express these in terms of materials and energy flows rather than the traditional, abstract monetary units.

The basic principles of industrial ecology are thus clearly expressed as follows[64]: '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.' The group studied six main streams from this angle: iron, glass, plastic, lead, wood and paper, and food produce.

One of the main findings was the so-called 'disconnection' between two stages of a stream. This means that 'two sectors in the same stream, which could be complementary and develop in close interaction with each other, are oriented in quantitatively/qualitatively divergent directions'[64]. For instance, 80% of the net output of steel in Belgium is intended for export due to the opening of European borders. Under the authority of the European Community of Coal and Steel (ECCS), the Belgian steel industry thus developed rapidly, without any relationship with the development of the metal-production sector. The opening of outside markets encouraged an excessive growth of a heavy steel industry aimed mainly at the export market, to the detriment of its specializing in more elaborate technological products. As a result, the steel industry was completely disconnected from the metal-construction sector, an unlinking that has made the Belgian steel industry very dependent on exports for selling a rather commonplace product, by consequence of which it is vulnerable to competition on the world market whilst providing an inadequate response to domestic needs.

Another very significant example is that of the unlinking of farming and breeding[64]. In the traditional pattern, there was a certain balance between farming and breeding in a mixed farming concern: the by-products and waste of mixed farming were used to feed the livestock. The animal density remained low, and animal excrements (liquid and solid manure) constituted the basis for soil amendments, sometimes supplemented with mineral fertilizer. The 'modernization' of agribusiness has destroyed this pattern. Livestock, which has become much more important, is fattened with industrial feed made out of imported raw materials.

Breeding has thus progressively cut itself off from farming activities as far as food resources are concerned. The same is true for animal excrements: the considerable mass of excrements can no longer be completely used up because it far surpasses the manuring capacity of the farmland. In both cases (breeding and farming), the by-products have outstripped their natural outlets, and have become waste with disposal problems.

The authors reached the conclusion that the general features of the way the Belgian industrial system works (i.e. opening, specialization, and sectoral unlinking) attest to the internationalization of the Belgian economy, and result in three main forms of dysfunction[64]:

1. The economic opening of the Belgian system leads to the ecological opening of the materials cycles. Consumption residues, which could constitute a resource, are increasingly considered as waste, the disposal of which is a problem.
2. Operation of this economic system requires large energy expenditure. On this point, the analysis of the Brussels group particularly highlights the fact that the increase in primary energy comes less from the increase in end consumption than from a certain type of organization of the energy chain itself, as well as of the industrial system as a whole.
3. The structure of the circulation of materials in the industrial system generates pollution. For example, the present organization of the food chain causes the degradation of surface water.

The Belgian group also developed some interesting ideas on the subject of waste, by underscoring that the notions of 'raw materials' and 'waste' only mean something from the point of view of a system where the circulation of materials is open. Contrary to the current assumption, in which the waste problem is seen as being due to an increase in production and consumption[64]: 'our consumption of raw materials and our production of waste constitute a consequence of the structure of the circulation of raw materials in our industrial system. As for the recycling of waste, we have to realize that the main difficulties are found not at the collection, or even at the sorting stage, but upstream of collection, that is, in the real possibilities of waste disposal in the current structure of our production system.'

According to Francine Toussaint, the main instigator of the project and trade engineer currently working for the Brussels administration, the expression 'industrial ecology' seems to have come up on its own, spontaneously, without having been read or heard elsewhere. Even though the work summarized the basic ideas of industrial ecology with remarkable clarity, its reception was extremely reserved. 'We really had the feeling that we were a voice preaching in the desert' remembers Francine Toussaint. Eventually, the group of friends branched off in different directions, each pursuing their own career, and, despite its interest and originality, the 'Belgium ecosystem' was soon forgotten.

The Japanese view

Japan deserves particularly to be mentioned in the history of industrial ecology. In the late 1960s, the Ministry of International Trade and Industry (MITI), noting the high environmental cost of industrialization, commissioned one of its independent consulting agencies, the Industrial Structure Council, to do some prospective thinking. About 50 experts from a large variety of fields (industrialists, senior civil servants, representatives of consumer organizations) then explored the possibilities of orienting the development of the Japanese economy toward activities that would be less dependent on the consumption of materials, and based more on information and knowledge.

During the 1970 Industrial Structure Council session, the idea came up (without its being possible, apparently, to attribute it to a specific person) that it would be a good thing to consider economic activity in 'an ecological context'.

The final report of the Industrial Structure Council, called 'A Vision for the 1970s', was made public in May 1971. Complying with the recommendations of the report, the MITI immediately set up about 15 work groups. One of these, the Industry-Ecology Working Group, was specifically commissioned to further develop the idea of a reinterpretation of the industrial system in terms of scientific ecology.

The small group was coordinated by Chihiro Watanabe, a young urban engineer, who was then in charge of environmental problems within an MITI agency, the Environmental Conservation Bureau. [After having occupied a variety of positions in MITI for 26 years, Chihiro Watanabe is today a Professor at the Tokyo Institute of Technology and Adviser to the Director of the International Institute for Applied Systems Analysis in Laxenburg, Austria[65].] With the assistance of several outside experts, the members of the Industry-Ecology Working Group began by conducting systematic research of the scientific literature, then consulted with the best international specialists. It was in the course of a US tour in March–April 1973, that Chihiro Watanabe met with one of the great figures of modern ecology, Eugene Odum, at Georgia State University, in Atlanta (who, none the less, did not appear to be particularly interested in the Japanese approach).

After a year's work, in May 1972, the Industry-Ecology Working Group published its first report, a Japanese document of more than 300 pages, a summary of which is available in English[66]. According to Chihiro Watanabe, the report was widely distributed within the MITI, as well as among industrial organizations and the media, where it was considered to be 'stimulating' but also still very 'philosophical'. A second, more concrete report, including case studies, was published a year later in the spring of 1973.

It is difficult to evaluate the exact legacy of the Industry-Ecology Working Group, but there is no doubt that its approach has greatly contributed to the design and implementation of many important MITI research programmes on industrial technology. In April 1973, for instance, the Secretariat of the Minister in charge of MITI officially recommended that a new policy be developed on the basis of the ecology principle, with the accent on energy aspects.

In August 1973, 2 months before the first oil shock, MITI submitted a first budget request for the Sunshine Project. The project, which aimed to develop new energy technology (particularly in the area of renewable energy), was started in July 1974. A few months before the second oil shock, in 1978, MITI launched a supplementary programme, the Moonlight Project, devoted to technology intended to increase energy efficiency. In 1980, MITI founded the New Energy Development Organization (NEDO), then in 1988 launched the Global Environmental Technology Program.

Finally, the New Sunshine Program, devoted to advanced energy technology in view of, among other objectives, achieving an important reduction in greenhouse gas emissions was started in 1993. The New Sunshine Program is itself a component of a broader programme, New Earth 21[67–69].

Without falling into the usual stereotypes on Japan (long-term strategic vision, systemic approach, etc.), we have to acknowledge that it is the only country where ideas on industrial ecology were ever taken seriously and put into practice on a large scale, even though they were already diffusely present in the USA and Europe[70]. The consequences of this are not to be neglected, given that it is through technology developed in the context of an economy that has fully integrated ecological constraints that Japan intends to maintain its status as a great economic power.

A basic principle underlies this strategy: replace material resources with technology. This is why technological dynamics is at the heart of Japanese thinking on industrial ecology[71–77].

This approach, however, is not original per se: research on technological dynamics has been pursued in Europe and the USA for many years by a number of authors such as Jesse Ausubel and Arnulf Grübler[78–86]. However, whereas this thinking has been incorporated in long-term and large-scale industrial strategies in Japan, it has been traditionally (and still remains) mainly academic in the West.

A new departure with *Scientific American*

Every year in September, the popular scientific monthly *Scientific American* publishes an issue on a single topic. In September 1989, the special issue was on 'Managing Planet Earth', edited by William C. Clark (Harvard University), himself an influential member of the early industrial ecology 'invisible college'[87]. The issue featured an article by Robert Frosch and Nicholas Gallopoulos, both then at General Motors, called 'Strategies for Manufacturing' (the original title proposed by the authors was 'Manufacturing—The Industrial Ecosystem View', but was not accepted).

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

However, as Robert Frosch indicated during his lecture, 'Towards an Industrial Ecology', presented before the UK Fellowship of Engineering in 1990[88]: 'The analogy between the industrial ecosystem concept and the biological ecosystem is not perfect, but much could be gained if the industrial system were to mimic the best features of the biological analogy'.

On the occasion of the first symposium on industrial ecology, which took place in Washington in May 1991 under the authority of the National Academy of Science and chaired by Kumar Patel of Bell Labs[89], Robert Frosch pointed out that the idea had been around for a long time: 'The idea of industrial ecology has been evolving for several decades. For me the idea began in Nairobi with discussions at the United Nations Environment Program (UNEP), where we were concerned with problems of waste, with the value of materials, and with the control of pollution. At the same time, we were discussing the natural world and the nature of biological and ecological systems. There was a natural ferment of thinking about the human world, its industries, and its waste products and problems and about the coupling of the human world with the rest of the natural world...'[90].

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

Although the ideas presented in Frosch and Gallopoulos's article were not, strictly speaking, original, the *Scientific American* article can be seen as the source of the current development of industrial ecology. In Washington, the National Academy of Engineering (NAE) had shortly before launched the Technology and the Environment Program, organizing symposia and publishing their reports. The first of these, published in 1989, 'Technology and the Environment', already contains many of the ideas that evolved in the direction of industrial ecology[1]. Braden Allenby, an AT&T executive who spent a 1-year fellowship with the NAE Technology and the Environment Program, presented the first doctoral dissertation on industrial ecology in 1992[91–95].

Ideas on industrial ecology were also disseminated among business circles on the basis of the *Scientific American* article, but indirectly. Hardin Tibbs, a British consultant who was working in Boston in 1989 for the company Arthur D. Little, says that reading Frosch and Gallopoulos's article inspired him to write a 20-page brochure called 'Industrial Ecology: A New Environmental Agenda for Industry'. Arthur D. Little published the text in 1991. It was published again in 1993 by Global Business Network, a consulting company near San Francisco joined by Hardin Tibbs, which develops prospective scenarios for its member companies[96].

In substance, Tibbs's brochure basically reproduces the ideas contained in the Frosch and Gallopoulos article, but Hardin Tibbs' decisive contribution was to translate them into the language and rhetoric of the business world, and to present them in a very summarized form in a document just a few pages long, stamped first with the Arthur D. Little label, then with that of the Global Business Network. The Hardin Tibbs brochure quickly sold out, then hundreds of xeroxed copies of it were circulated, spreading Frosch and Gallopoulos's ideas throughout the business world. Other authors, also inspired by the Frosch and Gallopoulos article, began to write papers disseminating the idea in both academic and business circles[97–99].

Directions and challenges for industrial ecology

Eight years after the seminal article of Frosch and Gallopoulos, one can see the industrial ecology approach evolve in two main directions:

Eco-Industrial parks, and islands of sustainability

The most immediate application of the ecological concept of food webs between companies lies in the creation or retrofitting of industrial zones where waste or by-products of one company are used as resources by another company: hence the concept of 'eco-industrial parks' (EIP)[100–108]. A number of EIP projects are under way in the USA, Europe and Asia. This systemic approach goes further than the case-by-case waste exchanges programmes; many of them where launched in the 1970s with a limited success, although quite a few are still in operation today[109–112].

More generally, there is the idea of creating 'industrial biocenoses' around certain specific industrial activities (thermal power plants, steel mills, paper mills, sugar cane, etc.). Such industrial clusters would have minimal emissions[56,113–116]. In fact, the idea of systemic waste exchanges can be extended beyond the boundaries of an industrial zone, and can lead to regional thinking, like the concept of 'islands of sustainability'[25,117,118].

However, in order to design sound industrial ecosystems, EIP or larger structures, there is an urgent need for good industrial metabolism studies, based on the relevant methodology for a given socioeconomic and geographical context (at present there are different methodologies for industrial metabolism). It should be strongly reminded that Kalundborg also has its drawbacks, and that almost all the published literature on the Kalundborg symbiosis is second-hand information or very preliminary work. One of the first tasks of the newly created Symbiosis Institute devoted to the development and promotion of the Kalundborg experience will be to perform a detailed study of the material flows, and a thorough assessment of the economic and policy aspects as well.

In addition, there is an urgent need for a systematic exploration of the concepts of scientific ecology in the perspective of industrial ecology, since the work done so far in this direction has been very preliminary[119]. This will also prevent the excessive development of a 'feel-good industrial ecology' based on ideological assumptions like 'in Nature there are no wastes', or that 'natural ecosystems live in a fragile equilibrium'. Especially misleading is the idea that we should 'mimic nature': in the industrial ecology perspective, we should certainly get inspiration from the biosphere, and design human structures compatible with its normal functioning, but this may not necessarily mean designing structures and objects with 'organic shapes', using only 'natural' materials.

Demateralization–decarbonization and the service economy

The second main direction relates to the development of concepts and strategies for the optimization of the flows of materials within the economy, which is largely based, as said earlier, on technological evolution. This implies an increase in resource productivity, or dematerialization, which is not a trivial concept (for example, lighter objects might have a shorter life, generating more waste). The concept of resource productivity has a long history, and was raised originally in the context of the relative diminishing demand for mineral resources, and later of the fear of scarcity[120–125]. In the past few years, the issue of dematerialization has attracted renewed interest, dematerialization being seen as a positive trend and a desirable strategy[126–136].

Obviously, dematerializing the economy would also imply diminishing the global consumption of energy (since there would be less matter to extract, transform and transport). Already now, a company like Shell explicitly considers a 'dematerialization scenario' in its long-term prospective studies[137]. For the time being, however, the main approach in relation to energy is the 'decarbonization' strategy, with the objective of decreasing the relative content of carbon in fuels, which means shifting from coal to petrol, then to natural gas and ultimately to solar or nuclear hydrogen[138–142].

One very promising approach to what may be called 'systemic dematerialization' is the strategy of service economy, which promotes the selling of services instead of products[143–146]. Systemic dematerialization refers to the fact of increasing the resource productivity not only at the level of the product, but at the level of global infrastructures, in order to reduce not only the total material throughput, but also, most importantly, to decrease its speed within the industrial system, thus minimizing the problem of dissipative emissions during normal use.

Finally, there is a need for integrating industrial ecology, design for environment, cleaner production, pollution prevention, into new management practices (cooperative management, over-the-fence management). Education of engineers, economists, managers and natural scientists becomes crucial, in order to deal with a serious cultural problem: ecologists (not only political ecologists, but scientific ecologists as well) usually do not know about the industrial system. However, engineers, and people from industry in general, have a very naïve view of nature and are very defiant against ecologists and ignorant about scientific ecology[23,147–149].

An attraction to profit...and to elegance

Ever since its emergence about two centuries ago, the Western industrial system has never ceased to change. In the long run, from a very general historical perspective, industrial ecology may one day appear as a sort of 'natural' stage, which will have allowed the industrial system to continue to evolve, just as primitive bacteria once 'invented' aerobic respiration to get an advantage out of oxygen, a toxic waste that had been rejected by the metabolism of the first forms of life on Earth.

One lesson that could be remembered from all the previous attempts towards industrial ecology is that the evolution of industrial system is far from linear (from worse to better); in fact, one reason for the difficulty in implementing industrial ecology is that dominant ideas in the economy tend to the opposite direction, like favouring the opening of materials cycle and built-in obsolescence.

Today, however, beyond the political ecologist view and fashionable rhetoric on sustainable development, the actual motivation for this evolution obviously lies in an increased economic competitiveness: industrial ecology is a way for corporations to better exploit their products and resources (including their waste) more efficiently, and therefore more profitably.

As surprising as it may seem, one strong motive that could ensure a lasting success for industrial ecology might very well be aesthetic. An industrial system that generates more wealth with fewer resources and fewer impacts on the biosphere would incontestably be more elegant. As Jesse Ausubel, one of the pioneers of the industrial ecology, says: 'The goal of industrial ecology is a more elegant, less wasteful network of industrial processes'[150]. A more elegant industrial society, a more intelligent economy: this is probably a challenge that engineers should engage, and, with them, many political and economic players, and ordinary citizens.

References

1 Ausubel, J. H. and Sladovich, H. E., *Technology and Environment*. National Academy of Engineering, National Academy Press, Washington, DC, 1989.
Patel, C. K. N., *Proceedings of the National Academy of Sciences of the United States of America*, 1992, **89**, 798–799
Allenby, B. R. and Richards, D. J., *The Greening of Industrial Ecosystems*. National Academy Press, Washington, DC, 1994.
Richards, D. J. and Frosch, R. A., *Corporate Environmental Practices. Climbing the Learning Curve*. National Academy Press, Washington, DC, 1994.

2 Socolow, R., Andrews, C., Berkhout, F. and Thomas, V. *Industrial Ecology and Global Change*. Cambridge, UK, Cambridge University Press. (Volume based on the Office for Interdisciplinary Earth Studies 5th "Global Change Institute", organized by T. Graedel, W. Moomaw and R. Socolow, held in Snowmass, CO, 19–31 July 1992.)

3 Schulze, P., *Engineering Within Ecological Constraints*. National Academy Press, Washington, DC, 1996.
Ausubel, J. H. and Langford, H. D., *Technological Trajectories and the Human Environment*. National Academy Press, Washington, DC, 1997.

4 Gaedel, T. E. and Allenby, B. R., *Industrial Ecology*, Prentice Hall, Englewood Cliffs, NJ 1994.

5 Allen, D. T. and Rosselot, K. S., *Pollution Prevention for Chemical Processes*. Wiley, New York, 1997.

6 Ayres, R. U. and Kneese, A. V., *Production, Consumption, and Externalities*. Resources for the Future, Inc., Washington, DC, 1969.

7 Ayres, R. U., in *Technology and Environment*, ed. J. H. Ausubel and H. E. Sladovich. National Academy of Engineering, National Academy Press, Washington, DC, 1989, pp. 23–49.

8 Ayres, R. U., *International Social Science Journal*, 1989, **121**, 363–373.

9 Ayres, R. U., Norberg-Bohm, V., Prince, J., Stigliani, W. M. and Yanowitz, J., Industrial metabolism, the environment, and application of materials-balance principles for selected chemicals. Research report RR-89-11, IIASA, Laxenburg, October 1989.

10 Stigliani, W. M. and Anderberg, S., *IIASA Options*, September 1991, 4–10.

11 Stigliani, W. M. and Anderberg, S., Industrial metabolism at the regional level: the Rhine Basin. Working paper no. WP-92-10, IIASA, Laxenburg, January 1992.

12 Stigliani, W. M. and Jaffe, P. R., Industrial metabolism and river basin studies: a new approach for the analysis of chemical pollution. Research report RR-93-6, IIASA, Laxenburg, September 1993, 45 pp.

13 Stigliani, W. and Anderberg, S., in *Industrial Metabolism. Restructuring for Sustainable Development*, ed. R. U. Ayres and U. E. Simonis. United Nations University Press, Tokyo, 1994, pp. 119–162.

14 Lohm, U., Anderberg, S. and Bergbäck, B., in *Industrial Metabolism. Restructuring for Sustainable Development*, ed. R. U. Ayres and U. E. Simonis. United Nations University Press, Tokyo, 1994, pp. 103–118.

15 Ayres, R. U., Industrial metabolism. Theory and policy. FS II 92-406, Wissenschaftszentrum Berlin für Sozialforschung (WZB), Berlin, 1992, 18 pp.

16 Ayres, R. U., Eco-restructuring: the transition to an ecologically sustainable economy. Working paper no. 93/35/EPS, INSEAD, Center for the Management of Environmental Resources, Fontainebleau, May 1993, 31 pp.

17 Ayres, R. U., in *Clean Production Strategies. (Developing Preventive Environmental Management in the Industrial Economy)*, ed. T. Jackson. Lewis Publishers, Boca Raton, 1993, pp. 165–188.

18 Ayres, R. U. and Simonis, U. E., *Industrial Metabolism. Restructuring for Sustainable Development.* United Nations University Press, Tokyo, 1994.
Ayres, R. U. and Ayres, L. W., *Industrial Ecology. Towards Closing the Materials Cycle.* Edward Elgar, Cheltenham, UK, 1996.
19 Baccini, P. and Brunner, P., *Metabolism of the Anthroposphere.* Springer-Verlag, Berlin, 1991.
20 Brunner, P. H., Daxbeck, H. and Baccini, P., in *Industrial Metabolism. Restructuring for Sustainable Development*, ed. R. U. Ayres and U. E. Simonis. United Nations University Press, Tokyo, 1994, pp. 163–193.
21 Hodgson, G. M., *Futures*, May 1994, 392–403.
Hodgson, G. M., *Economics and Evolution, Bringing Life Back into Economics.* Polity Press, Cambridge, 1993.
Stokes K. M., *Man and the Biosphere. Toward A Coevolutionary Political Economy.* M. E. Sharpe, Armonk, NY, 1994.
22 Wolman, A., *Scientific American*, **213**, 1965, 179–190.
23 Côté, R. P., The Industrial Ecology Seminar: Principles, Topics for Discussion and Dictionary. School for Resource and Environmental Studies, Faculty of Management, Dalhousie University, Halifax, Nova Scotia, Industrial Park as an Ecosytem Project, December 1995.
24 Gertler, N., *Industrial Ecosystems: Developing Sustainable Industrial Structures.* Massachusetts Institute of Technology, Technology and Policy Program, Cambridge, MA, 1995, 141 pp.
25 Schwarz, E. J. and Steininger, K. W., *The Industrial Recycling-Network. Enhancing Regional Development.* University of Graz, Department of Economics, Research Memorandum no. 9501, Graz, Austria, April 1995, 18 pp.
26 Sullivan, M. S. and Ehrenfeld, J. R. *Total Quality Environmental Management*, 1992, **2**, 143–157.
27 Keoleian, G. A. and Menerey, D. *Air and Waste*, 1994, **44**, 645–668.
28 Hoffman, C., The industrial ecology of small and intermediate-sized technical companies: implications for regional economic development. Report prepared for the Economic Development Administration COM-74-10680, Texas University, May 1971, 31 pp.
29 Hoffman, C. and Shapero, A., Providing the industrial ecology required for the survival and growth of small technical companies. An action program for the Ozarks Region. Report prepared for the Ozarks Regional Commission. Multi-Disciplinary Research, Inc., Austin, May 1971, 82 pp.
30 Gussow, D. and Meyers, J., *Industrial Ecology*, 1970, **1**, 1.
31 Odum, H. T. and Pinkerton, R. C. *American Scientist*, 1955, **43**, 331–343.
32 Margalef, R. *The American Naturalist*, 1963, **97**, 357–374.
33 Hall, C. A. S., *Bulletin of the Atomic Scientific*, 1975, **31**, 11–21.
Hall, C. A. S., *Maximum Power. The Ideas and Applications of H. T. Odum.* University Press of Colorado, Niwot, CO, 1995.
34 Vernadsky, W. I., *Transactions of the Connecticut Academy of Arts and Sciences*, 1944, **35**, 487–517.
Hutchinson, E. C., *The Scientific Monthly*, 1948, **LXVII**, 393–398.
35 Brown, H., *Scientific American*, 1970, **223**, 194–208.
36 Cole, D. J. A. and Brander, G. C., in *Ecosystems of the World*, Vol. 21, ed. D. W. Goodall. Elsevier, Amsterdam, 1986.
37 Folsome, C. E. and Hanson, J. A., in *Ecosystem Theory and Application, Environmental Monographs and Symposia*, ed. N. Polunin. Wiley, New York, 1986, pp. 269–288.
38 Lasseur, C., in *Preparing for the Future—ESA's Technology Programme*, Vol. 4, No. 1, March, European Space Agency, Paris 1994, pp. 12–13.
39 Lasseur, C., Verstraete, W., Gros, J. B., Dubertret, G. and Rogalla, F., in *Advances in Space Research*, in press.
40 Lasseur, C., Verstraete, W., Gros, J. B., Dubertret, G. and Rogalla, F. MELISSA—an example of artificial ecosystem. Poster presented at 30th Cospar (Committee on Space Research), ESA/ESTEC, Hamburg, Germany, 10–21 July 1994.
41 Cloud, P. *Geologische Rundschau*, 1977, **66**, 678–696.
42 Georgescu-Roegen, N., in *U.S. Economic Growth from 1976 to 1986: Prospects, Problems and Patterns*, ed. H. H. Humphrey. Government Printing Office, Washington, DC, 1976, pp. 62–91.
43 Georgescu-Roegen, N. *Growth and Change*, 1979, **10**, 16–23.
44 Georgescu-Roegen, N., in *Energy Policy:The Global Challenge*, ed. P. N. Nemetz. Butterworth, London, 1979, pp. 107–127.
45 Georgescu-Roegen, N., in *Future Sources of Organic Materials*, ed. L. E. St-Pierre and G. R. Brown. Pergamon Press, Oxford, 1980, pp. 79–87.
46 Georgescu-Roegen, N., *Eastern Economic Journal*, 1986, **XII**, 3–25.
47 Georgescu-Roegen, N., in *Organization and Change in Complex Systems*, ed. M. Alson. Paragon House, New York, 1990, pp. 225–234.
48 Daly, H. E., *Journal of Political Economy*, 1968, **76**, 392–406.
Grinevald, J., in *Entropy and Bioeconomics*, ed. J. C. Dragan *et al.* Nagard, Milan, 1993, pp. 241–258.
49 Georgescu-Roegen, N., *Atlantic Economic Journal*, 1978, **VI**, 15–21.
50 Georgescu-Roegen, N., in *Self-Organization and Dissipative Structures*, ed. W. C. Schieve and P. M. Allen. University of Texas Press, Austin, 1982.
51 Georgescu-Roegen, N. *Materials and Society*, 1983, **7**, 425–435.
52 Georgescu-Roegen, N., *Atlantic Economic Journal*, 1984, **XII**, 21–31.
53 Hall, C. S., Cleveland, C. J. and Kaufmann, R. *Energy and Resource Quality: The Ecology of the Economic Process.* University Press of Colorado, Niwot, CO 1992 (2nd edn).
54 Vigneron, J., in *Ecologie industrielle*, ed. P. Esquissaud. Hermann, Paris, 1990, pp. 1–26.
55 Economic Commission for Europe (ECE), *Non-waste Technology and Production.* Proceedings of an International Seminar by the Senior Advisers to ECE Governments on Environmental Problems on the Principles and Creation of Non-waste Technology and Production, Paris, 29 November–4 December 1976. Pergamon Press/United Nations, Oxford, 1978.
56 Nemerow, N. L., *Zero Pollution for Industry. Waste Minimization Through Industrial Complexes.* Wiley, New York, 1995.
57 Taylor, T. B. and Humpstone, C., *The Restoration of the Earth.* Harper and Row, New York, 1972.
58 Farvar, M. T. and Milton, J. P., *The Careless Technology: Ecology and International Development.* Natural History Press/Doubleday & Co., New York, 1972.
59 Dasmann, R. F., Milton, J. P. and Freeman, P. H., *Ecological Principles for Economic Development.* Wiley, London, 1973.
60 Zaitsev, V. A., *Russian Chemical Industry*, 1993, **25**, 1–4.
61 Ermolenko, B. V., *Russian Chemical Industry*, 1994, **26**, 3–17.
62 Zaitsev, V. A., *Russian Chemical Industry*, 1994, **26**, 1–2.
63 Yurtov, E. V., Shkinev, V. M. and Khromykh, N. V., *Russian Chemical Industry*, 1994, **26**, 20–24.
64 Billen, G., Toussaint, F., Peeters, P., Sapir, M., Steenhout, A. and Vanderborght, J.-P., *L'Écosysème Belgique. Essai d'Écologie Industrielle.* Centre de Recherche et d'Information Socio-politique—CRISP, Bruxelles, 1983.
65 Watanabe, C., The interaction between technology and economy: national strategies for constrained economic environments. The case of Japan 1955–1992. Working paper WP-95-16, IIASA, Laxenburg, February 1995, 98 pp.
66 Watanabe, C., *Industry–Ecology: Introduction of Ecology into Industrial Policy.* Ministry of International Trade and Industry (MITI), Tokyo, 1972, 12 pp.
67 Ministry of International Trade and Industry (MITI), Trends and future tasks in industrial technology. Developing innovative technologies to support the 21st century. Summary of the white paper on industrial technology. MITI, Tokyo, September 1988, 29 pp.
68 Ministry of International Trade and Industry (MITI), New Sunshine Program. New Sunshine Program Promotion Headquarters, Agency for Industrial Science and Technology (AIST), Ministry of International Trade and Industry (MITI), Tokyo, 1992, 40 pp.
69 Ishida, Y., *The Futurist*, July–August 1993, 20–24.
70 Richards, D. J. and Fullerton, A. B., *Industrial Ecology: U.S.–Japan Perspectives.* National Academy Press, Washington, DC, 1994.
71 Watanabe, C., *The Bridge*, 1993, **23**, 815.

72 Watanabe, C., An ecological assessment of Japan's industrial technology system. Special lecture to MIT. Massachusetts Institute of Technology, Cambridge, MA, June 1993, 42 pp.

73 Inoue, H., *New Technology Japan*, 1992, special issue, 1–17.

74 Watanabe, C., Santoso, I. and Widayanti, T., *The Inducing Power of Japanese Technological Innovation*. Pinter Publishers, London, 1991.

75 Watanabe, C., *Technological Forecasting and Social Change*, 1995, **49**, 127–145.

76 Yoshikawa, H., *Technological Forecasting and Social Change*, 1995, **49**, 195–213.

77 Akimoto, Y., *Technological Forecasting and Social Change*, 1995, **49**, 165–173.

78 Ausubel, J. H., *The Sciences*, 1993, **33**, 14–19.

79 Lee, T. and Nakicenovic, N., in *Life Cycles and Long Waves*, Vol. 340, *Lecture Notes in Economics and Mathematical Systems*, ed. T. Vasko, R. U. Ayres and L. Fontvieille. Springer-Verlag, Berlin, 1990, pp. 1–17.

80 Grübler, A., *The Rise and Fall of Infrastructures. Dynamics of Evolution and Technological Change in Transport*. Physica Verlag, Heidelberg, 1990.

81 Grübler, A., Industrialization as a historical phenomenon. Working paper WP-95-29, IIASA, Laxenburg, March 1995, 64 pp.

82 Grübler, A., in *Life Cycles and Long Waves*, ed. T. Vasko, R. Ayres and L. Fontvieille. Springer-Verlag, Berlin, 1990, pp. 118–146.

83 Grübler, A., *Technological Forecasting and Social Change*, 1991, **39**, 159–180.

84 Grübler, A., Technology and global change: land-use, past and present. Working paper WP-92-2, IIASA, Laxenburg, 1992, 65 pp.

85 Grübler, A., *Daedalus*, 1996, **125**, 19–42.

86 Nakicenovic, N., in *Life Cycles and Long Waves*, ed. T. Vasko, R. Ayres and L. Fontvieille. Springer-Vèrlag, Berlin, 1990, pp. 147–192.

87 Clark, W. C. and Munn, R. E., *Sustainable Development of the Biosphere*. IIASA/Cambridge University Press, Laxenburg, 1986.

88 Frosch, R. A. and Gallopoulos, N. E., in *The Treatment and Handling of Wastes*, ed. A. D. Bradshow *et al.* Chapman and Hall, London, 1992, pp. 269–292.

89 Patel, C. K. N., *Proceedings of the National Academy of Sciences of the United States of America*, 1992, **89**, 793–878.

90 Frosch, R. A., *Proceeedings of the National Academy of Sciences of the United States of Amrica*, 1992, **89**, 800–803.

91 Allenby, B. R., Design for environment: implementing industrial ecology. Doctoral Dissertation for Rutgers University, Ann Arbor, ME University Microfilms, Publication no. 9232896, 1992.

92 Allenby, B. R., *International Environmental Affairs*, 1992, **4**, 56–68.

93 Allenby, B. R., *MRS Bulletin (Materials Research Society)*, 1992, **17**, 46–51.

94 Allenby, B. R., *Total Quality Environmental Management*, 1993, **2**, 303–308.

95 Allenby, B. R., *IEEE Circuits and Devices*, 1994, **10**, 24–28.

96 Tibbs, H., *Industrial Ecology. An Environmental Agenda for Industry*. Global Business Network, Emeryville, CA, 1993.

97 Lowe, E., *Total Quality Environmental Management*, 1993, **3**, 73–85.

98 Pizzocaro, S., Theoretical approaches to industrial ecology: Status and perspectives. Draft for discussion, Politecnico di Milano, Dipartimento PPPE, Milan, October 1994, 8 pp.
Pizzocaro, S., *Disseny Communicacio Cultura*, No. 10, September 1994, Barcelona, pp. 80–92.
Manzini, E. and Pizzocaro, S., Ecologia industriale. Milano (Italy), Istituto per l'Ambiente, Quaderni di ricerca No. 4, 1995, 89pp.

99 O'Rourke, D., Connelly, L. and Koshland, C. P., *International Journal of Environment and Pollution*, 1996, **6**, 89–112.

100 Côté, R. P., Ellison, R., Grant, J., Hall, J., Klynstra, P., Martin, M. and Wade, P., Designing and operating industrial parks as ecosystems. Report of the project 'The Industrial Park as an Ecosystem'. Dalhousie University, School for Resource and Environmental Studies, Halifax, Nova Scotia, August 1994, 300 pp.

101 Lowe, E., *Eco-Industrial Park Design Concept*. Indigo Development, Oakland, Ca, 1993.

102 Weitz, K. and Martin, S. A., Regulatory issues and approaches for encouraging eco-industrial park development. Report prepared for 'Designing, Financing and Building the Industrial Park of the Future, An International Workshop on Applications of Industrial Ecology to Economic Development', Institute of the Americas, University of California, San Diego, 4–5 May 1995, 38 pp.

103 Lowe, E. A., Moran, S. A. and Holmes, D. B., Fieldbook for the development of eco-industrial parks. Report prepared for the Office of Policy, Planning and Evaluation by Indigo Development. US Environmental Protection Agency, Washington, DC, 1996.

104 Lowe, E. A. and Warren, J. L., The source of value: an executive briefing and sourcebook on industrial ecology. Future Studies Unit, US Environmental Protection Agency, Washington, DC. Prepared by Indigo Development and Pacific Northwest National Laboratory under contract DE-AC06-76RLO 1830, April 1996.

105 President's Council On Sustainable Development (PCSD), *Eco-Industrial Park Workshop Proceedings*, 17–18 October 1996, Cape Charles, Virginia. PCSD, Washington, DC, February 1997.

106 Hileman, B., *Chemical and Engineering News*, 1995, May 29, p. 34.

107 Victory, K. M., *Business and the Environment*, 1995, **VI**, 2–6.

108 Frankel, C., *Tomorrow*, 1996, pp. 26–27.

109 Deloy, J. C., in *Non-waste Technology and Production*, ed. Economic Commission for Europe (ECE). Pergamon Press/United Nations, Oxford, 1978, pp. 247–251.

110 Kulander, K. E., Lindfors, L.-Q. and Lohrdén, E., in *Non-waste Technology and Production*, ed. Economic Commission for Europe (ECE). Pergamon Press/United Nations, Oxford, 1978, pp. 317–324.

111 DiPietro, R., *BioCycle*, January 1994, p. 75–76.

112 Pesacreta, P., Review of industrial waste exchanges. Report EPA-530-K-94-003, US Environmental Protection Agency, Waste Minimization Branch, Office of Solid Waste, Washington, DC, 1994, 61 pp.

113 Ayres, R. U., *Creating Industrial Ecosystems: A Viable Management Strategy?* INSEAD, Center for the Management of Environmental Resources, Fontainebleau, November 1994.

114 Pauli, G., in *Steering Business Toward Sustainability*, ed. F. Capra and G. Pauli. United Nations University Press, Tokyo, 1995, pp. 145–162.

115 Mangan, A., *By-product Synergy: A Strategy for Sustainable Development: A Primer*. Business Council for Sustainable Development—Gulf of Mexico, Austin, TX, April 1997.

116 Krieger, J. H., *Chemical and Engineering News*, July 8, 1996, 8–16.

117 Wallner H. P. and Narodoslawsky, M., *Journal of Cleaner Production*, 1995, **2**(3–4), 167–171.
Wallner H. P. and Narodoslawsky, M., *Journal of Environmental Systems*, 1995, **24**(3), 221–240.

118 Wallner, H. P. and Narodoslawsky, M., *Journal of Environmental Systems*, 1995, **24**, 221–240.

119 Allenby, B. R. and Cooper, W. E., *Total Quality Environmental Management*, 1994, **3**, 343–354.

120 Malenbaum, W., *World Demand For Raw Materials in 1985 and 2000*. McGraw-Hill, New York, 1978.

121 Fischman, L. L., World mineral trends and US supply problems. Resources for the future. Research paper R-20, Washington, DC, 1980.

122 Humphreys, D., *Resources Policy*, 1982, **8**, 215–229.

123 Humphreys, D. and Briggs, S., *Resources Policy*, 1983, **9**, 4–22.

124 Auty, R., *Resources Policy*, 1985, **11**, 275–283.

125 Waddell, L. M. and Labys, W. C., *Materials and Society*, 1988, **12**, 59–86.

126 Herman, R., Ardekani, S. A. and Ausubel, J. H., in *Technology and Environment*, ed. J. H. Ausubel and H. E. Sladovich. National Academy of Engineering, National Academy Press, Washington, DC, 1989, pp. 50–69.

127 Kanoh, T., in *Science and Sustainability* (Selected Papers on IIASA 20th Anniversary), ed. IIASA. IIASA, Laxenburg, 1992, pp. 63–94.

128 Bernardini, O. and Galli, R., *Futures*, May 1993, 431–448.

129 Schmidt-Bleek, F., *Fresenius Environmental Bulletin*, 1993, **2**, 485–490.

130 Welfens, M. J., *Fresenius Environmental Bulletin*, 1993, **2**, 431–436.

131 Schmidt-Bleek, F., Where we stand now. Actions toward reaching a dematerialized economy. Declaration of the first meeting of the Factor 10 Club in Carnoules, France, September 1994. Wuppertal Institute, Carnoules, France, 26 October 1994.

132 Wernick, I., *Journal of the Minerals, Metals, and Materials Society*, 1994, 46, 39–42.

133 Hinterberger, F. and Seifert, E. K., in *Environment, Technology and Economic Growth: the Challenge to Sustainable Development*, ed. J. van der Straaten and A. Tylecote. Edward Elgar Publishing, Aldershot, forthcoming.

134 Wernick, I. K. and Ausubel, J. E., *Resources Policy*, 1995, **21**(3), 189–198.

135 Wernick, I. K., *Technological Forecasting and Social Change*, 1996, **53**, 111–122.

136 Wernick, I. K., Herman, R., Govind, S. and Ausubel, J. H., *Daedalus*, 1996, **125**, 171–198.

137 Dupont-Roc, G., *The Evolution of the World's Energy System 1860–2060*. Shell International Petroleum Company, Group Planning, London, 1994.

138 Ausubel, J. H., *Energy Systems and Policy*, 1991, **15**, 181–188.

139 Nakicenovic, N., *IIASA Options*, September 1992, 2–9.

140 Ausubel, J. H., *The Electricity Journal*, 1996, **9**, 54–60.

141 Nakicenovic, N., *Daedalus*, 1996, **125**, 95–112.

142 Ausubel, J. H. and Marchetti, C., *Daedalus*, 1996, **125**, 139–169.

143 Stahel, W. R. and Reday-Mulvey, G., *Jobs for Tomorrow. The Potential for Substituting Manpower for Energy*. Vantage Press, New York, 1981.

144 Stahel, W. R., in *Waste Minimization and Clean Technology: Waste Management Strategies for the Future*, ed. W. S. Forester and J. H. Skinner. Academic Press, London, 1992, pp. 91–97.

145 Stahel, W. R. and Jackson, T., in *Clean Production Strategies (Developing preventive environmental management in the industrial economy)*, ed. T. Jackson. Lewis Publishers, Boca Raton, FL, 1993, pp. 261–291.

146 Giarini, O. and Stahel, W. R., *The Limits to Certainty. Facing Risks in the New Service Economy*, 2nd revised edn. Kluwer Academic Publishers, Dordrecht, 1993.

147 Sears, P. B., *Science*, 1947, **106**, 1–3.

148 Ehrenfeld, J. R., in *The Greening of Industrial Ecosystems*, ed. B. R. Allenby and D. J. Richards. National Academy Press, Washington, DC, 1994, pp. 228–240.

149 Côté, R. and Hall, J., eds, The industrial ecology reader. Report of the project 'The Industrial Park as an Ecosystem'. School for Resource and Environmental Studies, Faculty of Management, Dalhousie University, Halifax, Nova Scotia, 1994.

150 Ausubel, J. E., *Technology in Society*, 1994, **16**(2), 139–154.