Advancing the concepts of industrial ecology in South African institutions

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INDUSTRIAL ECOLOGY SEEKS TO APPLY THE knowledge of systems in nature to the design and operation of industrial activities, to achieve integrated and sustainable relationships between the natural world and industry. Although the theoretical underpinning of the field corresponds in some ways to that of the emerging discipline of sustainability science, industrial ecology has evolved along two main directions that may be more practical for industry and policy-makers: 'eco-industrial parks' and islands of sustainability; and 'dematerialization–decarbonization' and the service economy. The opportunities and risks associated with applying the concepts of industrial ecology have been argued globally. This article provides an overview of how the concepts have already been applied to some extent in South Africa. We recommend how industrial ecology may be nurtured here, prioritizing areas where the field can be institutionalized.

Introduction

A recent commentary in this journal[1] introduced and defined the emerging field of sustainability science as use-inspired basic research, and discussed its main elements in some detail in the South African context:

- Location at the interface between human society and its sustaining natural environment;
- focus on the resilience of complex socio-ecological systems;
- a transdisciplinary approach to understanding system complexity and resilience;
- acknowledgement of the validity of multiple epistemologies, extending beyond the objectivity of science to include the subjectivity of alternative knowledge systems; and
- emphasis on learning and adaptation.

Many of these elements also manifest themselves in the field of 'industrial ecology'; indeed, it has been argued that these concepts underpin industrial ecology, which may therefore be regarded as the science of sustainability.[2] Industrial ecology is described as a systems-based, multidisciplinary discourse that seeks to understand emergent behaviour of complex integrated human/natural systems.[3] The difference between industrial ecology and sustainability science lies with the core disciplines whence they have emerged, namely, engineering and economics on the one hand, and the natural sciences on the other. Recent literature points to a growing unification of the two fields. It has been suggested, for example, that industrial ecology, unlike formal disciplines or fields of study, integrates multiple, mutually exclusive ontologies, and is thus conceptually complex in ways that are new and particularly challenging.[3] The merging of the two fields is further highlighted through the principles of industrial ecology, which are defined as follows:[4]

- Economies, society and nature co-evolve;
- economies and society are embedded in a larger natural system, which must function within its carrying capacity;
- material and energy flows in industry interact with the material and energy cycles in nature; the consequences are determined by the common properties of all matter;
- efficiency and resilience translate into the sustainability of an ecosystem, which depends largely on its capacity to withstand disturbance. This can contribute to the sustainability of an industrial ecosystem;
- wastes and pollution are (to a degree) minimized in nature, which should also apply to industry;
- treating companies as organisms and economies as ecosystems can emulate the natural diversity and interconnectedness of organisms in the economic system, and may eventually call for a systems approach to describe it;
- the importance of information and communication is underlined as a strategy for improving the interconnectedness within an industrial ecosystem;
- issues of locality should be addressed in terms of reducing a system's dependence on external resources, focusing on local interdependence, and managing production and storage of hazardous substances in a responsible manner.

Figure 1 illustrates how 'industrial ecology' is a construction between what is ecologically possible within the framework of the capacity of the ecosystems involved (the biosphere) and what is socially desirable and acceptable within the framework of a sustainable society.[5] Curve A represents connections between concern, ethical involvement and wishes for a new way of solving problems based on a holistic approach, which gives motivation and justification for implementing new industrial strategies (B). The connection between practical ecology and industrial ecology (C) must be made explicit, to manage this new challenge and to connect problem-solving to real life situations. Support from new scientific knowledge comes along arrow D.

These descriptions represent the latest theoretical and conceptual perspectives. However, given the would-be environmentally-benign manufacturing foundation of industrial ecology,[6] and attempts

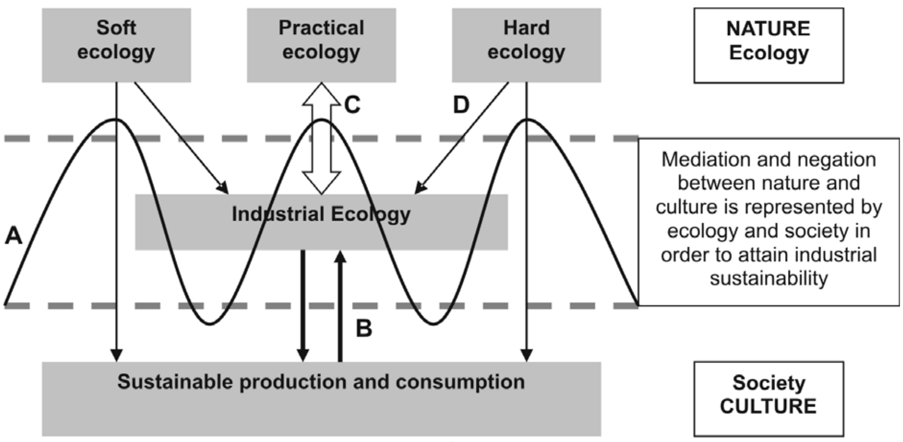

Fig. 1. Proposed relationship and interaction between ecology and sustainable production and consumption.[5]

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to institutionalize the field,[7] it has been noted[8] that the industrial ecology approach has evolved into two main, more practical directions.

Eco-industrial parks, and islands of sustainability

The concept of 'eco-industrial parks' (EIPs)[9] is the most immediate application, which aims to reconstruct industrial zones where waste or by-products of one company can be used as resources by another business; this is also termed industrial symbiosis. This systemic approach goes further than case-by-case waste exchange programmes. In general, the idea is to create 'industrial biocenoses' around certain specific industrial activities, for example, thermal power plants, or the processing of agricultural products, and that such industrial clusters would have diminished (gaseous) emissions and waste streams. The concept of 'islands of sustainability' has emerged,[10] extending this idea beyond the boundaries of industrial zones, towards regional thinking. Much emphasis has been placed on research into 'industrial metabolism',[11] which is based on appropriate methods for a given socio-economic and geographical context[8] to design sound industrial ecosystems, EIPs or larger structures.

Dematerialization–decarbonization and the service economy

Strategies to optimize the flows of materials and energy within the economy that are based on technological evolution are the second main elements of industrial ecology. They seek to increase the productive use of resources, or dematerialization,[12] which is not a trivial concept—lighter objects might have a shorter life, generating more waste; this has been the experience of the electronics industry.[8] It further implies reducing the global consumption of energy, because there would be less matter to extract, transform and transport. The main approach in relation to energy, however, is currently on 'decarbonization' strategies, with the objective of reducing the amount of carbon emission per unit of energy consumed, as with renewable energy systems, and carbon sequestration schemes.[13] Research on industrial ecology has been classified into two groups[14] to this end:

- Analytical support for 'green engineering' and environmental policy, which relate to tools for green engineering, improvement in life-cycle assessment, aggregation of environmental impacts, and effectiveness of range of innovative policy approaches; and
- the dynamics of technology, economics and environmental impact, as they relate to the environmental effects of material and energy consumption, the potential for material and energy efficiency, the relation of technological and economic development to changes in consumption patterns, and the potential for technology to overcome environmental impacts and constraints.

The online supplement for this article (at www.sajs.co.za) provides an overview of globally perceived opportunities and risks associated with applying industrial ecology in terms of the two main directions in which industrial ecology has evolved,[15–28] and summarizes related international experiences.[29] We argue that such examples and experiences are valuable for understanding and institutionalizing the field in South Africa. This article describes how the concepts of industrial ecology have already been applied in this country to some extent; supporting details are also provided in the online supplement. Our overall objective is to establish how industrial ecology may be further advanced in the South African context by prioritizing areas to institutionalize the field here.

Applications of industrial ecology in South Africa

Experiences in South Africa relating to industrial ecology are summarized in a table in the online supplement; selected examples are used for further discussion.

Eco-industrial parks and industrial symbiosis

Eco-industrial parks (EIPs) are not new in this country. The Nuclear Energy Corporation of South Africa (NECSA), for example, owns and manages an EIP between Pretoria and Hartbeespoort Dam, with over 80 tenants with shared services, including recycling.[30] No by-product exchanges occur, however. This type of 'eco-estate' is not characteristic of many international EIPs, which involve:[31]

- Collective setting of available utilities;
- the collective processing of waste streams;
- mutual exchange of materials and energy;
- consume residual products from remote companies; and
- deliver residual products to remote companies.

The characteristics of foreign EIPs do, nevertheless, manifest in the planning of South African industrial development zones (IDZs), for instance, the Coega IDZ near Port Elizabeth.[32,33] Although the concept of international EIPs is envisaged for the IDZs, the ideal has yet to become practice. Lessons can be learnt from regional applications of industrial symbiosis, such as the Integrated Waste Exchange (IWE) programme of the Cape Metropolitan Council (CMC) (see online supplement).[34–36] A study was initiated to investigate the success of the programme in terms of economic efficiency, based on a cost-benefit analysis and its possible environmental and social consequences.[37] The study and a separate review[38] indicates that this approach has achieved only limited success. The reasons have been attributed to: lack of marketing strategies; lack of follow-through; lack of legislative support; and lack of financial support by the CMC.

The limited success is typical of industrial symbiosis projects launched by local and regional authorities, and not the private sector (see the comparison of Dutch and American experiences in the online supplement). The market potential for the IWE programme has nevertheless not yet been fully realized and, because its implementation is believed to still be in an initial phase, further pioneering strategies will be required to increase its success.[38]

Dematerialization–decarbonization and the service economy

The public and private sectors in South Africa have in the past adopted only the tools that are used in terms of the dematerialization and decarbonization focus of industrial ecology, e.g. life-cycle assessment (LCA) and material flow analysis (MFA),[39] to a limited extent.[40] The recent establishment of the Designated National Authority (DNA) for the Clean Development Mechanism (CDM) in South Africa[41] has revitalized the application of these tools. The CDM provides the means to support financially projects that minimize greenhouse gas (GHG) emissions (see online supplement);[42,43] the industrial ecology tools are used to quantify potential GHG reductions.

Projects to minimize GHG emissions have also created opportunities to improve material usage.[44] For example, the manufacturing of blended cement at all of the South African cement plants[45] reduces energy consumption, as well as offering an opportunity for improved industrial ecology, because the additives can be waste from iron and steel manufacture (blast furnace slag) or from coal combustion (fly ash).[46] Thirteen CDM projects have at present been approved and registered through the South African DNA.[41]

The development of other similar projects, as investment in developing countries increases,[36] will support further applications of industrial ecology and the associated tools.

Advancing industrial ecology in the South African context

The adoption of industrial ecology in South Africa suggests that the most progress in terms of institutionalizing the field can be made through industrial symbiosis strategies at local and regional level. Three different stages in the evolution of industrial ecology initiatives for brown field sites have been conceptualized,[27] namely, regional efficiency, regional learning, and the sustainable industrial district (see online supplement). A selection stage precedes these three stages in the case of green field sites. At the selection stage, the actors that will form the core of the socio-technical system are selected. This selection can involve criteria related to the perceived process of sustainable development in a specific context.[27]

The life cycle of industrial ecology can also be expressed in terms of phases in time and the type of relationship between organizations in an area;[27] these are often interconnected.[24] South Africa still finds itself in the birth and growth life-cycle phases, with some informal and formal networks, and mostly in the regional efficiency stage, although regional learning has been occurring in certain instances due to, for example, the establishment of waste minimization clubs[38] and the increase in cleaner production initiatives.[47]

Obstacles to initiation and management of an industrial ecosystem have been noted:[48]

- Company concerns with regard to propriety or confidential information;
- negotiating balance of payments;
- reluctance on the part of a business to be involved in inflexible contractual commitments that do not relate directly to their core activity; for instance, guaranteeing a waste stream for a contractual period;
- supervision and operation of co-treatment facilities; and
- the complexity of managing the wastes produced by the companies.

An additional barrier in South Africa is that there is no legislative support for industrial symbiosis; specifically, there is no clear guidance as to the responsibilities of the parties associated with the waste streams. Five mechanisms have been proposed to promote industrial symbiosis:[38]

- Working through public-private partnerships, for example, between local authorities who operate treatment facilities and landfill sites, industries that discharge problem waste to these facilities and sites, waste companies that specialize in waste re-use and recycling, and national government that is responsible for legislative guidelines;
- using the South African National Cleaner Production Centre (NCPC)[49] to develop and assist with the implementation of appropriate technologies and procedures for industrial symbiosis;
- use of trading platforms to link waste generators and waste re-users and recyclers;
- introducing funding mechanisms, particularly to enhance and support the exchange of low value commodities; and
- linking waste minimization clubs, waste exchanges and future industrial ecological parks and zones.

In terms of the latter, specific research needs have been identified to review and promote best practice in industrial regions (see online supplement).[50] For example, efforts are well under way for a scoping exercise for a regional case study of heavy industries in the Rustenburg area, based on the Kwinana industrial area in Western Australia.[50, 51] It is envisaged that a changing nature of industrialization in South Africa can eventually be instilled through such efforts, culminating in a comprehensive approach to industrial ecology, whereby all process systems and equipment, with plant and factory design, will eventually be fully compatible with existing industrial ecosystems as a matter of course.[52]

Conclusions

If production and consumption methods in human controlled systems could be made to emulate the efficiencies of natural systems, then greater sustainability would ensue, and a means would emerge to address the growing amount of waste produced by industry and a consumption-driven society.[53] To this end, new uses and innovative techniques for exploiting waste materials need to be identified in South Africa. This is the domain of industrial ecology that draws on some vision of an ecological network of interconnected actors exchanging matter and energy. The ecological metaphor leads to the usage of certain tools, such as material flow analysis (MFA), and life-cycle assessment (LCA). Systems can thereby be derived that better use the emissions and waste flows of industry and domestic consumption. Waste could be minimized by applying a disposal system for industry via an ecological framework, whereby by-products are converted into re-usable products or resources. New paradigms of production and consumption are needed to recycle and exchange by-product materials and capture and exchange waste energy in a sustainable manner.[53]

One of the more intricate implementations of industrial ecology lies in the establishment of industrial ecosystems (where an industrial estate operates as an 'ecosystem'), with residual energy and materials being traded or sold between companies or co-treated for ultimate disposal. Industrial facilities individually implement waste minimization programmes and cleaner production initiatives under this system. The estate, as a whole, looks for the potential for on-site re-use, recycling, recovery or co-treatment for disposal of the wastes that cannot be economically managed by the individual facilities. A few such industrial ecosystems have been set up abroad; it is envisaged that the field of industrial ecology may be institutionalized in South Africa through this routeCindustrial ecology can thus be used to realise the concept of sustainability. The science of sustainability may thereby not only manifest itself in the thinking of research institutions, but also in policy, planning and management practices of government and industry. We have identified a number of barriers that need to be overcome to facilitate the adoption of industrial ecology in South African institutions, and ongoing regional case studies could lead to solutions that will overcome these barriers. The role of economic development officials and researchers should be to promote policies that will remove the obstacles to the recovery of industrial resources, and to educate the public and private sectors as to the benefit of industrial symbiosis. As such, more emphasis should be on the development of mechanisms that would more effectively encourage individual companies to manage waste streams effectively while leaving them the necessary freedom to develop new and profitable uses for by-products.

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The institutionalization of the concepts of industrial ecology

The attempts to integrate the concepts of industrial ecology in international institutions are summarized in Table 1.[6]

Strategic opportunities and risks associated with the application of industrial ecology and international experiences

A hierarchical model has been proposed for a systems approach for strategic sustainable development.[15] Subsequently, it has been argued that industrial ecology (IE) has much potential as a concept that can be applied to and used on all five levels of the hierarchical model;[16] such applications are summarized in Box 1.

However, if industrial ecology is not used within such a structured, holistic model, i.e. only at singular levels of such a model, there are many risks that it can actually contribute to unsustainability, thereby making sustainability policy and management more difficult:

- Policies, approaches, technologies and the tools, instruments and techniques associated with industrial ecology should be applied with caution, to avoid suboptimal solutions. For example, the 'Jevon's paradox'[17] and the 'rebound effect' [18] hold that efficiency will increase consumption, because of the desires inherent in human nature. An industrial ecology example is the much-cited fossil fuel/raw-material resource-based Kalundborg application (see the next section for a description of the example),[19] which illustrates that industrial ecology can also be used under the substitutability and the eco-efficiency assumptions; such applications may put long-term sustainability at risk, because levels 1 and 2 of strategic sustainable development models may be compromised (see Box 1).[16]
- The fundamental and normative, as well as the practical and instrumental, stages of the sustainability concept must be taken into account when applying the techniques of industrial ecology. If the eco-industrial park or local industrial symbiosis approaches are used to contrast individual product-based environmental life cycle assessments[20] or an environmental management system (EMS) of an individual company, conflicting suggestions for policy and management may arise. The LCA and EMS tools may support waste reduction of a single product life cycle or company, i.e. eco-efficiency, while the

Box 1

Level 1. Principles for the constitution of the system
- IE argues for systems interdependency between economic and social subsystems and the parent ecosystem
- IE contributes to material and energy flow principles
- IE systems and networks philosophy has the potential to contribute to social principles, e.g. with inter-organizational corporate social responsibility management

Level 2. Principles for a favourable outcome of planning within the system; principles for sustainability as the desired outcome
- IE provides material and energy flow limits and thresholds of ecological sustainability

Level 3. Principles for the process to reach the above outcome of sustainability, e.g. principles of sustainable development to research sustainability
- IE offers planning principles

AND/OR
- IE offers constructs that can be used as hypotheses in sustainability systems analysis, from which systems planning principles can be derived

Level 4. Actions and concrete measures
- IE offers suggestions for material and energy flow reduction
- IE offers suggestions for material and energy flow substitution, e.g. recycling of matter and cascading of energy
- IE provides a network and systems approach for these reductions and substitutions

Level 5. Tools and metrics to monitor and audit
- IE offers inter-organizational management systems and concepts, e.g. regional environmental management and auditing systems (REMS)
- IE can be used to develop systems-level indicators
- IE suggests for 'what if?' scenarios, the economic, ecological and social effects of which one can measure and calculate for decision-making, policy and management

Table 1. The institutionalization of industrial ecology.

Institutions	Mechanisms
Academia and other research institutions	The systems orientation of industrial ecology empowers it to be able to address questions beyond the scope of many other, more narrowly circumscribed disciplines. This characteristic of industrial ecology answers, in part, calls for the establishment of interdisciplinarity, with sufficient power and breadth to cope with today's complex socio-technical problems. The institutionalization of industrial ecology has been helped along by the presence of researchers from many other established fields. In a sense, industrial ecology is a 'melting pot' for these contributors, who have migrated from other fields.
Industry	• Case-by-case waste exchange programmes; internationally, many were launched in the 1970s with limited success, although a few are still in operation today[a]. • The use of life-cycle assessment (LCA) is found in most well-established consumer products companies. The ISO 14000 environmental management standard contains a standard for LCA (ISO 14040-43)b. Supply chain protocols, now in place for many large products-orientated companies, frequently require that suppliers to these companies carry out LCAs or at least provide basic material and energy flow data.
Government	Material flow accountingc is beginning to appear in the national statistical accounting practices of a few countries. This set of practices, although not yet widely influencing the policy process, is being moved along by the formation of an international group of industry ecology practitioners and economists from national bureaus that have convened several meetings and gathered around some common research themes.

[a]Pesacreta P. (1994). Review of industrial waste exchanges. US Environmental Protection Agency report EPA-530-K-94-003, Waste Minimization Branch, Office of Solid Waste, Washington, D.C.
[b]These can be obtained from Standards South Africa. Online at: www.sabs.co.za/Business_Units/Standards_SA/index.aspx
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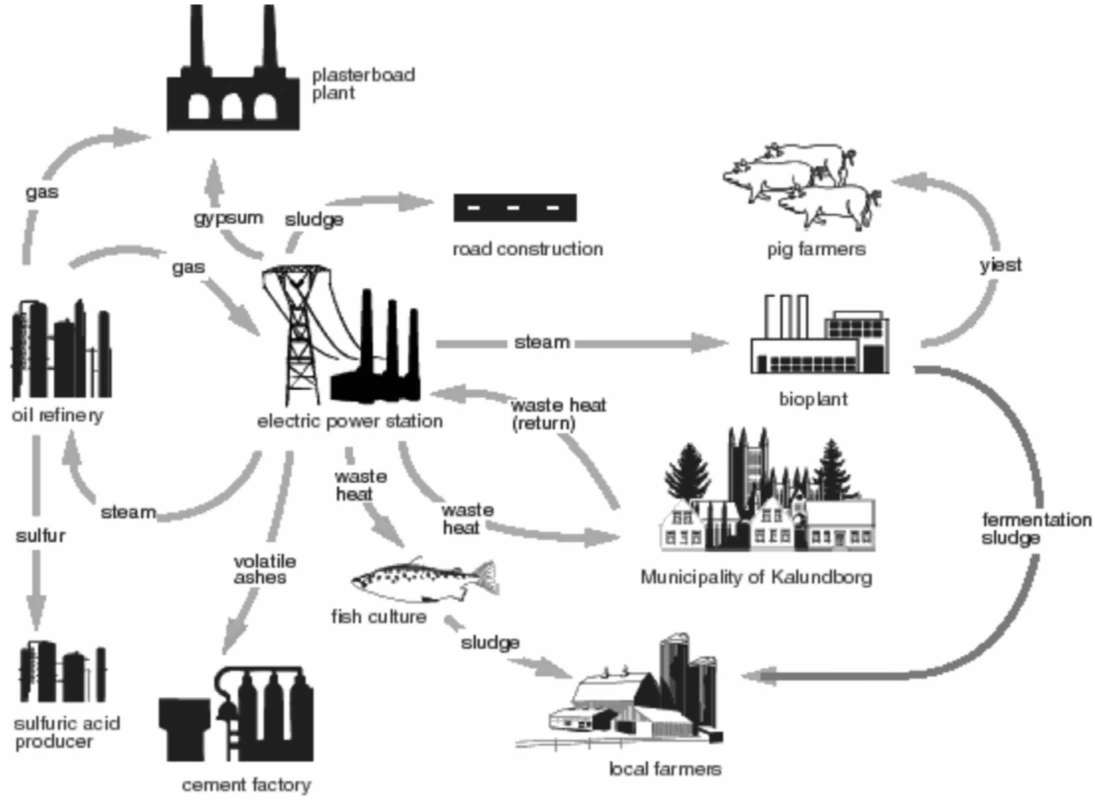

Fig. A. Network of companies in the Kalundborg symbiosis. From: www.indigodev.com/Kal.html

industrial ecosystem approaches may require waste to be used as raw material or as fuels in a network of companies, to reduce the environmental burden of the system as a whole.[16]

- Two stages for a paradigm shift must be considered to make progress on local and regional sustainable development, i.e. the paradigmatic and the practice stages.[16] In the practice stage industrial ecology offers tools and techniques for studying networks of physical flows of matter and energy, with the main contribution being a systems approach that complements the more traditional intra-organizational approaches. In the paradigmatic stage the contribution is the use of the natural ecosystem metaphor. However, the ecosystem metaphors of locality, cooperation, interdependency, community, connectedness and diversity may not adequately describe social theories.[16] For example, models have been developed to optimize the cooperation and inclusion of community cultures to maximize a paradigm shift towards recycling of materials and energy flows.[21]
- The emphasis of industrial ecology on networks and inter-organizational environmental management can have negative effects, if long-term continuous improvement is not considered.[16] The notion of 'flexible platforms' should be incorporated, whereby investments and other applications in the process of sustainable development should always be planned in a way that also enables continuous future improvement.[22] If not, unhealthy dependencies and technological 'lock-ins'[23,24] or path dependencies[25] can occur. Networking can thus hamper innovation. In turn, although technological innovation still holds the high ground as the most promising potential path towards sustainability, it is becoming evident that innovative processes for a sustainable future must depart from those of the past.

These risks indicate that the field of industrial ecology has been developed without a strategic perspective. The lack of strategic thinking and understanding can lead to reductionism and costly piecemeal approaches, or to failing to see the holistic, big picture, the intent of industrial ecology. The understanding of the evolution of industrial systems over time toward sustainable or unsustainable ways of operation is especially important for the purposes of environmental performance analyses and subsequent future planning of policy and management[26]. Furthermore, industrial ecology has mainly been developed from applied and natural sciences. The human-dimensions in terms of social sciences, cultural studies, management and organizational aspects are still limited in the field.[16] In some cases, e.g. the Rotterdam harbour and industry complex, social sciences approaches have been used in addition to techno-economics, ranging from organizational learning to the analyses of industrial districts, as a means to reflect on the industrial ecology developments for decision-support purposes.[27] Although the difficulties and possibilities to measure the ecological, economic and social dimensions of sustainability have been critically examined, it has been argued that the different available tools and metrics are complementary and can be used to support each other.[28] The examples provided, and other experiences of industrial ecology[29] (as summarized in Table 2), are valuable for understanding and institutionalizing the field in South Africa.

Danish example of industrial symbiosis

The small city of Kalundborg in Denmark provides the currently best-known example of industrial symbiosis in action. The primary business includes an oil refinery, power station, gypsum board facility, and a pharmaceutical company that share ground water, surface water, wastewater, steam, and fuel, and exchange a variety of by-products that become inputs in other processes. The network of companies in the Kalundborg symbiosis, showing the extent of the material and energy exchanges in 1995, is illustrated in Fig. A (more details can be found at www.indigodev.com/Kal.html). Symbiosis in Kalundborg

Table 2. Some international experiences and case studies of industrial ecology.

Countries	Summary of experience and/or case study
Sweden[a]	The paper explores how IE can contribute to the environmental management work of local authorities and how municipal organizations can contribute to local and regional IE. In addition to specific knowledge on an individual case study, it is found that substance flow analysis is a tool with which more general knowledge can be produced for use beyond the individual municipality in other municipal environmental management and IE projects.
Finland[b]	The importance of considering both the quantitative and the qualitative side of material and energy flow tools is discussed. Flows of the Finnish forest industry and wood fuel use are examined to arrive at a conclusion that a nutrient-rich forest contains high levels of nitrogen and phosphorus although, in quantitative terms, stem wood is the main raw material of the industry. Furthermore, many opportunities for recycling are identified. The case study is also an illustrative example of the fact that metaphors such as 'closed loops of industrial ecosystems' are different from industrial and economic practice; nutrient flows extend over regional and national borders.
Belgium[c]	The study alerts one to the risks and difficulties that may appear in the use of results of substance flow analysis in policy planning and implementation, focusing on chromium flows in the Flemish regional economic system of the country. It is shown that the results of the study, and hence eventually the implications it yields for policy, are affected by the substance being studied, the data that are available as well as the region being investigated.
Germany[d]	The Rhine-Neckar region of the country is used to indicate that larger regions than those usually addressed in industrial symbiosis at the industrial site/park level can also yield fruitful opportunities for closing material loops. It is suggested that information technology tools can be used in such larger regional industrial ecosystem applications to improve networking and cooperation between regional small- and medium-sized companies. The paper addresses the need to consider carefully the system boundaries that should be used in IE, i.e. an individual substance flow, the product(s), the process(es), the organization(s), the networks, industrial parks or some larger region and where to draw the line for product life cycles and inter-regional flows.
United Kingdom[e]	An evolving national industrial symbiosis programme in Britain is described that is exploring the local and regional company networks of material and energy flows. The role of a coordinating body, a key actor or an 'anchor tenant' of industrial symbiosis networks is highlighted and it is shown that all cases are different, with their distinct situational factors.
Netherlands and the USA[f]	Comparative analyses between the two countries conclude that Dutch IE projects appear to be more successful than the American counterparts. The difference in success is attributed to the fact that the US projects were initiated by local and regional governments whereas the Dutch projects were usually started by the companies themselves.
Australia[g]	Planning principles for local and regional development of eco-industrial parks in Queensland are considered. The paper specifically addresses the question of system boundaries, and considers the importance of the supportive role of local and regional public authorities for such parks.
Singapore[h]	The conceptual bridges of landscape ecology and IE are explored, focusing on Singapore's Jurong Island. It is shown how landscape ecology concepts and approaches can be used to help planners and managers to understand integrated or hybrid human industrial, residential or urban infrastructural and natural systems.
China[i]	Some Chinese experiences are reflected upon with the aim of bridging industrial symbiosis to the concepts of corporate environmental management. Environmental or green supply chain management is an inter-organizational environmental management approach that looks beyond the borders of a single company. Environmental supply chain management and environmental life cycle management tools can complement industrial symbiosis studies through also including those flows that cross local and regional borders. It is further observed that when locally integrating two supply chains, a process that could evolve into a local industrial ecosystem may be initiated.
Asian developing countries[j]	Based on experiences of different countries in the Asia-Pacific region, it is suggested that developing countries there could adopt IE as a long-term strategy tool for the planning of national development and economic strategies. In this way it may be possible to avoid the mistakes that were made and problems that arose when rapid industrialization and economic growth took place in the developed countries of the region. Although the international networking in IE research and projects is seen as useful for learning about efficient concepts, strategies and technologies and from the experience of past industrialization, it is the indigenous resources and ability to utilize these that determine the success of industrial ecology in developing countries.
Kenya[k]	A case study on charcoal in Kenya is used to show that the application of IE must be approached with a different emphasis in developing countries than in developed countries. It illustrates that the life cycle management approach can yield environmental gains, help to reduce poverty, reduce human health problems and enhance social development, all of which are critical for sustainable development on the continent. However, lack of appropriate institutional, legal and policy support systems is observed as a barrier for IE applications on the Africa continent in general.

[a]Lindqvist A. and von Malmborg F. (2004). What can we learn from local substance flow analyses? The review of cadmium flows in Swedish municipalities. *J. Cleaner Prod.* **12**, 909–918.
[b]Antikainen R., Haapanen R. and Rekolainen S. (2004). Flows of nitrogen and phosphorus in Finland: the forest industry and use of wood fuels. *J. Cleaner Prod.* **12**, 919–934.
[c]Timmermans V. and van Holderbeke M. (2004). Practical experiences on applying substance flow analysis in Flanders: bookkeeping and static modelling of chromium. *J. Cleaner Prod.* **12**, 935–945.
[d]Sterr T. and Ott T. (2004). The industrial region as a promising unit for eco-industrial development: reflections, practical experience and establishment of innovative instruments to support industrial ecology. *J. Cleaner Prod.* **12**, 947–965.
[e]Mirata M. (2004). Experiences form early stages of an national industrial symbiosis programme in the UK: determinants and coordination challenges. *J. Cleaner Prod.* **12**, 967–983.
[f]Heeres R.R., Vermeulen W.J.V. and de Walle F.B. (2004). Eco-industrial park initiatives in the USA and the Netherlands: first lessons. *J. Cleaner Prod.* **12**, 985–995.
[g]Roberts B.H. (2004). The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study. *J. Cleaner Prod.* **12**, 997–1010.
[h]Yang P.P.-J. and Lay O.B. (2004). Applying ecosystem concepts to the planning of industrial areas: A case study of Singapore's Jurong Island. *J. Cleaner Prod.* **12**, 1011–1023.
[i]Zhu Q. and Cote R.P. (2004). Integrating green supply chain management into an embryonic eco-industrial development: a case study of the Guitang Group. *J. Cleaner Prod.* **12**, 1025–1035.
[j]Chiu A.S.F. and Yong G. (2004). On the industrial ecology potential in Asian developing countries. *J. Cleaner Prod.* **12**, 1037–1045.
[k]Kituyi E. (2004). Towards sustainable production and use of charcoal in Kenya: exploring the potential in life cycle management approach. *J. Cleaner Prod.* **12**, 1047–1057.

has resulted in substantial economic and environmental benefits. Since the publicity of Kalundborg's symbiosis in the early 1990s, researchers have been investigating many questions that are also relevant for the South African context: Why did this phenomenon occur in Kalundborg? Are there other regions exhibiting industrial symbiosis? How can such systems be replicated? Are they strictly the product of self-organization by economic entities, or can they be planned in a structured manner? Answering these critical questions requires the engagement of a variety of disciplines: science, engineering, economics, business, policy, environmental management, systems engineering, law, and planning.

South African cases

South African case studies that show elements of industrial ecology are summarized in Table 3.

Table 3. South African case studies with elements of industrial ecology.

Activity	Initiative	Characteristics and identified critical aspects
Industrial Waste Exchange	Sedibeng District Municipality[a]	• A model for reducing industrial waste currently disposed of to landfill. • Industries were concerned about confidentiality of the information supplied. • Waste streams were identified and the re-use potential of the identified material evaluated. • No technical obstacles to exchanging material were present. • The majority of the waste outflows had a possible user. • Most of these users showed interest in possible exchanges. • Many legal constraints were identified, with the very restrictive definition of waste being the most complicated of all. • Transport of material is another constraint. Waste is invariably classified as a mixed load with higher transport costs as a result. • A change in the definition of 'waste' to enable improved 'waste' exchange between industries is needed. • Industries participating in waste exchange programmes should stay in control of the organization that is established for that purpose and information supplied by industry remains confidential. • A form of brokerage or subscription based membership for the sharing of information is preferred.
	Cape Metropolitan Council[b]	• 'Virtual eco-industrial parks' – industries not in close proximity to each other. • Most material listings are for relatively low-value material, i.e. paper and plastic. • Producing companies see waste exchange as an opportunity to make money instead of paying for disposal. • Existing recycling companies looking for new input streams have made most material requests. • Between 0.16% and 1.26% of the total waste stream generated in the Cape Metropolitan Area was exchanged. • Market potential not yet fully realized. • This waste exchange does not reduce transport distance or related emissions. • Local material exchange partnerships should be promoted.
Eco-industrial Parks	Capricorn Park near Muizenberg[c]	• EcA 68-ha business and technology park.o-friendly. • Fully serviced. • Subscribes to a leading environmental management system. Note: Although termed an eco-industrial park, IE principles are not included in the description.
	Krugersdorp and Bronkhorstspruit[d]	• Proposed eco-industrial parks with focus on greenhouse farming using bio-organic fertilizers. Note: These were planned by a company using waste management technology with the aim of zero waste to landfill.
	Darling eco-industrial park[e]	A windfarm is being planned in the area. • An eco-industrial park is planned to provide local employment in industries that will benefit, not destroy, the environment.
	Pelindaba eco-industrial park[f]	• Shared services, including recycling. • No by-product exchanges occur.
Cleaner Production	Waste minimization clubs[g]	• Most existing waste minimization clubs in South Africa share the following characteristics: • Comprise between 6-12 cooperating companies. • Hold regular meetings to share information and experiences. • Every member has access to consultant time usually employed to undertake a waste minimization assessment. • Members have access to students for a defined period, free of charge, to assist in identifying and implementing opportunities. • Regular newsletters are published. • Members sign a declaration of commitment. • Annual membership fees are paid. • Most clubs are subsidized by national or local government, Water Research Commission or donor funding. • Each club has a constitution and bank account. • Waste minimization clubs are mainly sector based.

[a]Department of Environmental Affairs and Tourism (2006). National Waste Management Strategy: Industrial Waste Exchange Baseline Study Report Sedibeng District Municipality. Online at: www.deat.gov.za/nwmsi/

[b]Department of Environmental Affairs and Tourism (2005). National Waste Management Strategy Implementation - Recycling – Review of Industrial Waste Exchange. Online at: www.deat.gov.za/nwmsi/

[c]Capricon Park. Online at: www.capricorn.co.za/

[d]New era in solid-waste disposal. *Engineering News* (Johannesburg) 10 March 2000. Online at: www.engineeringnews.co.za

[e]African Development Bank (2004). The Darling Wind Farm - A Kick Start for Wind Power in South Africa? *Finesse Africa Newsletter.* Online at: www.afriwea.org/en/darlipp.htm

[f]NECSA eco-industrial park. Online at: www.necsa.co.za/

[g]Department of Environmental Affairs and Tourism (2004). Assessment of the Status Quo of Cleaner Production in South Africa. Final Report. Online at: www.environment.gov.za/Documents/

Table 4. Quantitative cost–benefit analysis (market affecting factors) of Cape Town's Integrated Waste Exchange programme.

	Costs	Benefits
Material provider	Time for exact material detail determination. Time for listing on the website. Time for searching on the website. Transport costs of exchanged material.	Revenue for exchanged material.Avoided transport costs to landfill site. Avoided disposal costs. Environmentally friendly image.
Material receiver	Costs of exchanged material. Time for exact material detail determination. Time for listing on the website. Time for searching on the website. Transport costs.	Avoided raw material costs. Environmentally friendly image.
IWE website catalogue owner	Investment IWE planning and realization. Maintenance and care costs. Brokering costs.	Avoided costs of material handling and disposal. Savings due to delayed regional landfill project. IWE promotion. Environmentally friendly image.

The Integrated Waste Exchange programme of the Cape Metropolitan Council

The Waste Management Department of the Cape Metropolitan Council (CMC) launched an Integrated Waste Exchange (IWE) programme in May 2000 as a pilot project.[34] The primary objective was to reduce the industrial waste streams going to the Cape Metropolitan Area (CMA) landfill sites and to use optimally known reserves of valuable materials in the area.[35] The programme was built on a previous industrial symbiosis project, initiated in the 1990s as part of a larger portfolio of cleaner production demonstration projects in the Cape Town region, with the aim to map and exploit financial, market and supply chain linkages between small and medium-sized enterprises, and thereby optimize environmental and economic performances.[36] The IWE programme influenced potential material exchanges through a web-based catalogue[34] managed by a contracted broker. In 2002 eighty-five companies and one hundred and sixty-six material listings were entered into the IWE website catalogue.

The cost-benefit analysis of the CMC IWE integrated waste exchange programme

A qualitative cost-benefit analysis (market-affecting factors) of the Integrated Waste Exchange programme of Cape Town is provided in Table 4.[34]

Overview of the Clean Development Mechanism

The purpose of the Clean Development Mechanism (CDM) is to assist developing countries (not included in Annexure 1 of Article 12 of the Kyoto Protocol) in achieving sustainable development and in contributing to the ultimate objective of the United National Framework Convention on Climate Change, and to assist developed countries (included in Annexure 1) in achieving compliance with quantified emission limitation and reduction commitments under Article 3 of the Protocol.[42] CDM specifically aims to lower the overall cost of reducing greenhouse gas (GHG) emissions released to the atmosphere in developing countries, by forming a means for international trading of GHG emissions. Annex 1 countries can thereby purchase reduced GHG emissions in non-Annex 1 countries and the funds are allocated to reduce the implementation cost of the CDM eligible project in the host country, i.e. South Africa. The host country has to give a final approval for each CDM project through its DNA.[43]

Stages versus the life cycle phases of industrial ecology.

The stages as compared to the life cycle phases of industrial ecology[27] are summarized in the following Table 5.

Further research requirements

Research is needed to review and promote best practice of industrial symbiosis[50] is illustrated in Fig. B.

Table 5. Stages versus life-cycle phases of industrial ecology.

		Phases in time			
Stages	Description	Birth	Growth	Maturity	Decline
Regional efficiency	Autonomous decision-making by companies; coordination with local companies to decrease inefficiencies through local social networks. Is characterized by identifying and making use of existing win-win situations.	Easily inserted into development	Possibilities for win-win	Narrow search for win-win	No incentive to search for eco-efficiency; if induced, search might lead to 're-birth'
Regional learning	Based on mutual recognition and trust; companies and other partners exchange knowledge, and broaden the definition of sustainability on which they act. Other stakeholders may become involved as well. Thus, both goal and range of membership are broadened.	Difficult due to unestablished networks	Learning coincides with natural tendency of the group	Need to counteract inertia	
Sustainable district	Actors develop an evolving strategic vision on sustainability and base their activities on this vision.			Need to counteract inertia	

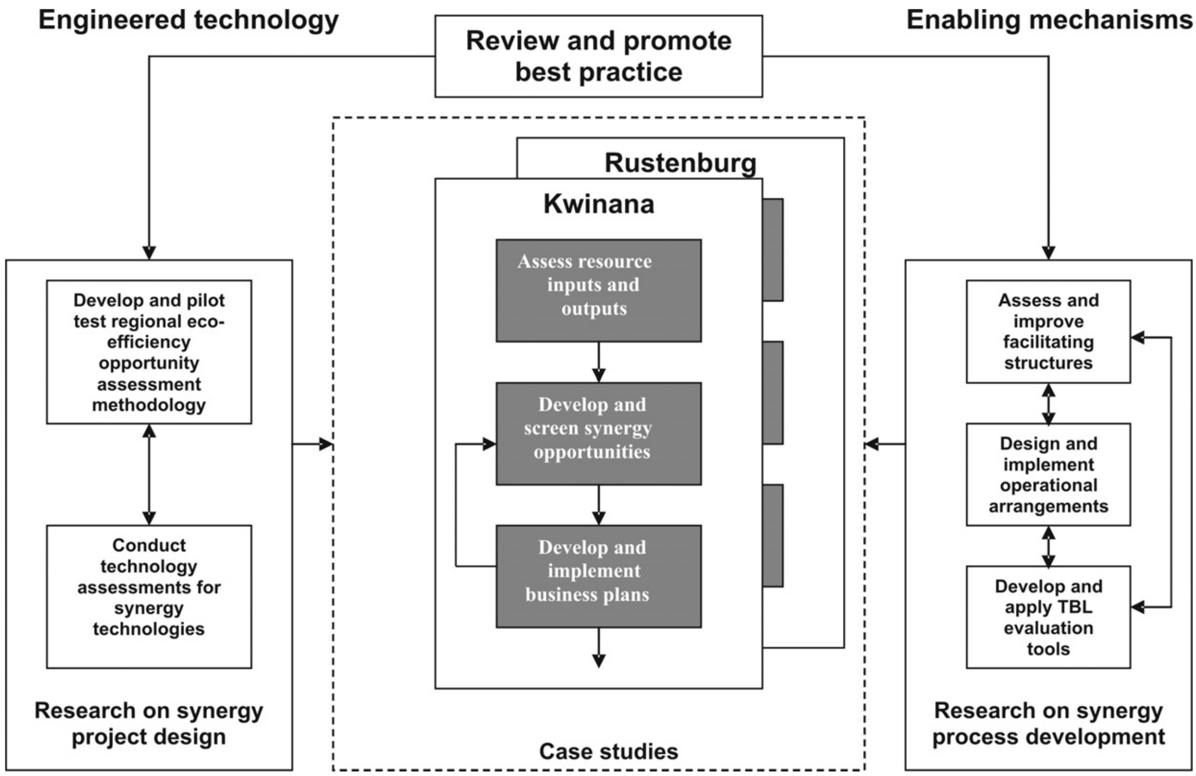

Fig. B. Research needs to review and promote best practice of industrial symbiosis.

Emergence of eco-industrial infrastructure

The emergence of eco-industrial infrastructure is illustrated in Fig. C.[52]

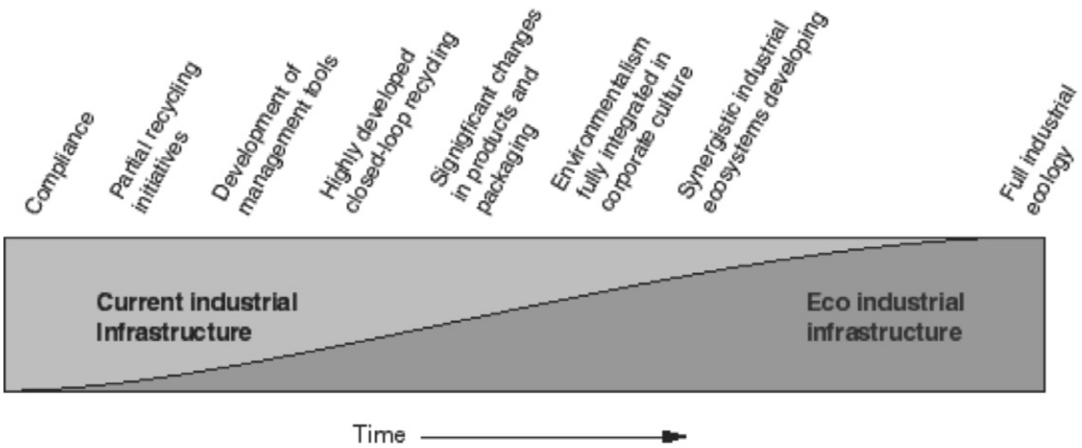

Fig. C. The emergence of eco-industrial infrastructure.