"Uncovering" Industrial Symbiosis

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Summary

Since 1989, efforts to understand the nature of interfirm resource sharing in the form of industrial symbiosis and to replicate in a deliberate way what was largely self-organizing in Kalundborg, Denmark have followed many paths, some with much success and some with very little. This article provides a historical view of the motivations and means for pursuing industrial symbiosis—defined to include physical exchanges of materials, energy, water, and by-products among diversified clusters of firms. It finds that "uncovering" existing symbioses has led to more sustainable industrial development than attempts to design and build eco-industrial parks incorporating physical exchanges.

By examining 15 proposed projects brought to national and international attention by the U.S. President's Council on Sustainable Development beginning in the early 1990s, and contrasting these with another 12 projects observed to share more elements of self-organization, recommendations are offered to stimulate the identification and uncovering of already existing "kernels" of symbiosis. In addition, policies and practices are suggested to identify early-stage precursors of potentially larger symbioses that can be nurtured and developed further. The article concludes that environmentally and economically desirable symbiotic exchanges are all around us and now we must shift our gaze to find and foster them.

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Introduction

Looking back, 1989 was an inspirational year for industry and environment. Following the Bruntland Commission report in 1987 came two key events. The seminal article by Frosch and Gallopoulos (Frosch and Gallopoulos 1989) in *Scientific American* envisioned "industrial ecosystems" in which "the consumption of energy and materials is optimized and the effluents of one process . . . serve as the raw material for another process." That same year, a cluster of companies from different industries that were intensively sharing resources was unexpectedly uncovered in Denmark and then described in the international press (Knight 1990; Barnes 1992). What we have come to call "the industrial symbiosis at Kalundborg" provided a concrete realization of the industrial ecosystems Frosch and Gallopoulos theorized.[1]

Industrial symbiosis has been defined as engaging "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow 2000). Since 1989, efforts to understand the nature of symbiosis and to replicate in a deliberate way what was largely self-organizing in Kalundborg have followed many paths, some with much success and some with very little.

This article provides a historical view of the motivations and means for pursuing symbiosis, with a focus on assessing planned versus spontaneous symbiosis. By examining 15 proposed projects brought to national and international attention by the U.S. President's Council on Sustainable Development beginning in the early 1990s, and contrasting these with another 12 projects observed to share more elements of self-organization, recommendations are offered to stimulate the identification and uncovering of already existing symbioses. In addition, policies and practices for governments, nongovernmental organizations (NGOs), and businesses are suggested to identify early stage "precursors" or "kernels" of symbiosis that can be nurtured and developed further.

Pursuing Industrial Symbiosis

Although industrial symbiosis may appear to have leapt fully grown onto the sustainability stage, notions of trading and resource exchange are as ancient as primitive peoples sharing animal parts. Scrap dealers, charities organizing clothing drives, and companies buying and selling residual materials on line are engaging in resource exchange. To distinguish industrial symbiosis from other types of exchanges, my colleagues and I have adopted a "3–2 heuristic" as a minimum criterion. Thus, at least three different entities must be involved in exchanging at least two different resources to be counted as a basic type of industrial symbiosis. By involving three entities, none of which is primarily engaged in a recycling-oriented business, the 3–2 heuristic begins to recognize complex relationships rather than linear one-way exchanges. A simple version of this is a wastewater treatment plant providing cooling water for a power station and the power station, in turn, supplying steam to an industrial user. The words "kernel" and "precursor" have been chosen to describe instances of bilateral or multilateral exchange of these types that have the potential to expand, but do not yet meet the fuller 3–2 definition of industrial symbiosis. See figure 1.

The symbiotic relationships described above are presumed to provide environmental benefits, although these benefits have seldom been carefully measured. They occur in single-industry dominated clusters such as petrochemical complexes as well as multi-industry ones such as Kalundborg. In general, three primary opportunities for resource exchange are considered (Chertow et al. 2007): (1) By-product reuse—the exchange of firm-specific materials between two or more parties for use as substitutes for commercial products or raw materials. (2) Utility/infrastructure sharing—the pooled use and management of commonly used resources such as energy, water, and wastewater. (3) Joint provision of services—meeting common needs across firms for ancillary activities such as fire suppression, transportation, and food provision.

Many motivations exist for pursuing industrial symbiosis, either directly or indirectly as a result of trying to meet other objectives. The most

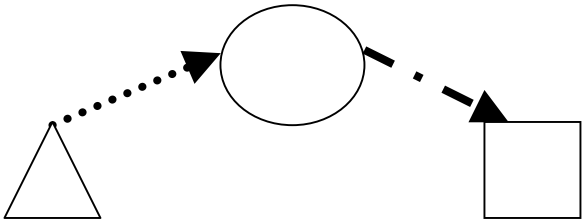

Figure 1 Example of 3–2 symbiosis involving a minimum of three different entities exchanging at least two different resources.

obvious motivations are conventional business reasons; for example, resource sharing can reduce costs and/or increase revenues. At another level, industrial symbiosis can enhance long-term resource security by increasing the availability of critical resources such as water, energy, or particular raw materials through contracts. In some cases, companies pursue symbiosis in response to regulatory or permitting pressure requiring industrial operators to increase efficiency of resource use, reduce emissions, or eliminate waste.

Historically, what is often described as "spontaneous co-location" of businesses in industrial districts has been shown to give rise to many public and private benefits including labor availability, access to capital, technological innovation, and infrastructure efficiency (Marshall 1890; Krugman 1991; Desrochers 2001; Duranton and Puga 2003). Still, the modern literature on these "agglomeration economies" generally overlooks environmental benefits of agglomeration through resource sharing (Chertow et al. 2006). Although self-organizing industrial districts have been observed to produce many advantages over the last hundred years, people involved in planning eco-industrial parks (EIPs) and other concrete manifestations of industrial symbiosis have anticipated many other types of benefits as key rationales for advancing projects, including economic development broadly, remediation of pollution associated with heavy industry, water and land savings, and greenhouse gas reductions, as discussed below.

Because industrial development is a form of economic development, there has been interest in using the concept of industrial symbiosis in the form of eco-industrial parks (EIPs) to (1) revitalize urban and rural sites, including brownfield redevelopment, (2) promote job growth and retention, and (3) encourage more sustainable development. An eco-industrial park project was proposed as a way to attract jobs through "clean" economic development in a poor rural U.S. county in Virginia (Hayes 2003). In China, a sugar refining company grew by following the path of the supply chain for that industry, thereby providing solutions for two important problems: decreasing the environmental impacts of sugar refining through reuse of by-products and increasing employment by using these by-products to fuel new enterprises (Zhu and Côté 2004; Zhu et al. 2007). Figure 2 shows the expansion of the Guitang Group beyond sugar refining into related industries that use materials from the two key by-product streams from sugar cane production: molasses (the sugar refining residue) and bagasse (the fibrous waste product).

Business development strategies involving industrial symbiosis are being used in some countries to alleviate environmental degradation where contamination has already occurred at the "end of the pipe." Van Berkel (2004), a leading industrial symbiosis researcher from Australia, describes the use of resource exchange as an approach to addressing the high volume of wastes from mineral, metal, and energy production in Australia. One well-studied example is the Kwinana Industrial Area in Western Australia, operating since the 1950s, composed of numerous mineral processing industries. Between 1990 and 2001, the number of core process industries at Kwinana increased from 13 to 21 and the number of symbiotic exchanges increased from 27 to 106. Of these, 68 involved core process industries and 38 involved services and infrastructure (Altham and Van Berkel 2004, Van Beers et al. 2007).

The differential distribution of rain, surface water, and groundwater has led many communities to ask whether there could be more sustainable ways to use water. The symbiosis in Kalundborg, Denmark began because of the low availability of groundwater and the need for a

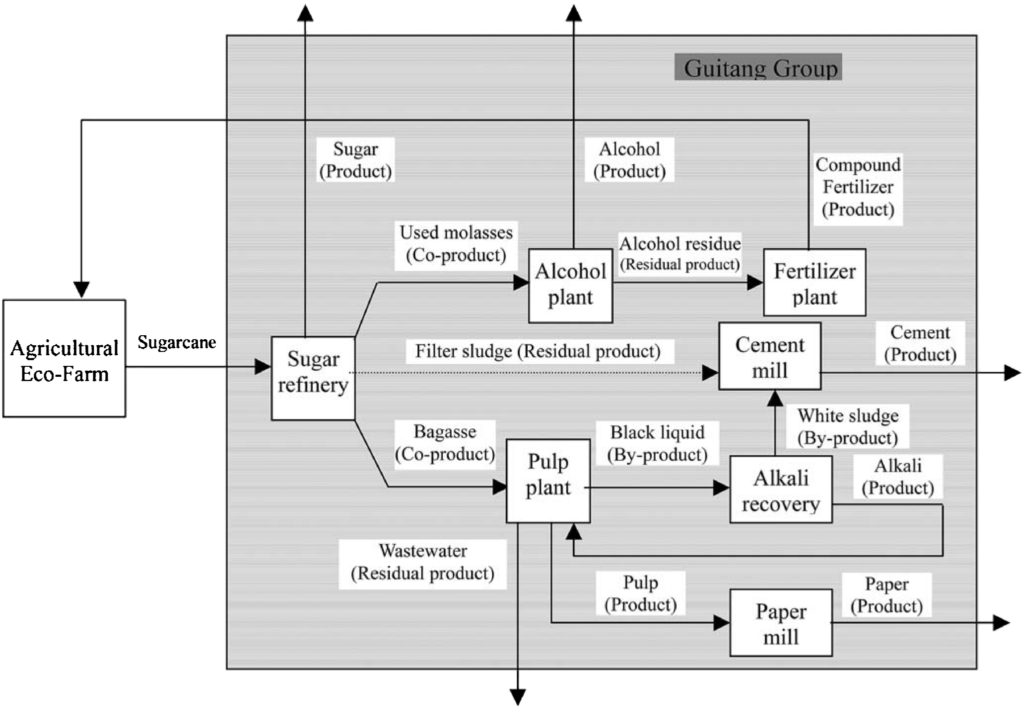

Figure 2 The Guitang Group, beyond sugar refining. *Source:* Zhu and Côté 2004, 1028. Used by permission from authors.

surface water source which, once identified, became a key part of the resource exchange network there (Christensen 1998). Several AES power plants in the United States associated with eco-industrial development in areas concerned with water availability in Hawaii, Puerto Rico, and New Hampshire use millions of gallons of sewage water per day for cooling water.

In many parts of the world, land that was formerly arable has, over time, degraded with the intrusion of salt water. In Narrogin, Australia, farmers are now planting mallee trees that soak up groundwater with their deep roots, helping to prevent the rise of the saline water table (Barton 1999). The opportunity provided by the kernel of tree planting to build industrial symbiosis around it has resulted in construction of a pilot plant designed to process the harvested shrubs to produce one megawatt (1 MW)[2] of renewable energy, 700 tonnes[3] per year of eucalyptus oil, and 200 tonnes per year of charcoal as a possible substitute for black coal in high-temperature metallurgical reactors (Department of the Environment and Heritage 2004; Enecon 2006).

Concentrations of industry are often heavy generators of greenhouse gases associated with global climate change. Discussions in Alberta, Canada's industrial heartland, raised the idea of establishing tree plantations near the oil and petrochemical industries located there, not only to compensate for CO_2 emissions, but also to provide employment and renewable materials (Alberta's Industrial Heartland Association 2000; Côté 2003). A heavy industry area in eastern Australia focused on minerals processing and chemical production makes a sizeable contribution to greenhouse gas emissions because of raw material consumption, transport, and waste disposal (Sustainable Gladstone 2005). The Australian government is examining the extent to which by-product reuse and exchange can result in reduction of greenhouse gases in the Gladstone Industrial Area.

So far, we have recounted business benefits of symbiosis across companies, as well as experiments and opportunities for resource conservation. Symbiotic activity can also come into play in response to a regulatory situation. In the United States, for example, the Public Utilities Regulatory Policy Act (PURPA) bestowed certain pricing benefits on facilities willing to co-generate steam and electricity, which stimulated many industrial plants to become "qualifying facilities" under the law.[4] Rules regarding scrubbing of flue gases in power-generating facilities in several countries have led to many symbioses involving the use of scrubbed sulfur for production of gypsum wallboard. Even when a law does not directly command reuse, a less tangible "license to operate" in the form of regulatory permits or greater social acceptance can be associated with projects showing environmental benefits (Gunningham et al. 2003; Chertow and Lombardi 2005).

Thus, there are many reasons for pursuing industrial symbiosis, beginning with the most basic desire of businesses to be profitable and competitive. Important social, environmental, and regulatory drivers also exist, which play out differently in different parts of the world, as illustrated by the examples above. At the same time, although there are numerous measurable benefits, the classic expression—"if (the subject under discussion) is so advantageous, why aren't we seeing a lot more of it?"—is applicable to industrial symbiosis. In fact, many barriers to industrial symbiosis are identified and detailed in the literature. In addition to the usual problems of business development, these barriers are rooted in the operational, financial, and behavioral issues raised by the need to work across organizations (Lowe et al. 1995; Chertow 2000; Chertow 2003; Gibbs 2003; Ehrenfeld and Gertler 1997; Mirata 2004).[5] Neither are the externalities of symbiotic arrangements all positive in the minds of citizens concerned about pollution and health effects of industry. Indeed, one town's economic development can be another town's emissions source or traffic jam.[6]

Planning and Self-Organization in Industrial Symbiosis

A surprising aspect of industrial symbiosis now well known to researchers and policy makers has been that efforts to plan industrial ecosystems to achieve the benefits described above have resulted in many failures. Gibbs (Gibbs 2003) and colleagues investigated 63 "eco-industrial" sites: 30 in the United States and 33 in Europe. The work of the Gibbs team found little success in the United States and somewhat more success in Europe. After carefully examining the data, Gibbs concluded that "initiatives based upon the interchange of wastes and cascading of energy are few in number and difficult to organize" (Gibbs et al. 2005).

Half of the U.S. sites the Gibbs team reviewed were associated with the work of the U.S. President's Council on Sustainable Development (USPCSD), formed during the Clinton administration. In its report, *Sustainable America*, the USPCSD (1996, 104) recommended that "Federal and state agencies should assist communities that want to create eco-industrial parks that cluster businesses in the same area to create new models of industrial efficiency, cooperation, and environmental responsibility." These 15 so-called "eco-industrial parks" were at various stages of planning or implementation, including four sites funded by the U.S. Environmental Protection Agency in Chattanooga, Tennessee; Baltimore, Maryland; Brownsville, Texas; and Cape Charles, Virginia. The sites were announced at a PCSD task force meeting in October 1996. The author attended this meeting ten years ago and oversaw an independent telephone and Internet survey of these 15 projects completed in 2005. The results are shown in table 1.[7]

The USPCSD consensus definition of an eco-industrial park was as follows:

> A community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community. (USPCSD 1997, 36)

Gibbs and colleagues (Gibbs et al. 2002) determined that of the 15 projects (including the Burnside Industrial Park in Nova Scotia, Canada, cited by both Gibbs and colleagues 2002 and the USPCSD in 1996), five were open, three had failed, and seven were still identified as "planned."

Table 1 Status of eco-industrial park project sites profiled by the U.S. President's Council on Sustainable Development, 1996

Name, location listed in 1996[8]	*Summary as of 2005*	*Gibbs et al. category (2002–2004)*	*Revised category 2005–2006*
1. Fairfield Ecological Industrial Park—Baltimore, Maryland	Existing industrial park when funded by US-PCSD, now no longer pursuing EIP concept. As of 2002, changed name to Fairfield Eco-Business Park.	Open	Open with changed concept
2. Brownsville Eco-Industrial Park—Brownsville, Texas	Planned as regional exchange and data base; Bechtel Corp. performed some data base development.	Failed or stalled	Regional exchange concept failed
3. Riverside Eco-Industrial Park—Burlington, Vermont	Now called Intervale Community Food Enterprise Center supporting land and farm-based enterprises.	Planned	Open with changed concept
4. Burnside Eco-Industrial Park—Halifax, Nova Scotia, Canada	Opened "Eco-efficiency Centre" in 1998 oriented to research and development; augments existing large industrial park.	Open	Open as an industrial park with R&D center
5. Port of Cape Charles Sustainable Technologies Industrial Park—Cape Charles, Virginia	Opened as EIP in 2000, final sale of assets occurring spring 2005.	Open	Closed
6. Civano Industrial Eco-Park—Tucson, Arizona	Residential "new town" development planned to seek "sustainable technology" businesses even if no EIP.	Failed or stalled	Never emerged[i]
7. The Volunteer Site—Chattanooga, Tennessee	Plans to convert the Volunteer Army Ammunition Plant site to an environmental technology center were never completed.[ii]	Planned	Never emerged, open as traditional industrial park
8. East Bay Eco-Industrial Park—Alameda County, California	Planned as resource recovery park for waste diversion by Alameda County Waste Management Authority; has not come to fruition as EIP.[iii]	Planned	Planned, changed concept
9. Green Institute Eco-Industrial Park—Minneapolis, Minnesota	Original project focus to create jobs in poor neighborhood; today "Phillips Eco-Enterprise Center" has created over 100 jobs.	Open	Open as sustainable development project
10. Plattsburgh Eco-Industrial Park—Plattsburgh, New York	From original emphasis on EIP with ISO 14000/EMS Program; now called Plattsburgh Airbase Redevelopment Corp., with 60 tenants.	Failed or stalled	Open as standard industrial park[iv]
11. Raymond Green Eco-Industrial Park—Raymond, Washington	Original plan to develop a park "within a second growth coastal forest" did not occur; described by local officials as having been "planned around a manufacturing business that didn't materialize."[v]	Planned	Never emerged

12. Skagit County Environmental Industrial Park—Skagit County, Washington	Plan to develop an industrial park with some EIP features did not have a site determined and local government staff reported there was little activity following a 1996 feasibility study.[vi]	Planned	Never emerged
13. Shady Side Eco-Business Park—Shady Side, Maryland	Envisioned renovating existing facility in disadvantaged community; successor organization domain name for sale, no further mention.[vii]	Planned	Never emerged
14. Stonyfield Londonderry Eco-Industrial Park—Londonderry, New Hampshire	Private developer named in 1998. Anchor tenant—720-MW gas-fired power station—opened in 2003 and facility sold to creditors in 2004.[viii]	Open	Open, but status uncertain
15. Trenton Eco-Industrial Complex—Trenton, New Jersey	Intended as a network of firms organized by multistakeholder group; early feasibility study done in 1998, city staff report interest lost in project by 1998.[ix]	Planned	Never emerged

Sources: [i] Briggs 2005; [ii] Hewett 2003; [iii] Bakke 2005; [iv] PARC-USA 2005; [v] Chaffee 2005; [vi] McCullough 2005; [vii] Food Planet.com 2005; [viii] AES gives Granite Ridge power plant back to bank 2004, [ix] Tagliaferri 2005.

Although the 15 proposed projects were all labeled "eco-industrial parks" a decade ago, none adheres to the idealistic vision of the USPCSD above (Chertow 2004). Yet neither do simple labels such as "planned" or "failed" give a nuanced sense of what occurred. Gibbs and colleagues categorized ten projects as either "planned" (seven) or "failed or stalled" (three). The Brownsville, Texas, concept did not take hold, but although two others of these ten failed as EIPs, they did become conventional industrial parks (Chattanooga and Plattsburgh). I record only one project in California's East Bay as still "planned," although the concept has changed. Now called the Alameda County EIP, it was, from the start, sited by a waste transfer station with a plan to become a resource recovery park (Liss 2005), although this vision, too, has been deferred by market realities (Bakke 2005). A fifth project in Burlington, Vermont, opened with a changed concept as the "Intervale Community Food Enterprise Center." The Web site describes a new public market "to be built on the site of the *former* Eco-Park" (Intervale 2005, emphasis added). The other five in our survey had achieved few results: we were told in various ways that, after a time, "nothing happened." Sometimes this was after a feasibility study or an initial request for proposals, or a series of meetings with stakeholders, but we had the impression that most were never embedded in the planning process but were ideas without a strong basis. These are labeled in table 1 as "never emerged."

Of the five projects categorized by Gibbs and colleagues as "open," the Fairfield Park in Baltimore reported changing its name in 2002 and leaving behind the EIP concept (Build Fairfield 2005). Both the projects in Minneapolis and Nova Scotia fulfilled the main objectives established in the PCSD case studies, but neither is a self-defined EIP (see below). Given the high failure rates of businesses, the fact that 2 of 15 original PCSD projects, in Londonderry, New Hampshire, and Cape Charles, Virginia, did open as self-defined EIPs could be viewed as a success. Unfortunately, both have run into serious difficulties since 2004. The Londonderry anchor tenant—a new 720-MW power plant—is operating but is in receivership, given the high price of natural gas and steep tax liabilities ("AES gives Granite Ridge power plant back to bank" 2004). Cape Charles still has an office building but has sold off its few remaining assets for other land uses (Slone 2005).

Upon further analysis, we can now see that the 15 projects were quite a mixed bag. The Brownsville, Texas, project, according to the USPCSD (1997) documents, was to be a regional materials exchange; it was clearly noted that "a defined 'eco-industrial park' is considered as one possible component of regional industrial symbiosis, *but not the driving force*" (emphasis added). With respect to the Burnside Industrial Park in Nova Scotia, the original PCSD (1997) documents name the key feature of Burnside as a "six year multi-disciplinary, multi-institutional study of requirements" using a cooperative partnership among academia, government, and the private sector. The Burnside Eco-Efficiency Centre largely fits this bill and continues to function as a living laboratory for research and demonstration, but the Burnside Park itself, with 1400 companies, does not meet the definition of an EIP above (Barchard 2005). The Green Institute project intended to create employment opportunities through a very small EIP and to incorporate environmental education in "the poorest and most diverse neighborhood in Minnesota." It has achieved success as "the Phillips Eco-Enterprise Center" with environmental building features and job creation organized by a grassroots group.

In reviewing the previous decade, then, we can see in these 15 projects, as well as many other early efforts such as those initiated in the private sector by the group now known as the U.S. Business Council for Sustainable Development (Forward and Mangan 1999; Chertow 2000), what paleontologists might call a series of "evolutionary experiments." Reexamining the original USPCSD documents, we see that a variety of approaches to eco-development were tried—from regional databases, to waste parks, to retrofits of existing parks—for a plethora of reasons—inner city development, rural development, and enhancing the "new town"[9] concept. They relied to a large extent on public funding and although some became active, others died off quickly. In time, however, it seemed as if all of the early projects were lumped together as a single idealized model and, when the success rate was found to

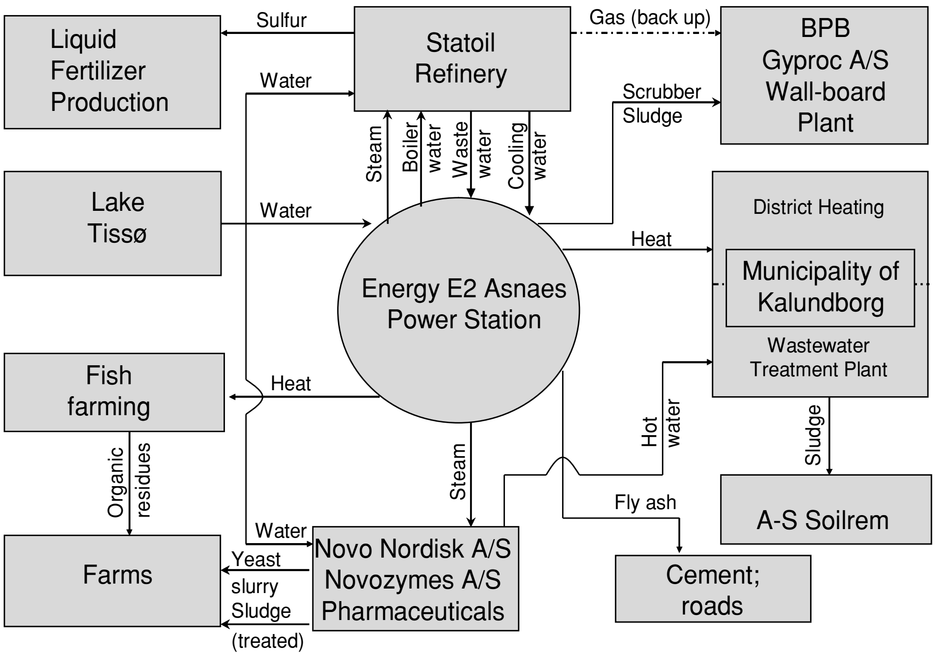

Figure 3 Industrial symbiosis of Kalundborg, Denmark.

be very low, the word got out that eco-industrial parks just do not work.

In looking back over this period, I suspect that some projects were prematurely put on the PCSD list in the first place to fill out the cohort for a meeting that would achieve media attention in October 1996. It was good for the government agencies to have more projects and good for many, especially those within small communities, to be recognized on the national stage and possibly be made eligible for public funding. Reviewing the projects codified on the Internet as a series of case studies by the Smart Growth Network (Smart Growth 2005), however, is like entering a time warp beginning in 1996 and trailing off after 1998. Of the dozens of "Google hits" called up for each of the projects, most are echoes of a handful of Web sites, even if the sites are relabeled with current dates. As a founding member of the fledgling U.S.–Canadian NGO called the Eco-Industrial Development Council I can say with certainty that dozens of evolutionary experiments continue in North America well beyond the PCSD projects, but they are seldom neatly packaged in an EIP box, thus casting the EIP concept as an artifact of cyberspace.

Clearly, a more robust model of industrial symbiosis is needed. Alternatively, many of the successful industrial ecosystems described in this article did not arise in the ways pursued by the PCSD. One feature that several of these have in common is the experience of a quiet period where firms engaged in exchanges among themselves, unconscious of a bigger picture, followed by an act of discovery that revealed the pattern of existing symbiotic exchanges and the resulting environmental benefits.

The most colorful case returns us to Kalundborg, Denmark (figure 3). The first exchanges were in the 1970s, and, by the late 1980s, at least ten additional exchanges had begun across multiple firms (Symbiosis Institute, 2003). Yet, until some local high school students prepared a science project in 1989 in which they made a scale model of all the pipelines and connections in their small community, the unique aspects of the project went largely unnoticed (Christensen 1998). Recognition of Kalundborg's symbiotic attributes was an uncovering of what already existed rather than the exploration of a new frontier. Following this high school project, still on display in Kalundborg, came the European media

(Knight 1990; Barnes 1992), and then academics (Engberg 1993; Gertler 1995) to describe the existing network from a broader environmental perspective.

Two fundamental conclusions have gained acceptance concerning the Kalundborg case. First, we see that rather than resulting from planning or a multistakeholder process such as the ones pursued through the President's Council on Sustainable Development, the Kalundborg symbiosis emerged from self-organization initiated in the private sector to achieve certain goals listed earlier, such as cost reduction, revenue enhancement, business expansion, and securing long-term access to water and energy. This implies that the symbiosis was not "seen" by outsiders because the exchanges emerged from the invisible hand of the market rather than direct government policy or involvement. Second, once a revelation was made, a coordinative function was found to be helpful in organizing more exchanges and moving them forward. In Kalundborg, for example, managers belonged to an Environment Club and a coordinative organization, the Symbiosis Institute, was launched in 1996 as part of Kalundborg's industrial development agency, specifically working to accelerate the number and complexity of new exchanges (Jacobsen 2005).

If key types of mixed industrial ecosystems are self-organizing and arise in this manner, then a similar pattern of discovery, in which preexisting symbioses were later recognized, would be observed in other locations. Indeed, we see this pattern repeated in several other multiple-industry ecosystems wherein significant industrial activity and interfirm sharing were found to be well established in practice, but never mapped and described using ecological metaphors. A common language has even emerged that reflects the notion of "uncovering" a pattern of trades more extensive or more interconnected than had been previously realized. Several examples have been found that follow this pattern of discovery in Australia, Austria, Germany, Finland, and the United States. These are discussed in turn below.

- In the example of Kwinana, Australia, discussed above, Van Berkel (Van Berkel 2004) writes that following through on the idea of examining large volume wastes from minerals processing in the context of the Mining, Minerals and Sustainable Development Project under the auspices of the World Business Council for Sustainable Development "*revealed* that quite significant regional by-product synergies *are already happening* in resource processing intensive regions" [emphasis added]. As noted earlier, this prominent and diversified Australian mineral processing area has over 100 symbiotic exchanges.
- Having become aware of Kalundborg, two Austrian researchers also wondered whether that industrial ecosystem would be found to be unique. In developing the concept of an "industrial recycling-network," Schwarz and Steininger (Schwarz and Steininger 1995, 1997) studied the spatially broader province of Styria and uncovered a network with a high degree of diversity and complexity. The researchers found exchanges consisting of hundreds of thousands of tons of materials including power plant gypsum, steel slag, sawdust, and recyclable paper and wood. Although the Kalundborg participants became conscious of the environmental characteristics of their exchanges over time, the Styrian companies were not generally aware of the ubiquitous networking of regional material flows, and the authors were concerned that these companies were missing out on additional benefits. They stressed the importance of a coordinative function as in Kalundborg to try to increase exchange and improve internal and external communication. The notion of recycling networks spread over the last decade so that a centralized "Regional Recycling Information System" (REGRIS) in the Oldenburger Munsterland Region of northwest Germany now supports the management of intercompany information flows, provides data to local firms about recycling opportunities, and coordinates recycling activities (Milchrahm and Hasler 2002).
- In Finland, Korhonen and colleagues (Korhonen et al. 1999) describe the city

of Jyväskylä where the energy supply is organized around co-production of heat and electricity and includes industrial wastes used as fuels in a highly efficient system. The system arose for economic/regulatory reasons, but was not consciously labeled as "industrial ecology" or "industrial symbiosis" prior to the intervention of professors there.

- In North Carolina, USA, staff members of the six-county Triangle J Council of Governments came to realize over time that their planning work to create the Industrial Ecosystem Development Project was actually based on a foundation of exchange activity. From 1997 to 1999, an inventory of business inputs and outputs was conducted and 182 businesses representing 108 different business segments responded to the inventory survey. According to the final project report, two-thirds of all those surveyed were characterized as having some experience with reuse (Kincaid 1999; Kincaid 2005). Of these, the researchers found that a surprising 36 percent had already engaged in activities beyond simple recycling, thus affirming favorable market conditions and a symbiosis mindset that was unseen prior to the survey (Kincaid 2005).

A parallel to the self-organizing kernels of industrial symbiosis described in the examples above can be drawn from an examination of the roots and development of business clusters as analyzed by Porter. In describing how these "geographic concentrations of interconnected companies and institutions" arise, Porter (Porter 1998b) notes many different motivating forces including the availability of specialized skills, role of existing suppliers, scarcity conditions, and availability of natural resources, as well as chance, although "what looks like chance may sometimes be the result of pre-existing locational circumstances" (Porter 1998a). Parallel to the dubious mission of creating eco-industrial parks from scratch, as we have seen, Porter highlights the difficulty of seeding clusters where no important preexisting locational advantages exist.

With respect to the role of government, Porter notes that "the appropriate policy towards cluster development is usually to build on existing or emerging areas that have passed a market test" (Porter 1998a). Many observers of industrial symbiosis similarly suggest the desirability of working from an established base, a conclusion affirmed here (Schwarz and Steininger 1997; Chertow 2000; Korhonen 2002; Baas and Boons 2004; Desrochers 2004; Jacobsen and Anderberg 2005). An industrial ecology view makes this especially clear, as it depends on the existence of material and energy flows for its craft.

Understanding Emerging Symbioses

From the analysis presented thus far, contrasting a planning approach with self-organization can be summarized in two stylized models of symbiosis as follows:

Planned EIP model. This model includes a conscious effort to identify companies from different industries and locate them together so that they can share resources across and among them. Typical U.S. planning for these systems has involved the formation of a stakeholder group of diverse actors to guide the process and the participation of at least one governmental or quasi-governmental agency with some powers to encourage development, such as land use planning and/or zoning, grant giving, or long-term financing.

Self-organizing symbiosis model. In this model, an industrial ecosystem emerges from decisions by private actors motivated to exchange resources to meet goals such as cost reduction, revenue enhancement, or business expansion. The individual initiative to begin resource exchange faces a market test and if the exchanges are successful, more may follow if there is on-going mutual self-interest. In the early stages there is no consciousness by participants of "industrial symbiosis" or inclusion in an "industrial ecosystem," but this can develop over time. The projects can be strengthened by post facto coordination and encouragement.

If, as described here, the self-organizing symbiosis model building from kernels of cooperation and exchange tends to be more successful, then we must examine it more closely to

Table 2 Projects sharing characteristics of uncovered industrial symbiosis referenced in this article

Project	*Relevant section reference*
Kwinana, Australia	See *Pursuing Industrial Symbiosis*
Gladstone, Australia	See *Pursuing Industrial Symbiosis* and Bossilkov and colleagues (2005)
Triangle J, North Carolina	Planned project that uncovered self-organized roots among member firms—discussed in *Planning and Self-Organization in Industrial Symbiosis*
Barceloneta, Puerto Rico	See *Understanding Emerging Symbioses*
Guayama, Puerto Rico	See *Understanding Emerging Symbioses*
Kalundborg, Denmark	Mentioned throughout
Styria, Austria	See *Planning and Self-Organization in Industrial Symbiosis*
Jyväskylä, Finland	See *Planning and Self-Organization in Industrial Symbiosis*
National Industrial Symbiosis	See *Policy Proposals for Uncovering Symbiosis (U.K. Symbiosis)*
Guitang Group, China	See *Pursuing Industrial Symbiosis*—some parts of symbiosis planned but others appeared opportunistically (Zhu et al. 2007)
Burnside Industrial Park, Canada	See *Planning and Self-Organization in Industrial Symbiosis*—symbioses not planned but later coordinated by the Eco-Efficiency Centre
Alberta Heartland, Canada	See *Pursuing Industrial Symbiosis*

look for patterns or common characteristics. The USPCSD projects provide a convenient, if nonrandom, sample of projects proposed through a process. We do not have a comparable set of self-organizing symbiosis projects to examine because, by their very nature, they are not known until there has been some success and an uncovering event occurs. Acknowledging the problem of selection bias, projects more closely resembling self-organizing symbiosis that are referred to throughout this article are listed in table 2.

Boons and Berends (2001) and Baas and Boons (2004) offer an important theoretical perspective suggesting how the emergence of industrial symbioses based on the exploitation of win-win situations among area firms could lead to a form of organization that embraces sustainable industrial development. Their three-part diagram is depicted in figure 4.

The first stage, regional efficiency, is described as "autonomous decision-making by firms; coordination with local firms to decrease inefficiencies (i.e., 'utility sharing')." Stage 2 broadens goals and membership into regional learning, where the authors see that "based on mutual recognition and trust, firms and other partners exchange knowledge, and broaden the definition of sustainability on which they act." The third stage, a sustainable industrial district, shows further evolution toward a strategic vision and collaborative action rooted in sustainability.

This diagram offers insight on two important questions: what do symbiotic relationships look like before they are broadly known and at what point are they "uncovered" in industrial ecosystems? Stage 1 shows that companies can cooperate for reasons of economic efficiency. Once a regional efficiency gains momentum based on autonomous decision-making, it may continue to thrive and enter the more advanced stage of learning denoted in Stage 2. With respect to awareness by the companies of the environmental benefits being gained, by definition, they cannot be "uncovered" before the exchanges are established, which is why attempts at creation outside of the market are likely to fail. The diagram does not offer a temporal explanation—that is, when the collection of companies involved at the regional efficiency stage might move to the subsequent stages illustrated.

In the case of Kalundborg, there were well-developed regional efficiencies (Stage 1) by the time the symbiosis was brought to broader attention and may even have entered Stage 2 given the informal informational networks there. Perhaps one way to understand the dominance of Kalundborg in the literature is to see it as having moved directionally further to the right of these stages than other relevant projects at the time

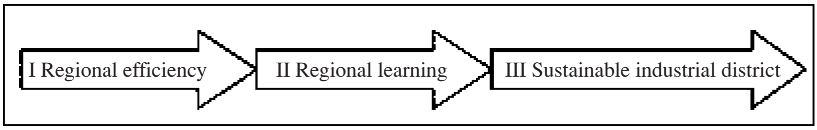

Figure 4 From regional efficiency to a sustainable industrial district. *Source:* Baas and Boons 2004. Used by permission from authors.

of uncovering. Nascent symbioses found earlier in their possible trajectories are less stable and, therefore, their futures are more uncertain, whereas Kalundborg was fairly well-developed at the time of its unveiling. Rather than seeing Kalundborg as chance or a historical accident, a fuller explanation would be to recognize that it built on existing scarcities (in the case of groundwater), opportunities (in the case of by-product use by new entrants), regulatory changes (in the case of reuse of organics and impetus to pursue flue gas desulfurization), and other locational advantages (including the port and the availability of industrial land).

With respect to the diagram from Baas and Boons, it is not clear that Stage 3 is coming any time soon nor that a strongly collective orientation will ever fully fit with the other imperatives of firms. Although these three stages are rooted in existing development, Baas and Boons also talk about an earlier "selection" stage for new or greenfield sites. Inclusion of this selection stage ahead of Stage 1 raises the previously unsuccessful prospect of development from scratch, before the symbioses take shape, although with two notable exceptions. Clearly, there have been planned developments, especially of single-industry dominated systems, that could successfully assemble core actors and organize benefits, as seen in many chemical and petrochemical complexes. The other exception occurs most notably in East Asia, where formal planning is much more institutionalized in countries such as China, Korea, and Singapore.

The symbioses mentioned in table 2, whether motivated by economic, social, environmental, or regulatory forces, have met a market test and continue onward. In these cases, two periods can be observed: the initiation phase before discovery and a second period when the symbiotic exchanges are developed further with some new entrants and some die-offs of specific trades. Then, at some unspecified time, an uncovering event occurs, usually catalyzed by members of a third party such as an academic institution or business association, thereby leading to greater awareness of the exchanges.

Some industrial groupings of companies, as in Australia's mineral processing industry and Austria's recycling network in Styria, find productivity-enhancing efficiencies through self-organization. Stronger regulatory roots combined with elements of self-organization are seen in those uncovered in Puerto Rico. In one case, the Barceloneta pharmaceutical companies teamed up in a private initiative to share wastewater processing in response to regulatory changes and, subsequently, further exchanges developed (Ashton 2003). In the case of Guayama, Puerto Rico, regulatory conditions negotiated with government drove a new power station development to use four million gallons[10] per day of municipal waste water and, in turn, to co-generate steam for a nearby refinery, with other exchanges following in their wake (Chertow and Lombardi 2005). Still, the grouping of companies that became involved did not call themselves by a name that expressed recognition of the environmental benefits, nor was there a clear coordinative function that might attract new exchanges, let alone an institutionalized sense of organizational learning. In fact, these projects were not attempting to follow a symbiosis model, nor were they fully conscious of the collective environmental benefits being gained. To generalize, then, at some point following self-organization, uncovering occurs, which opens the door for, but does not dictate, active coordination and further development of exchanges, as depicted in figure 5.

Given the phenomenon of "uncovering" relationships in industrial ecosystems, how can we establish more foresight in addition to hindsight? A role for government and policy ideas are offered in the following section.

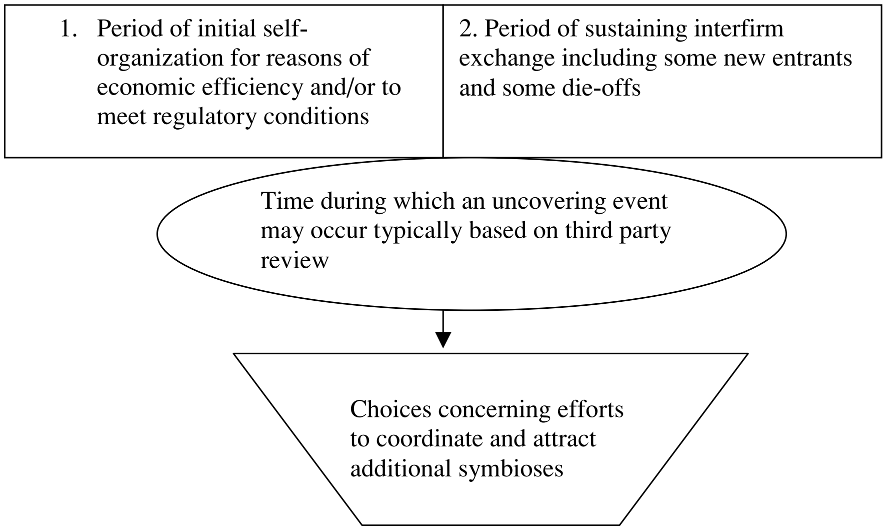

Figure 5 Empirical findings of industrial symbiosis progression.

Policy Proposals for Uncovering Symbiosis

The more spontaneous view of industrial symbiosis raises the question of whether a laissez-faire approach might be desirable, what role there could be for government, and, more fundamentally, whether there is any stage at which government intervention might be effective. Given the importance of coordination, it should also be asked who might best deliver this function, including various levels of government, nongovernmental organizations such as trade associations and universities, or on-site entities at industrial parks or clusters.

A basic rationale for public involvement has been indicated by John Ehrenfeld (Ehrenfeld 2003). He points out that industrial ecosystems provide a greater level of public benefit than standard industrial networks because they offer increased environmental benefits. Consequently, they are likely to need some type of public assistance to continue to deliver public goods at this greater level because, left to their own devices, private firms will typically underdeliver them. Firms also face risks of association, such as an increased level of dependence on others and the extent of the transaction costs involved in participation across firms, including search and coordination costs, some of which could be borne externally (Ehrenfeld and Chertow 2002).

Three policy ideas, then, are useful for government and business to move industrial symbiosis forward during different stages of discovery. These are to:

1. bring to light kernels of cooperative activity that are still hidden;
2. assist the kernels that are taking shape; and
3. provide incentives to catalyze new kernels by identifying "precursors to symbiosis."

These three potential programs also imply *not* supporting projects, through public or private investment, that have much wishful thinking but no tangible kernels to roast.

Bring existing kernels to light: Academic researchers, having revealed many patterns of exchange, have a good sense of where others might lurk, especially based on industry type. Business managers know what large by-product exchanges they are engaged in but often lack access to information about their neighbors in different industries. As a start, reconnaissance teams of researchers and managers who can map the flows from heavy industry areas such as mining, steel, cement, and chemicals would be likely to uncover many kernels of exchange. As the research on recycling networks suggests, these exchange relationships are quite broadly dispersed and can even include smaller and less industrial companies. Systematic means of bringing these existing kernels to light through mapping of flows and identification of relevant institutions will inform how to proceed.

Assist kernels beginning to take shape. Where a kernel is known to exist and is emerging, it is an excellent candidate for assistance because it implies that at least two or three firms are already on a trajectory toward industrial symbiosis. As innovation research has shown repeatedly, it is much easier to continue on a given trajectory than to shift to another, perhaps explaining why many firms find it difficult to continuously innovate, thus missing out on key opportunities (Christensen 1997; Dosi et al. 1988). With respect to companies that adopt an industrial symbiosis mindset, it is likely that some of their managers will be able to spot new opportunities, as they will be thinking "what can we trade?" even knowing that additional transaction costs may be incurred by the establishment of further exchanges. Technical or financial assistance to facilitate the exchanges envisioned by these managers could accelerate the evolutionary process. In Guayama, Puerto Rico, for example, since the power plant opened in late 2002, symbiotic relationships have been proposed by two pharmaceutical companies for additional wastewater reuse, as well as by two chemical companies for specific by-product sharing (Chertow and Lombardi 2005).

A key question with existing kernels, however, is whether it is the company itself or an individual project champion (or champions) that drives the nascent symbioses. Here, attempts to help a kernel to "pop" must consider what will happen if key personnel are removed or retire. Thus, policy must strive to be sustainable even in the face of generational change, business mergers, and economic trends. One useful model here may be the creation or extension of NGOs that are business associations to assist with kernel development. An offshoot of the U.K. Business Council for Sustainable Development has now created the world's largest coordinating entity for by-product reuse within regional business clusters, called "The National Industrial Symbiosis Programme." NISP describes as its mission that it "facilitates links between industries from different sectors to create sustainable commercial opportunities and improve resource efficiency" (NISP 2005).

Identify and assess "precursors to symbiosis" as catalysts for new kernels. Many common environmentally related activities can be seen as precursors to symbiosis—defined as a resource exchange with a public goods component but involving only one or two firms or other organizations. Examples of these precursors to symbiosis are resource sharing projects involving (1) cogeneration, (2) landfill gas, and (3) wastewater reuse. These projects can be driven by the public or private sectors, but where they have begun for whatever array of reasons, they can be used as bridges to more extensive exchange. Another precursor to symbiosis is the existence of one successful material exchange, sometimes referred to as green twinning, which is shown to be financially and environmentally beneficial, such as air pollution control waste to gypsum board, or steel slag to cement (Forward and Mangan 1999). As a means of screening and targeting public investment in symbiosis, projects involving these and other precursors could be identified as meriting further investigation as likely kernels of industrial symbiosis.

As noted in figure 5, actors in "discovered" kernels have the choice to opt collectively for an increased level of coordination and/or consciously pursue more symbiosis. The act of uncovering is a critical inflection point at which public incentives to continue symbiosis and maintain the spillover environmental benefits could be offered, if desired by the key actors. The three roles outlined above of identifying kernels, assisting them to grow, and catalyzing new ones are all promising areas of policy development that can be done in ways that still recognize similarities and differences among projects. The development and implementation of policy in this arena needs to be informed by a sophisticated understanding of market function and firm behavior.

Conclusion

In general, the empirical research in industrial symbiosis discussed here corroborates and expands earlier threads in the literature in finding that attempts to plan "eco-industrial parks," particularly from scratch, that involve significant material and energy exchanges have rarely come to fruition in a sustainable way (Ehrenfeld and Gertler 1997; Chertow 1999; Baas and Boons 2004; Gibbs and Deutz 2004; Korhonen and Snaikin 2005). We do not yet see new industrial ecosystems emerging from highly structured planning processes in Asia, despite the potential to do so, although many symbiotic relationships have been identified (Liu et al 2004).[11] Rather, an emergent characteristic of geographically proximate firms successfully exploiting synergistic exchanges is their evolution from opportunistic business decisions. These kernels of symbiosis across firms, such as sharing groundwater or a specific material, are observed to be necessary preconditions for what sometimes become more extensive exchange networks. Certain identifiable precursors of symbiosis, such as co-generation or waste water reuse, also emerge from business decisions often rooted in regulatory situations and can lead to more extensive symbiotic cooperation as well.

Even when several exchanges have been implemented based on self-organization, the participants and neighbors generally have not recognized or described these phenomena in environmental terms, until some sort of uncovering event has occurred, either during the initial period or later on when exchanges are more deeply rooted. Policies prescribed to encourage the uncovering of symbioses include (1) forming reconnaissance teams to identify industrial areas likely to have a baseline of exchanges and mapping their flows accordingly, (2) offering technical or financial assistance to increase the number of interactions once some kernels are found to be in place, inspired by managers with a symbiotic mindset, and (3) pursuing locations where common symbiotic precursors already exist, such as co-generation, landfill gas mining, and waste water reuse, often as one-off activities, to determine whether they may be likely candidates for technical or financial assistance as bridges to more extensive symbiosis.

Additional research is needed to illuminate conditions under which kernels and precursors have survived and thrived. At the same time, although this article has focused primarily on positive externalities of firms, there are many negative ones, and some form of assessment of when a reasonable carrying capacity is reached in an area is also warranted. Evolutionary experiments should continue to provide better information on which industrial sectors tend to produce good participants, what the capacity limitations might be, and which incentives and behaviors are most effective in fostering on-going symbiosis.

Economically and environmentally desirable symbiotic exchanges are all around us. Identifying and fostering emerging industrial ecosystems offers the promise of many environmental and other benefits. Grounded in what has been learned empirically over the last 15 years about the phenomenon of business co-location known as industrial symbiosis, this article helps steer public and private actors to higher probability approaches to resource sharing in geographically related industrial areas by choosing projects with demonstrable kernels of self-organization that can emerge more fully as viable industrial ecosystems.

Notes

1. With respect to the vocabulary of industrial symbiosis, many related terms are used, such as industrial ecosystems, eco-industrial park, and industrial recycling network. Definitions of the various terms can be found in the *Encyclopedia of Energy* in the article "Industrial Symbiosis" (Chertow 2004).
2. One megawatt (MW) = 1×10^6 joule/sec (J, SI) $\approx 3.412 \times 10^6$ British Thermal Units/hr (BTU).
3. One tonne (t) = 10^3 kilograms (kg, SI) $\approx$ 1.102 short tons.
4. The U.S. Energy Policy Act of 2005 makes significant changes to the Qualifying Facility (QF) provisions of the Public Utility Regulatory Policies Act (PURPA) by, among other things, conditionally terminating the mandatory purchase and sale obligations for new QFs and tightening thermal output requirements for new qualifying cogeneration facilities (Hunton and Williams 2005).
5. Gibbs and colleagues (2002) summarize many of the descriptions of barriers as follows:

First, there are *technical barriers*, including the possibility that local industries do not have the potential to "fit together." Second, *informational barriers* may make it difficult to find new uses for waste products, relating to poor information regarding the potential market and potential supply. Third, *economic barriers* may inhibit the incentive to use waste streams as a resource if there is no reliable market for them. Fourth, *regulatory barriers* may prevent industries or industrial processes being linked together. Finally, there may be *motivational barriers* wherein firms, public sector agencies and other relevant local actors must be willing to co-operate and commit themselves to the process.

6. In addition, there has been concern for many years about the use of industrial by-products, especially in symbioses involving agriculture. This is an important environmental and health issue to be carefully examined in every case of by-product reuse, especially with increasing concerns about the spread of diseases (Lifset 2001; Chertow 2004). In the examples cited in this article I have found no widely reported evidence of environmental health problems resulting from by-product exchanges.
7. With thanks to K. Drakonakis, the survey involved contacting the last parties identified from the PCSD list and continuing until a further contact or related professional was reached to address the fate of the project. Internet searches were used to continue to track and document outcomes because project land does not, per se, disappear, but eventually goes to another use.
8. The names are drawn from the 1996 agenda available at <http://clinton2.nara.gov/PCSD/Publications/Eco_Workshop.html#v>.
9. The "new town concept" refers to an urban planning idea to design communities for self-sufficiency by mixing uses such as housing, industry, cultural resources, and shopping.
10. 1 gallon ≈ 3.8 liters.
11. Currently, Chinese and Korean policies are focusing on retrofit of existing parks to increase symbiotic exchanges as a means of conserving water and other resources and simultaneously increasing competitiveness.

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