Progress Toward a Circular Economy in China

The Drivers (and Inhibitors) of Eco-industrial Initiative

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:// Supporting information is available on the *JIE* Web site

Summary

Eco-industrial initiatives, which close industrial loops by turning wastes at one point in a value chain into inputs at another point, are attracting growing interest as a solution to the problem of sustainability of industrial systems. Although Germany and Japan have made important advances in building recycling incentives into their industrial systems and sought competitive advantage from doing so, China is arguably taking the issue even further (in principle) through its pursuit of a circular economy, now enshrined in law as an official national development goal. In this article, we review a number of the eco-industrial initiatives taken in China and compare them using a common graphical representation with comparable initiatives taken in the West and elsewhere in East Asia. Our aim is to demonstrate some common themes across the case studies, such as the transformation from the former linear economy to a circular economy and the evolutionary processes in which dynamic linkages are gradually established over time. We discuss the drivers of these eco-industrial initiatives as well as the inhibitors, setting the initiatives in an evolutionary framework and introducing a notion of Pareto eco-efficiency to evaluate them. We make the argument that China might be capturing latecomer advantages through its systematic promotion of eco-industrial initiatives within a circular economy framework.

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Introduction

The literature on industrial ecology (IE) is concerned at the macro level with bringing the industrial economy and the environment—or the economy and its natural limits—into some form of harmony; at the micro level it is concerned with the identification and analysis of a wide variety of "eco-industrial initiatives" that reduce the energy and resource intensity of industrial activities, largely through converting wastes from one process into inputs to another industrial process. At the macro level, the IE literature is concerned with identifying the processes through which this grand harmonization between industrialization and its natural limits may be effected and the kinds of measurement indexes that might be used to plot progress (or lack of progress) in approaching such a goal. At the micro level, one of the key concerns of the IE literature is to identify cases of synergistic interactions between firms, or industrial symbioses, through which wastes are converted into inputs, on the biomimetic model of the great natural cycles that have evolved on planet Earth. The literature has identified certain canonical cases of such industrial symbiosis, including Kalundborg in Denmark (Jacobsen 2006), and emerging cases, such as Kwinana and Gladstone in Australia (Van Beers et al. 2007) and now, increasingly, cases from China.

The China cases are the subject of this article. The eco-initiatives (or cases of industrial symbiosis) carried out in China have been seen as a key part of the solution for China's battle to address its environmental problems while maintaining its economic growth.[1] The goal of the eco-initiatives is to eventually establish a so-called circular economy, or what is otherwise known as a "closed-loop" economy. Such an endeavor is supported by a range of institutional and legal arrangements. The law proclaiming the circular economy as China's central development goal was passed in 2008 and came into effect in January 2009.[2] It is the world's first national law proclaiming an economy model different from the mainstream linear "raw materials in" at one end and "waste out" at the other—a model that still implicitly dominates mainstream economics, as if natural limits simply did not exist. China is clearly following the lead of Germany and Japan, which are among the most experienced and developed countries in institutionalizing industrial recycling initiatives (Moriguchi 2007).

In general, closed-loop initiatives are taken at three levels. Some are confined to a single enterprise or group of enterprises, enhancing energy and resource efficiency; this kind of initiative is generally recognized as "cleaner production." At the second level are initiatives taken at a cluster level or supply chain level, whereby a group of colocated firms (e.g., in an eco-industrial park [EIP]) share certain streams of resources and energy and so enhance their collective energy and resource efficiency. This is one of the key concerns of industrial ecology, described as industrial symbiosis—along with other concerns, such as identifying energy and material flows that could be described as industrial metabolism. In either case, the model is the cycles of nature, which keep replenishing the basic requirements for life, such as water, carbon, and nitrogen. When co-located in an industrial area and planned as such, the initiatives are sometimes known as "eco-industrial parks" (Lowe 1997).

The third level, so far found mainly in China, involves a whole city or whole municipal area where recycling and interconnected processes are promoted through economic and administrative incentives and, conversely, failures to recycle and to make industrial connections are penalized in some way. Demonstration sites are now found throughout China, as discussed in an expanding literature.

Although a historical perspective is salutary in clarifying just how prevalent were past industrial practices in turning wastes into sources for new products (Desrochers 2002a, 2002b), the scale of present efforts in relation to the challenges is miniscule. So far, the literature on eco-industrial initiatives analyzed at the meso level remains fragmented, with each of the few articles tending to analyze just one or a few cases—with some notable recent exceptions that take a broader perspective (e.g., Chertow and Lombardi 2005; Zhang et al. 2008, 2009, 2010). The gap in the literature that we target is a sustained comparison of the existing initiatives across different countries that puts the Chinese cases into the same setting and uses the same categories as some of the western examples, such as Kalundborg and

Kwinana, and recently emerged cases from elsewhere in East Asia, including Ulsan in Korea and Kawasaki in Japan.

In this article, we review progress achieved to date in implementing eco-industrial initiatives in China and compare that progress with a sample of results achieved elsewhere, using a common graphical approach. Our aim is to demonstrate some common themes across the case studies, such as the transformation from the former linear economy to a circular economy and the evolutionary process in which dynamic linkages are gradually established over time. We call them "eco-industrial linkages" to emphasize their ecological dimension. We do so in the aspiration that the process of monitoring and documenting such eco-industrial initiatives will contribute to a better understanding of the drivers and inhibitors of eco-industrial initiative and of the circular economy in general. We discuss the Chinese "circular economy" law and its impact in promoting and shaping eco-industrial initiatives, particularly in promoting the formation of new eco-industrial parks where industrial symbioses between firms can be designed in from the start rather than added on later as they are identified.

The central propositions of our article concern the category of "eco-industrial initiative" and how it can be turned into a widely used unit of economic and policy analysis, as well as an object of entrepreneurial initiative and regulatory concern. We indicate in the cases below how the individual eco-industrial areas or parks have evolved, so that the circularity of the flows within the group is enhanced as the number of connections between firms multiplies. These interconnections can be quantified in terms of "connectedness" or "connectance" of the group (Van Berkel 2009), by analogy with connectance of food webs in ecology (Hardy and Graedel 2002; Dai 2010). We discuss the drivers of eco-industrial initiative as well as the inhibitors, putting our discussion into an evolutionary setting where we can characterize such initiatives as leading groups of firms to a kind of "evolutionary stable state" or connectedness equilibrium—adding a business and profit dimension to the formulation. We conclude that careful implementation of the Chinese circular economy law could bring substantial competitive advantages to China in an era of intense global ecological awareness.

The Idea of the Circular Economy and Its Development in China

The interest of the circular economy and its promotion in China lies in the fact that it has moved beyond an "environmental" concept to become a mainstream development goal (Yuan et al. 2006; Geng and Doberstein 2008; Zhu 2008; Zhang et al. 2009). China's national leadership has clearly understood that continued development in the traditional linear manner, starting with resources taken from nature at one end and proceeding through production processes to the creation of wastes disposed in nature at the other end, is simply no longer feasible. It is destructive to the point of ruin, at both ends, and it is costly to both secure fresh resources all the time and lose resources in the form of waste: It is, in other words, both economically and ecologically inefficient.

This is an understanding that China shares with the rest of the developed world and in particular with Japan and Germany, where efforts to embed these insights into a regulatory framework have been made (Triebswetter and Hitchens 2005; Moriguchi 2007). But only in China has a circular economy been made the object of official development goals and been taken from the realm of environmental policy into the realm of development and economic policy—an extremely important step.

Although China's economic growth has been spectacular, averaging close to 9% per year for the past 3 decades, the level of energy and materials utilized per unit of gross domestic product (GDP) has been much greater than for more advanced economies—although the level is falling (e.g., Jiang 2009). The high intensity levels have led to both economic and ecological costs that are becoming unacceptable. So China is setting itself ambitious goals in terms of energy and materials (or resource) efficiency. We show in figures S1-1 and S1-2 (in the Supporting Information on the Web) what the trend for China's energy and resource efficiency has been, to demonstrate that there have indeed been improvements consistent with ecological modernization (Mol 2006).[3] Under the 11th Five-Year Plan (2006–2010), approved by the National People's Congress in March 2006, the goal for energy intensity was set to be 20% lower in 2010 than that in the end of 2005,[4] and the pronouncements made at the Copenhagen Climate Change summit, in December 2009, set the further objective to reduce China's "carbon intensity" by 40% to 45% by 2020, compared with 2005 levels. To achieve those goals, China is specifying a range of means, such as closing down inefficient factories and power plants—but also including the implementation of circular economy measures, through interconnecting the chains of resource and energy utilization. In this approach, wastes from one process can be captured and used as raw material for another, with energy generation being shared along the value chain, as an explicit developmental goal. Examples of these synergistic arrangements in the developed world are termed "combined heat and power" (CHP initiatives), and there are hundreds of such examples, particularly in northern Europe. China is drawing inspiration from these initiatives and making CHP a principle of industrial design throughout the economy and an important component in its eco-industrial initiatives.

In mid-2008, the Chinese People's Congress passed a national circular economy law, the Law for the Promotion of the Circular Economy, which came into effect on 1 January 2009. Although it was inspired by legislation in other countries, such as the Basic Law for Establishing a Sound Material-cycle Society passed in 2000 in Japan and the Closed Substance Cycle and Waste Management Act enacted in 1996 in Germany, the law in China seems to be the first in the world to make circular economy a national strategy of economic and social development. The Chinese law basically provides a framework within which incentives and disincentives (penalties) may be developed at multiple levels to promote firms and municipalities taking eco-industrial initiatives, and for the creation of networks of by-product exchange. The framework of the circular economy will be incorporated into the country's 12th Five-Year Plan, to cover the years 2011–2015; current reports indicate that the new Plan will include resource consumption efficiency measures as basic measures of eco-efficiency.[5]

Many empirical studies are now appearing in both the Chinese and the English-language literature, including firm-level studies of cleaner production, such as the work of Yuan and Shi (2009) on eco-industrial initiatives at a smelter; interfirm studies, such as those devoted to eco-industrial parks and "green" supply chains (see, e.g., Zhu et al. 2008); and regional studies, such as Dalian (Geng et al. 2009) or Liaoning (Xu et al. 2008). We now review the progress made in these eco-industrial initiatives taken in China, especially those taken at the level of eco-industrial parks that span different value chains and create synergies across wide groups of enterprises, before comparing them with some of the better known cases documented in the developed countries.

Eco-industrial Initiatives in China

Although eco-industrial development is a relatively new phenomenon in China, it is accelerating and now promises to become one of the main industrial development models in its application. A number of eco-industrial initiatives have been designed and implemented for the purpose of the circular economy since the concept was first introduced into China by Chinese scholars in the late 1990s (Zhu 1998). In 2005 the National Development and Reform Commission, in conjunction with five other ministries, launched the first batch of national pilot demonstration projects, which included seven industries, four types of economic activities, 13 industrial parks, ten provinces and cities, and 42 enterprises.[6] The second batch of national pilot demonstration projects was launched in 2007, among which were counted 31 enterprises from 11 key industries, 17 areas and enterprises engaging in four key activities, 20 industrial parks, and 17 provinces and cities.[7] Meanwhile, a program established by the Ministry of Environment Protection, in conjunction with two other ministries, designated a total of 50 EIPs across the country up to December 2010, as listed in figure 1.[8] Those include 11 EIPs approved for completion and 39 approved for construction.

Figure 1 Approved national eco-industrial parks (EIPs) up to December 2010 in China.
Source: Authors based on the list published by the Ministry of Environment Protection of China, available at http://kjs.mep.gov.cn/stgysfyq/m/200807/t20080718_125900.htm (in Chinese, accessed on 10 March 2011).

Although organized and maintained by different government agencies, these initiatives have seen a number of demonstration sites listed in both programs. In this section we review the leading Chinese eco-industrial initiatives through a graphical representation that brings out their major features and emphasizes their circular character, and then we compare these initiatives with some of their leading Western (and East Asian) counterparts. Our purpose is to emphasize that coindustrial initiatives being taken around the world can be compared and evaluated in a common setting—at least up to a point (and if one bears in mind the difficulties raised by Van Berkel [2010]). In each case, we seek to show how formerly separate chains of activities, which started with taking resources from nature and ended with dumping wastes back into nature, have been interconnected, with wastes being used as raw materials for the next process. Each of these fresh interconnections constitutes what we would call a new "eco-industrial initiative." The purpose in introducing the common graphical representation is to emphasize the *circularity* in the eco-industrial initiatives, through "closing the loops." Those eco-industrial initiatives evolve over time, with new material and energy exchanges being established and, on some occasions, old exchanges broken and reformed.

Sugar Industry: Guigang Group

The Guigang Group was founded as a state-owned entity to produce cane sugar in 1954. It started out as a conventional sugar mill, but over the years it has embodied more and more synergies as extra facilities have been built to turn wastes into raw materials for new processes. As the first national eco-industrial park designated by the central government in 2001, today the group is composed of a set of enterprises colocated in Guigang that share a number of resource and energy flows under a common corporate management; altogether up to 2008, the group has developed production capacities of 150 kilotonnes (kt)[9] of sugar, 150 kt of pulp and 150 kt of paper,

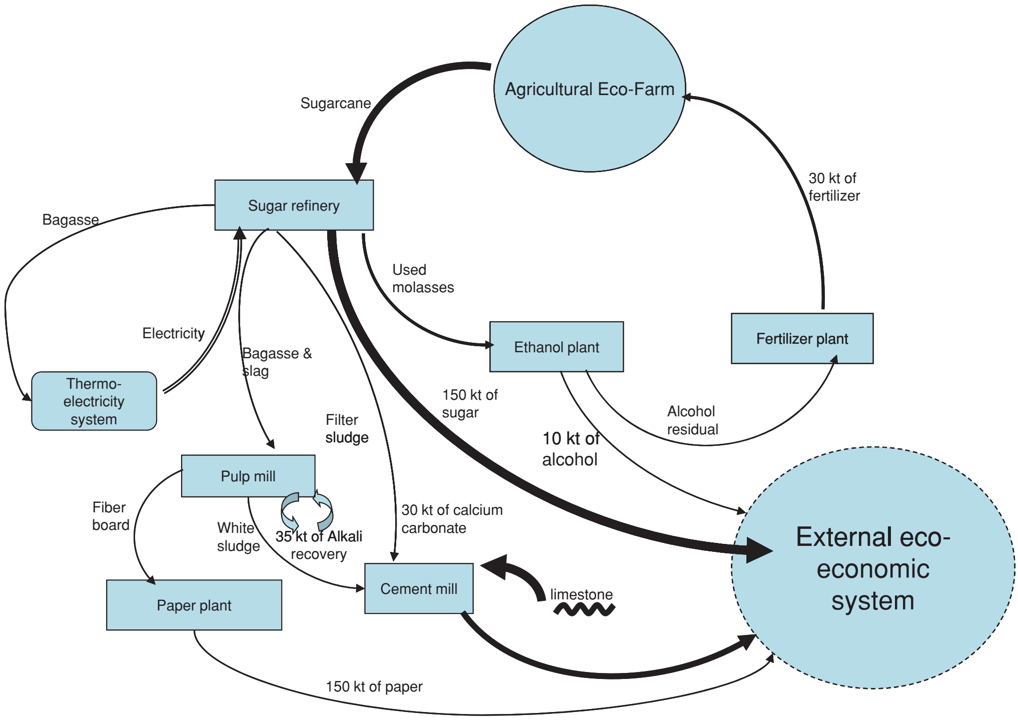


Figure 2 Selected industrial symbioses in the Guitang Group, Guigang City. The variation in the thickness of the lines is an indication of the magnitude of the flows; the squiggly lines indicate the raw materials taken from nature outside the eco-industrial parks. kt = kilotonne.
Source: Based on the work of Fang and colleagues (2007), Lowe (2001), Zhu and Côté (2004), and Zhu and colleagues (2007) as well as the company's Web site and its recent financial reports.

10 kt of ethanol, 30 kt of calcium carbonate for cement production, 85 kt of alkali, and 30 kt of fertilizer, with two main value chains, as shown in figure 2.[10] There is the sugar process itself, linked to an ethanol production facility, which has now closed the loop through wastes from the ethanol plant (vinasse) being converted into fertilizer and recycled back to the cane farms. The other main chain is concerned with paper, which starts with the crushed cane (bagasse) as raw material, converts this to a pulp, which is then turned into paper and sold to the wider economy. Since 1998, the group has started the operation in using the filter mud (after being dried) generated from the sugar refinery process as a raw material for cement production, thus creating a new value chain. Furthermore, bagasse is recycled as fuel for the production of heat and power, which are used in all the other industrial processes found in the Guigang Group. As these businesses expand, so the group extends its value chains into the surrounding economy. This is the essence of circular economy evolution.

Pingdingshan Coal Mining Group

The Pingdingshan Coal Mining Group (simply referred to as Pingmei) was established in 1955 as the first large-scale coal mine after China's 1949 revolution.[11] It has been very productive, but along the way it has accumulated piles of coal waste that amount to nearly 54 million tonnes and occupy an area of 2.66 square kilometers—plus emitting each year 2 million tonnes of coal gangue, 0.5 million tonnes of coal slime, and 0.2 million tonnes of fly ash. In

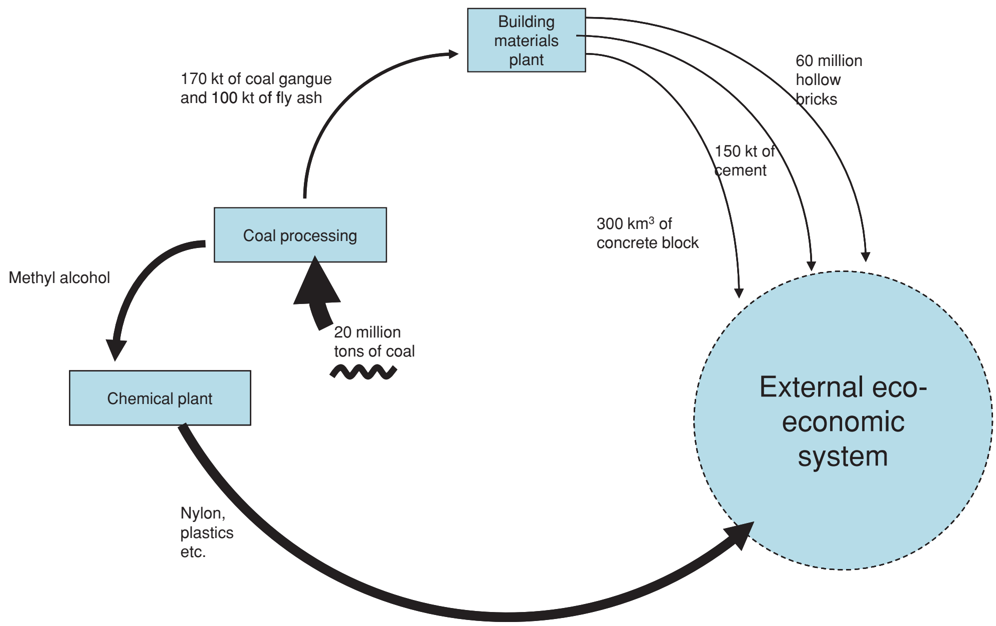


Figure 3 Selected industrial symbioses in the Pingdingshan Coal Mining Group. The variation in the thickness of the lines is an indication of the magnitude of the flows; the squiggly lines indicate the raw materials taken from nature outside the eco-industrial parks. kt = kilotonne; km = kilometer.
Source: Based on the work of Long and Zhang (2009) as well as Pingmei's Web site (www.pmjt.com.cn).

addition, it has caused extensive land subsidence and emissions of harmful gas and sewage. Beginning in the 1980s, Pingmei began to introduce recycling measures and cross-stream and downstream activities to utilize these wastes. By the first decade of the 2000s, Pingmei had created a major new building materials business based on the use of coal slime, fly ash, and coal gangue to make gangue cement, fly ash cement, and fly ash concrete blocks, with plans to expand this aspect of its business (figure 3). These initiatives represent substantial improvements in eco-efficiency. Of course, carbon dioxide is still being released—but all other contaminants are now being reused in new value chains to produce new products. As recognition of its progress, the group was listed as among the first batch of circular economy Pilot Demonstration sites.

Lubei Chemical Group

The Lubei Group is a chemical complex located in Wudi, Shandong Province, near the Bohai Sea. The predecessor of the group was initially established in 1977, and the first technology for coproduction of sulfuric acid and cement from gypsum was developed in the early 1980s thanks to R&D funding provided by the government. The Lubei Group is now a large state-owned industrial group covering 12 sectors, from building materials to light industry, power generation, and machinery production.[12] Annual outputs of the 52 member enterprises (as of 2005) include ammonium phosphate (350 kt), sulfuric acid (860 kt), cement (600 kt), sea salt (1,000 kt), sodium hydroxide (85 kt), and bromine (10 kt). Lubei is one of the largest producers of ammonium phosphate fertilizer in the world, as well as of cement and sulfuric acid.

There are three main value chains within the Lubei Group. The first is the sulfuric acid–ammonium phosphate–cement chain, as shown in figure 4. The sulfuric acid plant receives inputs of charcoal clay, coal, and high-sulfur coal to produce sulfuric acid and a waste, coal slag. The waste is fed into a downstream cement mill

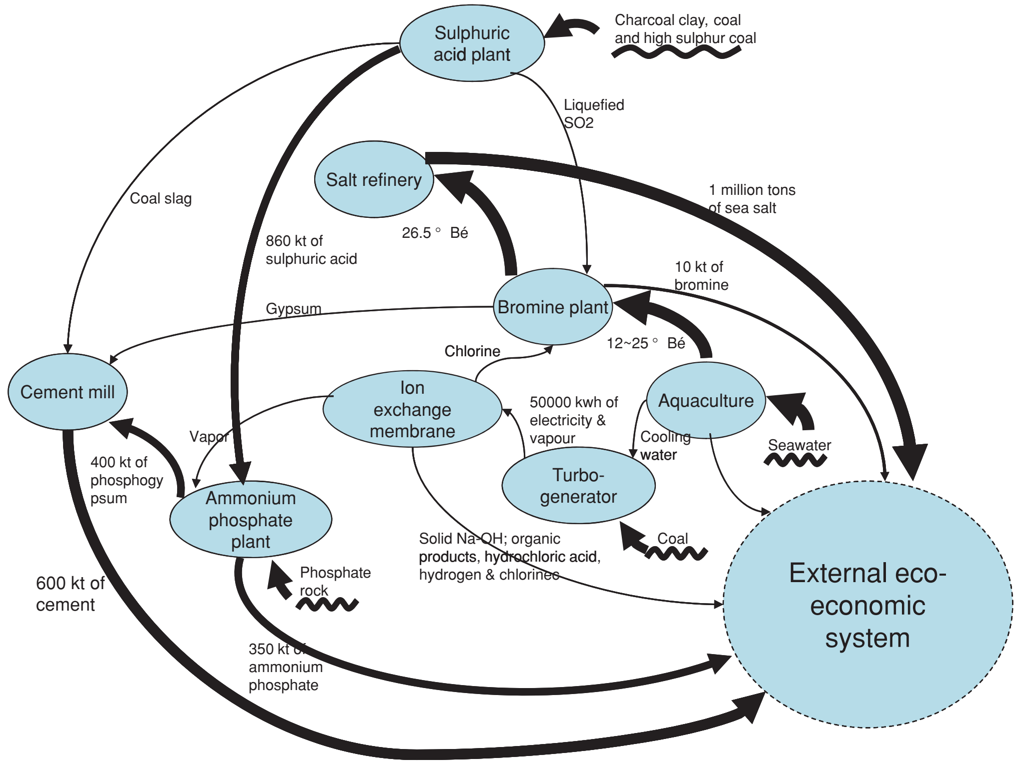


Figure 4 Selected industrial symbioses in Lubei Industrial Park. The variation in the thickness of the lines is an indication of the magnitude of the flows; the squiggly lines indicate the raw materials taken from nature outside the eco-industrial parks. SO_2 = sulfur dioxide; kt = kilotonne; kwh = kilowatt hour; NaOH = sodium hydroxide.
Source: Based on the work of Fang and colleagues (2007) and Yu and colleagues (2007) and on Lubei's Web site (www.lubei.com.cn).

(along with limestone as raw material), and the acid is fed into the ammonium phosphate plant, as well as being sold to the wider economy. The second chain is based on seawater utilization for various chemicals, such as salt and bromine. The third chain is a salt–alkali–electric power generation system. The main shared resource flows involve sulfuric acid and seawater, the main shared energy flows are steam and electric power, and gypsum and furnace slag are the main wastes. Ion exchange processes act as a link between the various flows, whereas some novel uses of former wastes include aquaculture for warm recycled water, which again enhances eco-efficiency. The building materials chain is notable at Lubei not only because it disposes of considerable wastes as raw materials for the various construction products (cement, hollow blocks, etc.) but also because of the savings in raw material (limestone) effected.

Suzhou Industrial Park

The Suzhou Industrial Park (SIP) was established in 1994 as part of a cooperation project between China and Singapore and started the official effort for obtaining the national EIP accreditation in 2002. The Park has attracted a vast number of international firms—altogether, 2,400 foreign-funded enterprises, of which 66 rank in the world's top 500 enterprises—as well as local entrepreneurial firms, covering such industries as chemical, pharmaceutical, health care, machinery, electronics, information technology

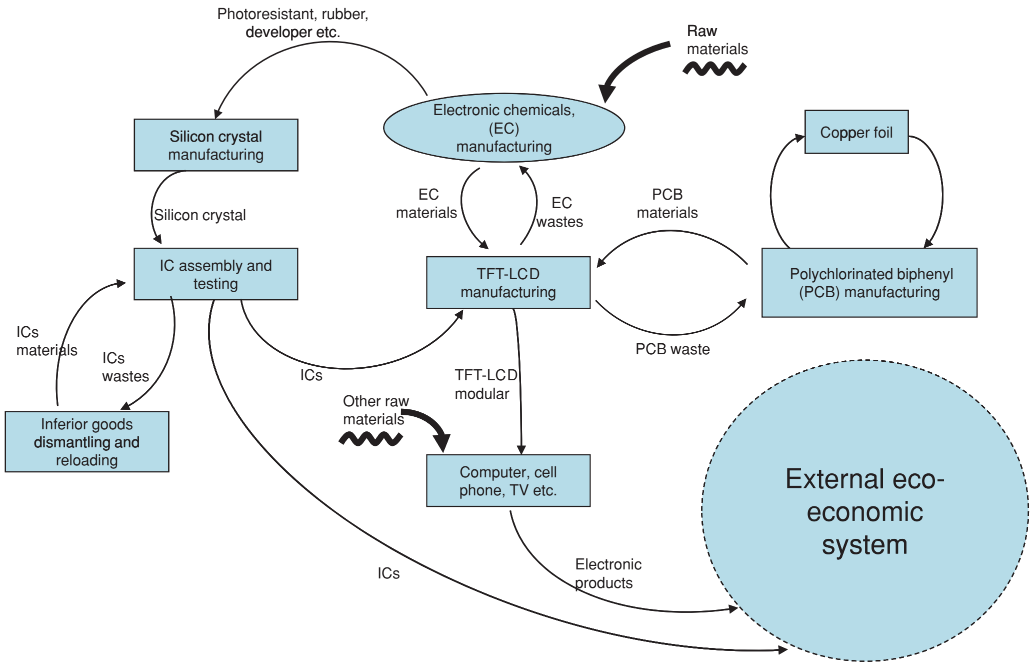


Figure 5 Selected industrial symbioses in Suzhou Industrial Park. The variation in the thickness of the lines is an indication of the magnitude of the flows; the squiggly lines indicate the raw materials taken from nature outside the eco-industrial parks. IC = integrated circuit; TFT-LCD = thin-film transistor liquid crystal display; PCB = polychlorinated biphenyl.
Source: Based on the work of Zhang and colleagues (2009).

(IT), and software.[13] In particular, SIP has attracted many leading IT manufacturers in the world, producing about 16% of the integrated circuit products in China and also serving as the largest export base of liquid crystal display (LCD) panels from China. The park currently has the largest gas-fired combined cycle cogeneration plant in China, serving as both a power generation and a district heating system and meanwhile reusing treated wastewater as cooling water. In addition to its achievement in wastewater and energy exchange between residential and industrial sectors, which has enhanced eco-efficiency, SIP has actively pursued a "value chain completion" strategy in its investment promotion by seeking to integrate firms in the park in wider chains of activity. Today SIP has enacted e-waste recycling across its IT value chain consisting of upstream electronic chemicals manufacturing through semiconductor and thin-film transistor LCD (TFT-LCD) production to downstream consumer products (figure 5). Overall the firms in SIP are achieving ecological standards that are vastly superior to national levels, such as in chemical oxygen demand (COD) and sulfur dioxide (SO_2) emissions, where the levels are one-eighteenth and one-fortieth of China's national averages, respectively.[14] In 2008, SIP and its sister industrial park, Suzhou New and Hi-tech Industrial Development Zone, were both recognized as two of the first three approved EIPs in China.

Tianjin Economic Technological Park

Established in December 1984, the Tianjin Economic-Technological Development Area (TEDA) was one of the first eco-industrial areas approved by the State Council for development along ecological lines. TEDA has launched a range of environmental initiatives since its establishment, aiming to create an industrial park

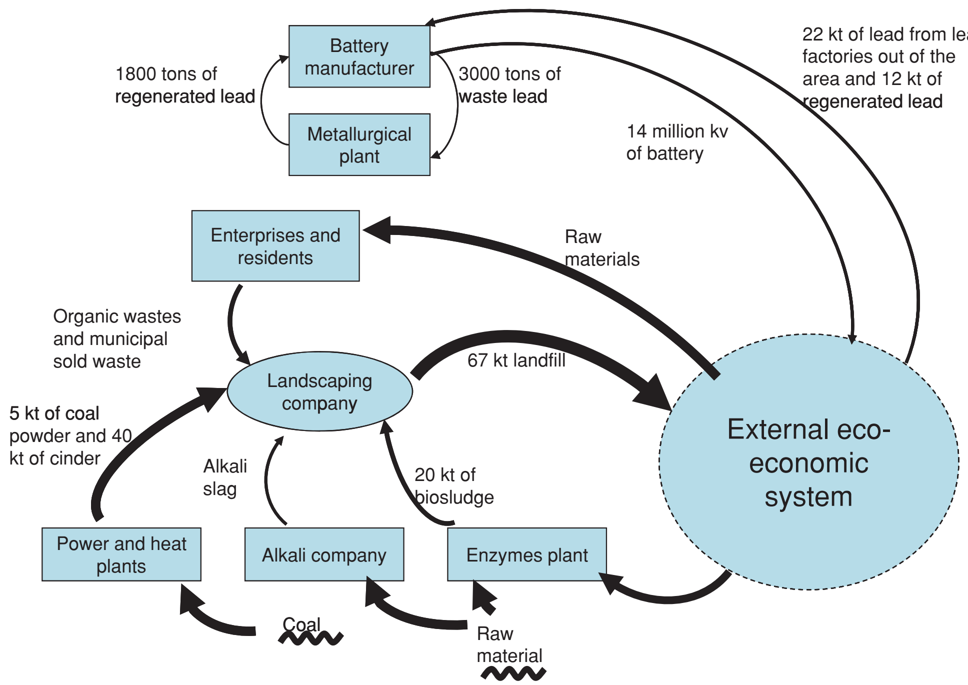


Figure 6 Selected material flows in the industrial symbiosis in the Tianjin Economic Development Area. The variation in the thickness of the lines is an indication of the magnitude of the flows; the squiggly lines indicate the raw materials taken from nature outside the eco-industrial parks. kt = kilotonnes; kv = kilovolts. Source: Based on the work of Tan and Bao (2006), Geng and Yi (2006), and Shi and colleagues (2010).

with leadership in green manufacturing and recycling of water and waste. Since the early 2000s the focus has been on transformation toward an eco-industrial park and the creation of a circular economy at the industrial park level.[15] As a result of those initiatives, the system of industrial symbiosis has evolved over time, with a number of wastewater, solid waste, and energy exchanges being established. For example, a wastewater treatment plant started operation in 2000, and a water reclamation plant was put into use in 2003, thus substantially reducing the need for freshwater inputs. A cogeneration power station was built in 2003 that uses treated wastewater as boiler supply water. A landfill company started operations in 2002 receiving coal powder, cinder, and alkali slag as input and converting biosludge from an enzyme company into fertilizer, thereby producing a useful product. In addition, a lead recycling company established in 2005 now provides a large amount of regenerated lead from used batteries and other lead waste from Tianjin and Beijing regions to another local battery company. Figure 6 highlights selected material flows that cross-link firms in the Tianjin area. In recognition of those efforts, TEDA has been adopted as one of the first three approved eco-industrial parks in China as well as a member of the first batch of circular economy Pilot Demonstrations.

International Comparisons

We now wish to place these Chinese eco-industrial initiatives on a comparable footing with those that have been taken elsewhere, to see the points of commonality. Certain initiatives have been studied now for several years, and their "spontaneous" evolution has been documented—as in the cases of Kalundborg in Denmark and Kwinana in Australia. We look first at these cases and then at two that have been identified more

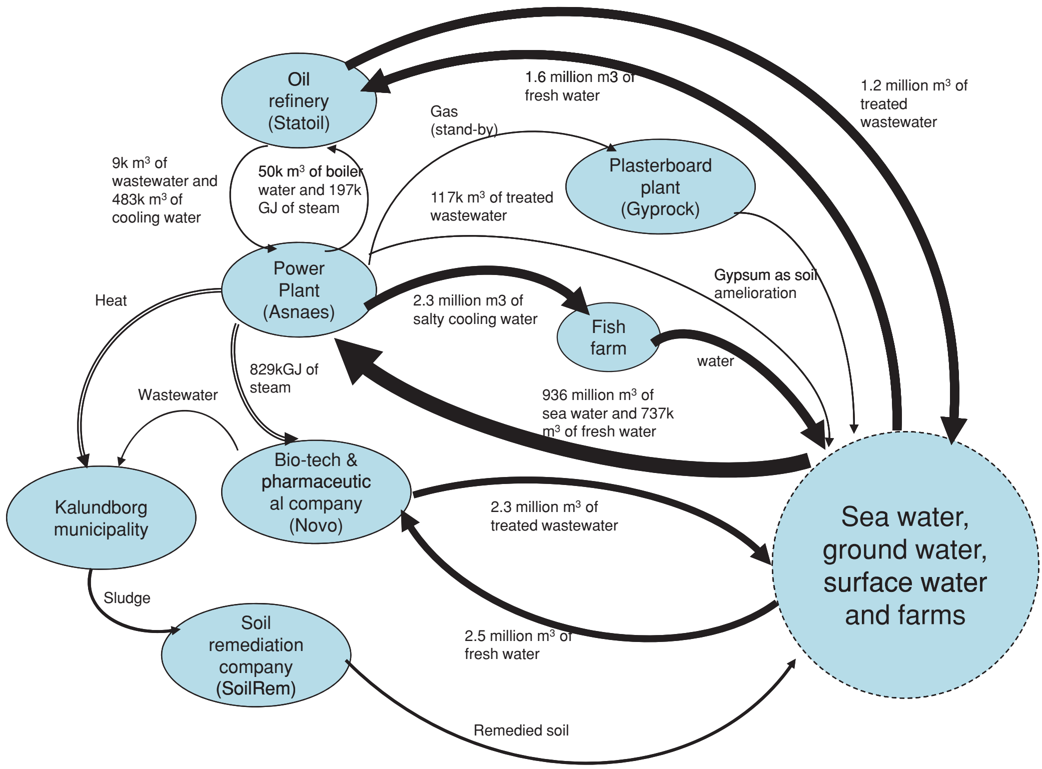


Figure 7 Selected industrial symbioses in Kalundborg, Denmark. The variation in the thickness of the lines is an indication of the magnitude of the flows. m = meters; k = thousand; GJ = gigajoules; CO_2 = carbon dioxide.
Source: Based on the work of Jacobsen (2006).

recently, in the industrial park of Ulsan in Korea and Kawasaki in Japan.

Kalundborg, Denmark

The Danish coastal town of Kalundborg is the most intensively studied spontaneous producer of industrial symbioses, or, as we describe them, eco-industrial initiatives, known in the IE literature.[16] It is located on the island of Seeland, 120 kilometers (km) west of Copenhagen, and best approached by ferry. The town is purely industrial and built around four basic industries—a coal-fired power plant (Asnaes), an oil refinery (Statoil), a pharmaceuticals and enzymes producer (Novo Nordisk), and a plasterboard manufacturer (Gyproc); the municipality also provides various shared utilities and services. Local synergies began to develop spontaneously in the 1970s and by the 1990s had developed into a network of by-product exchanges, as shown in figure 7. As described by Ehrenfeld and Gertler (1997), these linkages and by-product exchanges evolved over time, with a fresh exchange being established every 2–3 years (see table 1 in the work of Ehrenfeld and Gertler [1997]), and were in no sense planned as in the ideal model of an EIP, nor is the industry in Kalundborg self-contained, as numerous raw materials come in from outside. More recent studies (e.g., Jacobsen 2006) also indicate that the industrial symbiosis exchanges have been upgraded from time to time from generally low-value by-product exchanges, through a number of intermediate stages, to high-value by-product exchanges, which has resulted not only in steadily reduced intake of raw materials and resources during the past decade but also in the capture of economic benefits by individual firms in the complex. Kalundborg remains a benchmark for the cases of industrial symbiosis being identified now around the world and actively developed in China under the circular economy and EIP guidelines.

Kwinana, Australia

The Kwinana Industrial Area (KIA) is located on a coastal strip around 8 km long at a point 40 km south of Perth, in Western Australia. The area was developed first in the 1950s as a location for resource extraction and processing industries and is still dominated by alumina, nickel, and oil refineries as well as titanium dioxide production and a variety of fabrication and construction activities. Space is also devoted to utilities, including two power stations, two cogeneration plants, two air separation plants, port facilities, and water and wastewater treatment plants (Van Beers et al. 2009). It is one of the leading examples of spontaneous industrial synergy development, with nearly 50 regional synergies being identified, some of which are shown in figures 8A and 8B.[17] The main cross-connections resulting in improved resource and energy efficiency are those relating to (1) reuse of gypsum (calcium sulfate) from a chemical plant as a soil amendment, (2) reuse of lime kiln dust from a cement plant for desulphurization, (3) and reuse of silica fume from a fused alumina and zirconia producer in the building sector. In addition, many other synergies are under investigation or were tried and had to be abandoned, for various economic reasons. The recent addition of the BHP company's HiSmelt pig iron plant has created many new eco-industrial possibilities, including reuse of lime kiln dust from the cement and lime producer.

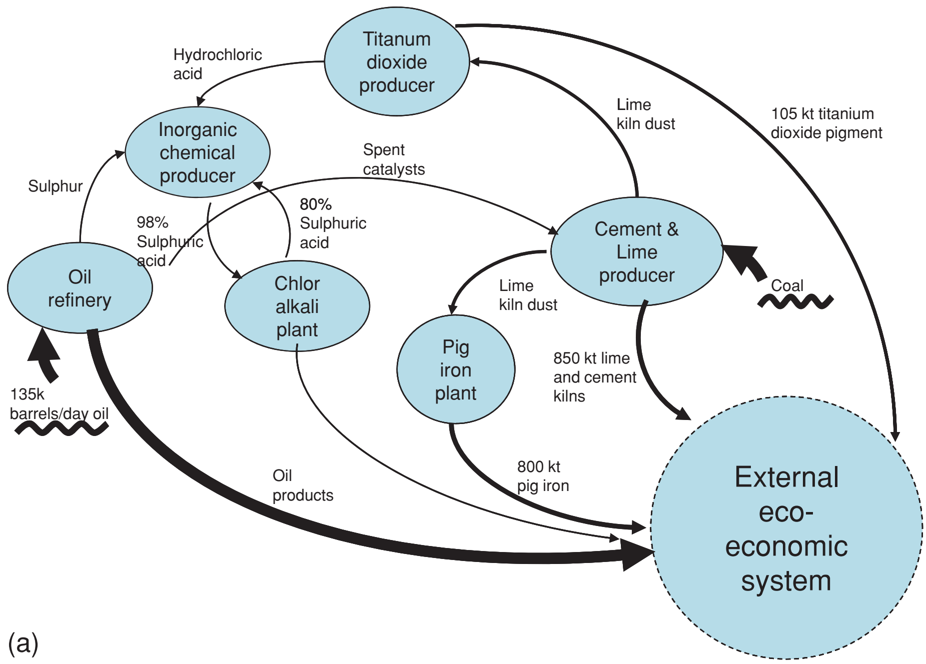
Ulsan, Korea

In 2005 Korea initiated an ambitious three-phase, 15-year development project that would create a number of eco-industrial parks under the guidance of the newly formed Korean National Cleaner Production Center (KNCPC). The first phase (2006–2010) was concerned with identifying eco-industrial improvement possibilities (industrial symbioses) and focusing development around two designated industrial parks, creating an energy-efficient by-product exchange (BPX) network. The second phase (2011–2015) is envisaged as spreading the concepts to 20 other parks. The third phase (2016–2020) would review the inevitable flaws and seek to eliminate them and would review the performance indicators developed for the initiatives (Park et al. 2008). The overall goal is a closed system across all the eco-industrial parks, with zero discharge. Ulsan is the most advanced of these initiatives.

Ulsan is a vast industrial complex in Korea, home to substantial sectors of Korean industry. Ulsan City was given the status of special industrial zone in 1962, and it has been a driver of industrial development in Korea ever since—largely spontaneously until 2006. There are more than 700 companies in the Ulsan industrial complex, some of them industrial giants such as Hyundai, Samsung Fine Chemical, and Kumho Petrochemical, and substantial progress has already been achieved between the companies themselves in identifying and acting on industrial synergies. According to Park and colleagues (2008), so far 70 symbioses have been identified—34 coming from collective utility systems (power, water, heat), 19 from by-product exchanges, nine from shared connections for steam, five from use of excess steam, and three from links for recycling of industrial water—some of which are shown in figure 9. Ulsan Metropolitan City is actively involved in promoting the expansion and further evolution of the Ulsan EIP.

Kawasaki, Japan

Kawasaki, a coastal city next to Tokyo with approximately 1.3 million residents, is an important industrial base in Japan that heavily relies on the chemical industry, the steel industry, the food industry, the petroleum industry, and the general machinery and appliances industries. The city was selected as one of the four eco-towns under the Eco-Town Program sponsored by the central government of Japan. Thanks to the program, at least 14 recycling and symbiotic projects have been established, not only involving



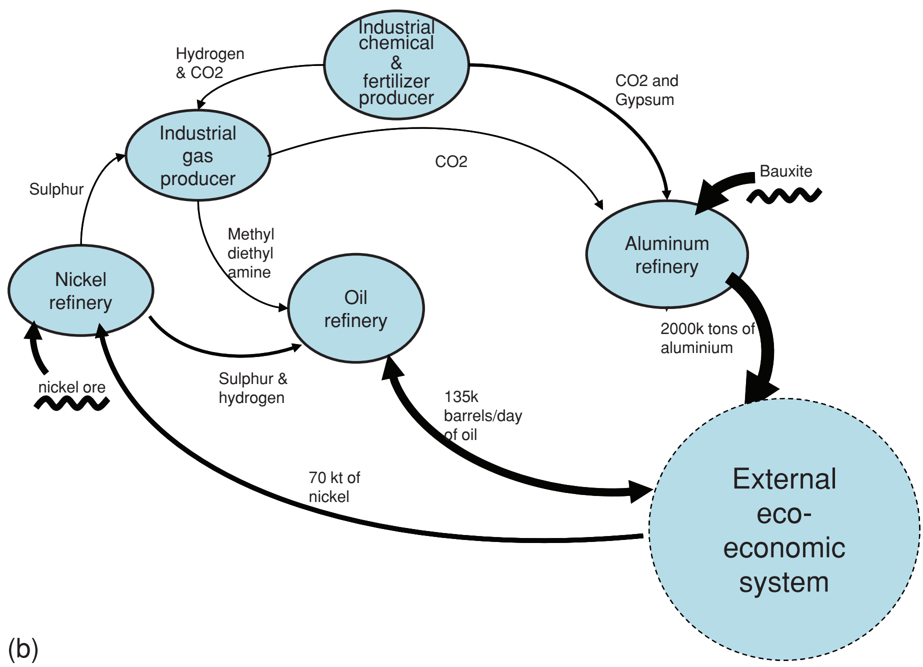


Figure 8 (A) Selected industrial symbioses in Kwinana, Australia (1) with focus on titanium dioxide. (B) Selected industrial symbioses in Kwinana, Australia (2) with focus on nickel. The variation in the thickness of the lines is an indication of the magnitude of the flows; the squiggly lines indicate the raw materials taken from nature outside the eco-industrial parks. kt = kilotonnes; k = thousand.
Source: Based on the work of Van Beers and colleagues (2007).

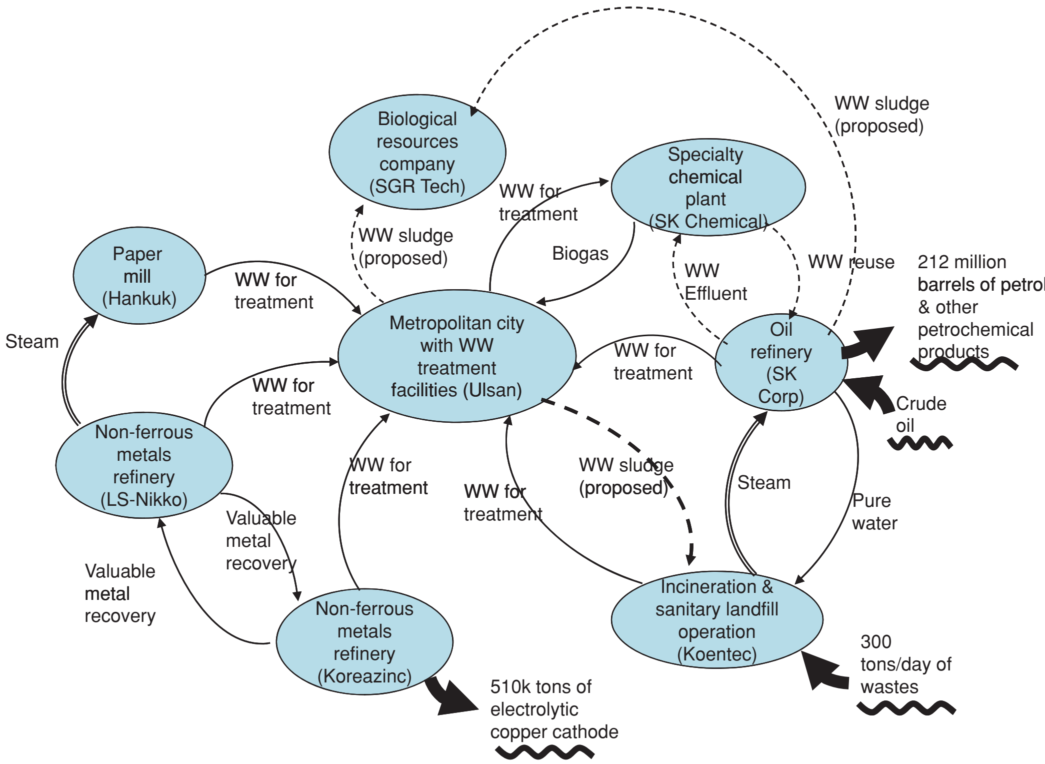


Figure 9 Selected industrial symbioses in Ulsan industrial complexes, Korea. The variation in the thickness of the lines is an indication of the magnitude of the flows; the squiggly lines indicate the raw materials taken from nature outside the eco-industrial parks. WW = wastewater; k = thousand.
Source: Based on the work of Park and colleagues (2008).

symbioses between industrial users but also extending to the broader urban area involving the use of municipal and commercial wastes (Van Berkel et al. 2009). Some of the projects and the linkages involved are highlighted in figure 10. The key players in those symbioses include a paper mill that takes paper wastes and recycled effluent from a wastewater treatment plant as main inputs; a steel refinery that uses scrap metals as raw materials and meanwhile provides blast furnace gas to the paper mill as the source of power; a cement mill whose production is based on alternative fuels (e.g., mixed plastics, organic waste and soot) and alternative raw materials (e.g., blast furnace slag) from the steel company as well as sludge and construction soils; and, finally, waste collectors and recycling firms that turn used home appliances, fluorescent bulbs, and plastics into feeds to industrial users.[18]

Discussion

Some observations can be drawn from the review of and the comparison between the leading eco-industrial initiatives in both China and more advanced countries. First, it can be observed that most of the initiatives both in China and in other countries apply to existing industrial parks or towns and aim to transform the previously linear value chain to a closed-loop production system. Only 1 out of the 30 eco-industrial parks approved by the Chinese central government up to December 2008 was purposefully-built—namely, Qindao New World Eco-Industrial Park, which was set up as a regional hazardous waste disposal center (MEP 2009). Similarly, none of the international cases discussed above was purposefully "designed" to be an eco-industrial park or an eco-town from the beginning.

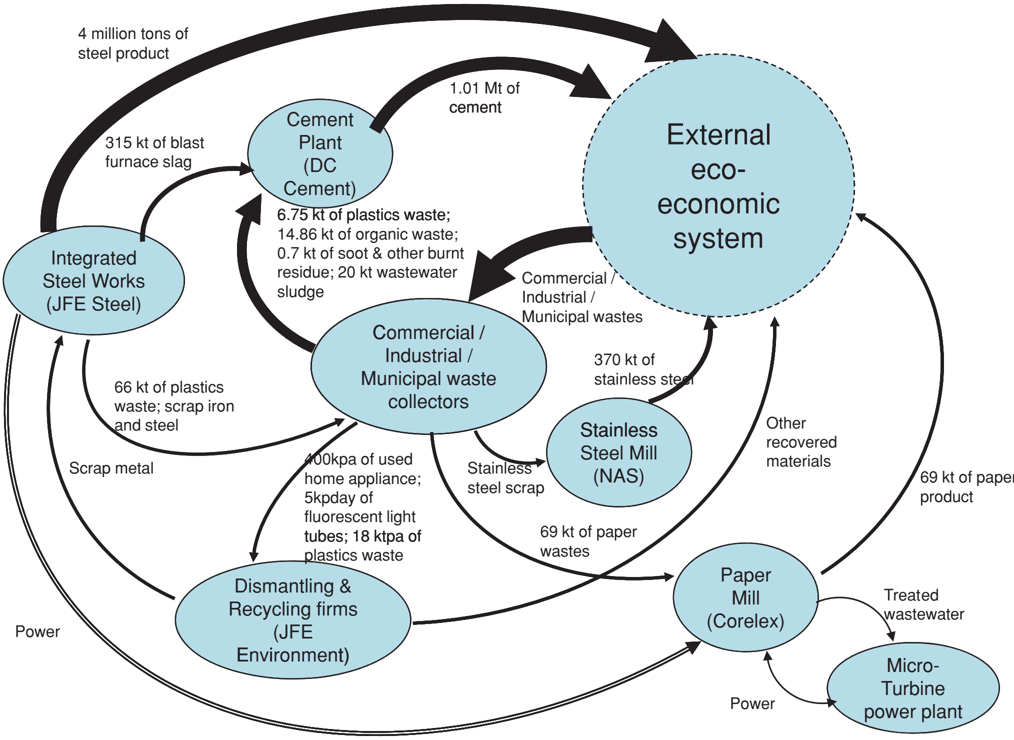


Figure 10 Selected industrial symbioses in Kawasaki, Japan. The variation in the thickness of the lines is an indication of the magnitude of the flows. Mt = megatonnes; kt = kilotonnes; ktpa = kiloton per annum; kpa = thousands of items per annum; kpd = thousands of items per day.
Source: Based on the work of Van Berkel and colleagues (2009).

Second, eco-industrial initiatives in both China and other countries are the result of evolution and transformation over decades. Activities involving environmental protection, supply chain integration, and capture of regional synergies occur spontaneously. The focus of eco-industrial initiatives shifts from an early concern with pollution control and cleaner production to development of a broader conception of industrial synergy. For example, the Suzhou Industrial Park was approved as the first National ISO1400 Demonstration Area in 1999 in recognition of its achievements, largely in the fields of cleaner production and waste management. Firms in the park began to introduce eco-industrial linkages inspired by the circular economy in 2002, and the park was then listed as one of the Circular Economy Pilot Projects in 2005. More recently, the park announced its aspiration to be recognized as a National Ecological Civilization Demonstration Park, with ambitious objectives.[19] A similar evolution can be observed in the case of Kwinana, under the aegis of the Kwinana Industries Council, as more and more regional synergies are identified and captured (Van Beers et al. 2007).

Third, compared with the international benchmarks, eco-industrial development in China is still at an early stage; therefore, symbiotic intensities resulting from the initiatives in general are still low. For example, according to the estimate by Van Berkel (2009), the leading initiative of the Guitang Group in China achieved five synergies among the five constituent firms in 2004, compared with 13 synergies among 11 firms achieved in Kalundborg in 2005, 47 synergies achieved among 22 firms in Kwinana in 2005, nine synergies achieved among 12 firms in Ulsan in 2004, and 14 synergies achieved among nine firms in Kawasaki in 2007.

Finally, the case studies in China indicate that the "visible" hand of the government plays a vital role in establishment of the eco-industrial initiatives in China, as would be expected in a "latecomer" country. Eco-industrial initiatives in China are mainly designed, supported, and managed by government at various levels. For example, 23 of the 30 eco-industrial parks approved by the Chinese central government up to December 2008 are directly managed by local municipal governments, whereas the remaining seven are managed by large state-owned enterprises. The eco-industrial initiatives need to be ratified by the government for firms to gain various financial and administrative supports, such as low-rate loans, tax relief, and priority in land supply. By contrast, a more autonomous approach is usually seen for management of eco-industrial initiatives in the international cases, including various industry organizations, such as the self-funded secretariat Kwinana Industrial Council (KIC) and the voluntary Gladstone Area Industry Network (GAIN) committee for the Gladstone Group in Australia (Corder 2008; Van Beers 2008). Comparing the two development models, we see that the role of government in a latecomer country such as China is important in enabling eco-industrial initiatives to take off at this early stage of development. Latecomers suffer well-known disadvantages of having to access established markets and technologies in the face of fierce competition, but, as pointed out by Gerschenkron (1962), they also derive advantages from initial low costs, from the capacity to draw on the technologies accumulated around the world, and from the ability to lay down fresh industrial pathways without having to replace legacy systems. They can use state agencies to drive their catch-up efforts, as seen repeatedly in the East Asian context (Lee and Mathews 2010). A latecomer perspective thus helps to explain why China could be moving ahead so rapidly with such comprehensive eco-industrial initiatives, as compared with the slower pace of developments in the more industrially advanced countries.

Having put these eco-industrial initiatives, taken in China and elsewhere, on a common graphical footing, we have probed them for their underlying drivers and characteristics and the evolutionary patterns that can be identified. We agree with Andersen (2007) that the idea of the circular economy is still largely confined to consideration of physical flows, and the economic drivers (and inhibitors) of eco-industrial initiatives have yet to receive sufficient attention. We now consider this aspect of the question with particular reference to China.

Drivers of Eco-industrial Initiatives in China: A Top-Down Approach and a Bottom-Up Approach

To facilitate the evolution of eco-industrial initiatives, countries seem to need both a top-down approach and a bottom-up approach. The former is ensured by institutional arrangements, such as regulatory requirements set in place by the Circular Economy Promotion Law and by the Circular Economy Pilot Demonstrations program and the Eco-industrial Park program established by various government agencies.

Yet a bottom-up approach is arguably more important, as suggested by Desrochers (2002b, 2002a, 2008) and others. In a brilliant series of articles, Desrochers has demonstrated beyond doubt that the idea of "industrial ecology" is as old as industrialism itself and probably a lot older, if we count in the closed-cycle practices of Asian village life in medieval times. Desrochers demonstrates with abundant examples that closing the loop was viewed as a good business opportunity in every facet of industrial activity, and he opens up a new field of inquiry by asking why such activities have become so "foreign" to modern industry, in which the linear model of "raw materials in" at one end and "wastes out" at the other end is totally dominant. In contrast to the Porter hypothesis proposed by Porter and Van der Linde (1995) and other proponents who hold that properly designed and enforced regulations can trigger innovative responses by firms, resulting in both more environment-friendly practices and more profits, Desrochers argues that market-driven actions to mitigate environmental harm, in particular the development of closed loops among firms that use one member's wastes as another's input, would be supported by enhanced private property rights (making due allowance for the critique mounted by Boons [2008] to the effect that modern eco-linkages can just as well be stimulated by regulatory initiatives).

We expect a prevailing bottom-up approach that sees more and more individual players taking eco-industrial initiatives and embracing the idea of circular economy, once those ideas make financial sense for them with changing market dynamics, triggered by factors such as higher prices of energy and resources and deregulation of market entry. But we insist that these initiatives be shaped by regulatory frameworks. China currently provides a rich source of these kinds of eco-industrial initiatives, both those mandated by state agencies and those created through private initiatives between firms.

For example, in China we see both enterprise-level and cluster-level eco-industrial initiatives being pursued, as in the cases of Guigang, Pingdingshan, Lubei, and many other, similar examples, as well as initiatives at the level of eco-industrial parks (e.g., Suzhou and Tianjin), where the hand of local and state government is clearly visible, driving initiatives that are shaped by the national Circular Economy Law.

Indeed, a major feature of the Chinese reforms since the late 1970s is their success in adopting the bottom-up approach instead of the big-bang reform that was seen in Eastern European countries (Chen et al. 1992; McMillan and Naughton 1992). Thus, in one Chinese industry after another, from textiles to steel to automotive and now electronics, we see a powerful combination of state-level administrative and institutional frameworks guiding investment into new channels combined with strong entrepreneurial initiative—such as in the cases of Chery and BYD in the automotive industry and now in electric vehicles or the case of Haier in the white goods sector. Massive entry by nonstate companies into new industries resulting from the reform has brought about a Schumpeterian (i.e., innovation-based) type of competition, which has fundamentally contributed to the prosperity of the Chinese economy (Mathews 2009). We believe that a similar approach is likely to emerge for the establishment of the circular economy as well, which will see individual, profit-driven firms taking greater responsibility and a higher level of initiative in the process.

Inhibitors of the Development of Eco-industrial Initiatives Toward the Circular Economy

China needs to overcome technological, financial, and institutional barriers to turn the current eco-industrial initiatives into a circular economy operating at a larger scale. Technological development has made many industrial closed-loop connections technologically feasible. For example, Nemerow (1995) discussed ten possible environmentally balanced industrial complexes involving 16 different industries and described how those complexes of plants could become "mini-foodwebs" with technical process compatibility. Financial barriers, such as large up-front capital investment required to support eco-industrial initiatives, call for financial innovations. Some of the financial instruments that potentially channel private and public funds into sustainable development have already been intensively discussed in the literature (UNFCC 2007; UNEP and SEFI 2008, 2009; Mathews et al. 2010), whereas the Chinese willingness to commit large investments in eco-friendly projects has been proven during the recent financial crisis.

Institutional barriers include those created by existing laws, both in advanced economies and in emerging economies. For example, in some countries a potential obstacle to utilization of by-products is location of companies in export zones, as regulations do not allow these companies to supply any local companies outside of the zone (Lowe 2001). In countries where environmental regulations are most strict and comprehensive, notably the United States, Germany, and Japan, some aspects of the recycling laws may actively discourage interfirm exchange of wastes, which is the essence of the eco-industrial initiative. Gertler (1995) and Desrochers (2002a, 2002b) have argued that environmental laws, particularly laws on toxic wastes and their control, have acted to inhibit firms' search for industrial waste reutilization. Indeed, Desrochers (2002a) contends that one of the factors involved in the "take-off" of industrial symbiosis at Kalundborg was Danish flexibility over the treatment of wastes; the country preferred to see wastes utilized by a partner firm rather than "controlled" through disposal. A similar argument is mounted by Schwarz and Steininger (1997) in relation to their discussion of industrial recycling in Austria. Of course, the same argument applies with even greater force to the Chinese case, where regulatory controls are still quite lax and opportunities for market-led "closing of the loop" are numerous. This might help to account for the difficulties encountered in getting regional eco-initiatives off the ground in the United States and in Germany (see, e.g., Sterr and Ott's [2004] discussion of the Rhine-Neckar region in Germany), compared with the progress made in China. There are lessons to be drawn from these examples that China, as a latecomer, will be able to act on when developing its own eco-industrial initiatives, and further study will no doubt reveal cases where flexibility has facilitated local initiative.

Criteria for Success of Eco-industrial Initiatives

In the interest of taking the study of eco-industrial initiatives further and placing those initiatives within an economic and evolutionary setting, we pose two criteria in examining the success of each such initiative and its evaluation: (1) It must improve the eco-efficiency of the group of firms as a whole while (2) improving the profit position of at least one firm without damaging the profit position of the others. The first criterion of eco-efficiency has been intensively discussed in the literature (e.g., Ehrenfeld 2005; Huppes and Ishikawa 2005), and a number of measurements for eco-efficiency have been developed and applied in previous studies, such as a tangible reduction in material throughput; in energy released; in carbon dioxide released; or in some biological measure, such as basic oxygen demand (BOD) of watercourses (Korhonen and Snäkin 2005).[20] As explained by Ehrenfeld (2005, 6), eco-efficiency is "fundamentally a ratio of some measure of economic value added to some measure of environmental impact." As such, the concept is able to discriminate between high-cost and low-cost environmental initiatives. But there can be no assumption that such eco-initiatives will improve the profit position of firms implementing them—unless they target such dynamic profit improvement as a strategic goal (Ekins 2005). The Chinese cases in particular reveal that there also needs to be a business dimension to such initiatives—such as a requirement for the eco-initiative to improve at least one firm's profit position without damaging that of the others. That is why we pose the second criterion—as a business driver of eco-industrial initiatives. Such an approach has an analogue with the definition of "Pareto efficiency" in mainstream economics, which states that an allocation of goods is subject to a "Pareto improvement" if a new allocation makes at least one person better off without making anyone else worse off. Hence, we suggest a notion of "Pareto eco-efficiency" improvement for a group of firms, whereby the eco-efficiency of the group as a whole is improved when the profit of at least one of the firms is improved (in a dynamic sense) without sacrifice to the profit position of the other firms.

Checking the leading Chinese initiatives as described in this article against those twin criteria, we have demonstrated impressive evidence that, up to the present, they seem to have made Pareto improvements in an eco-industrial sense, leading to the formation of an eco-industrial area or region. In this setting, we are interested in whether the group as a whole can evolve, through a series of eco-industrial initiatives, to the point where the firms in the group can reach a (temporary) "steady state," in the sense that no further eco-improvements are feasible, given the technology employed. In evolutionary theory, this is termed an "evolutionary steady state" and is the equivalent of equilibrium in real, evolutionary terms.

The analytical goal of this kind of approach is to prove an analogue of the central theorem of neoclassical economics, which states that under certain assumptions (convexity, etc.) the existence and uniqueness of a competitive equilibrium may be demonstrated and that it is Pareto efficient. This is a purely comparative static result, and the "equilibrium" obtained is a purely ideal phenomenon that has never been demonstrated in any real economy. By contrast, in the eco-industrial setting, we are interested in real activity sets that link firms together through their resource and energy flows and in real developmental changes to the configuration of activities encompassing "eco-industrial initiatives" that coevolve over time. We are interested in securing theorems that describe the development of an evolutionary stable state achieved by the application of evolutionary stable strategies (ESSs) in such a setting, which can be empirically demonstrated in terms of real connections between firms. An analogue of the central theorem in economics would be a theorem (or theorems) demonstrating the existence of an evolutionary stable state among a set of firms generated through the establishment of dynamic eco-linkages with each other, where the stable state is characterized as being Pareto eco-efficient. We pose this as a challenge for the field.

Such an approach would also provide a framework that would underpin the empirically verified advances both in China and elsewhere as industrial ecological initiatives enter the mainstream. It would be a way of advancing our understanding of eco-industrial initiatives in a form that is susceptible to modeling in an agent-based simulation system, where the agents are the firms interacting in terms of eco-industrial initiatives and where the evolutionary stable state could be determined experimentally.[21] Such agent-based simulations could also shed light on the fundamental issue, which is what drives the formation of these industrial symbioses at the micro-level or firm-level—or, as in China's case, what drives circularity. The interest of such agent-based simulations would lie in demonstrating the macro consequences (or emergent phenomena—in this case, closure of industrial loops) of multiple micro decisions, taken within different legal-institutional settings, which could capture the flavor of China's Circular Economy Promotion Law.

In this article, we have offered examples of the kind of economic analysis needed where closed-loop economic interfirm relations are seen as the norm, rather than the exception. Linear economic analysis remains the overwhelming (and unthinking) preference in formal economic modeling—driven by an assumption that economic activities can be thought of as "single production" activities rather than as "joint activities," which is actually the case in reality—as argued convincingly by Kurz (2006). We look forward to a renaissance in economic thought emanating from China that parallels the rise of eco-industrial initiatives on a large scale and that takes the circular economy as its inspiration and guide. Such a program calls for "root and branch" reform of economic analysis itself, which would dispense with the linear flow model and replace it with a circular flow model, bringing China, to use Mol's (2006, 29) phrase, to the "frontiers of ecological modernization."

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Notes

1. The literature on industrial ecology utilizes several terms to indicate the essentially "ecological" nature of industrial linkages that tend to close industrial loops—such as industrial symbiosis, industrial ecosystem, eco-industrial development, and eco-industrial park (see, e.g., Gibbs et al. 2005; Chertow 2007). We choose to use the term "eco-industrial initiative" because this seems to capture the flavor of the various approaches and coincides with our introduction of the concept of Pareto eco-efficiency, to be discussed later in the article.
2. The law is available at www.gov.cn/flfg/2008-08/29/content_1084355.htm (Chinese version) and www.fdi.gov.cn/pub/FDI_EN/Laws/GeneralLawsandRegulations/BasicLaws/P020080919377641716849.pdf (English version). The law and concept of "circular economy" continue to frame policy initiatives, as outlined by Chinese Premier Wen Jiabao in a report to China's annual parliamentary session in March 2010; he referred in particular to recycling industrial waste, using by-product heat and pressure to generate electricity and transform household solid waste into resources (see "China to Build Industrial System of Low-Carbon Emissions" in *China Daily*, available at www.chinadaily.com.cn/bizchina/2010-03/05/content_9542319.htm).
3. Graphs showing historical trends in China's energy intensity and resource efficiency are provided in the Supporting Information on the Web.
4. See www.xinhuanet.com/english/lh2006/.
5. See "Resource Output Efficiency to Be an Important Index of China's 12th Five Year Plan," *People's Daily*, 1 Feb 2010, available at:

http://english.peopledaily.com.cn/90001/90778/90862/6884575.html.

6. The full list is available at www.sdpc.gov.cn/hjbh/fzxhjj/t20051031_47606.htm (in Chinese).
7. The full list is available at www.sdpc.gov.cn/hjbh/hjjsjyxsh/W020071217410224312567.doc (in Chinese).
8. The full list is available at http://kjs.mep.gov.cn/stgysfyq/m/200807/t20080718_125900.htm (in Chinese).
9. One kiloton (kt) = 10^3 tonnes (t) = 10^3 megagrams (Mg, SI) $\approx 1.102 \times 10^3$ short tons.
10. Sources for the Guigang Group include the work of Fang and colleagues (2007), Lowe (2001), Zhu and Côté (2004), and Zhu and colleagues (2007).
11. Sources for the Pingdingshan Coal Mining Group (Pingmei) include the work of Long and Zhang (2009) and the company's Web site: www.pmjt.com.cn (in Chinese).
12. Sources for the Lubei Group include the work of Feng (2003) and Fang and colleagues (2007) and Lubei's Web site: www.lubei.com.cn.
13. The description of SIP is based on Zhang et al. (2009) and MEP (2009) and SIP's website.
14. See the official Web page of the Suzhou Industrial Park at www.sipac.gov.cn/english/zhuanti/jg60n/gjlnbtsj/.
15. Sources for the TEDA include the work of Shi and colleagues (2010) and, in particular on water resources, the work of Geng and Yi (2006).
16. Sources include the work of Ehrenfeld and Gertler (1997) and Jacobsen (2006).
17. Sources include the work of Van Beers and colleagues (2007) and Van Beers (2008).
18. The reduction of carbon dioxide emissions at a cement plant in Kawasaki through industrial symbiosis initiatives is also the subject of a recent study by Hashimoto and colleagues (2010).
19. See the article from the Suzhou Government Environmental Protection Bureau at www.szhbj.gov.cn/hbj/showinfo/showinfo.aspx?infoid=b8ed1843-f981-4996-850c-e7c2b4bccfae&siteid=1&categoryNum=009002 (in Chinese).
20. See, for example, the recent work by Chertow and Lombardi (2005) as well as more general eco-industrial measures, such as those discussed by Zhang and colleagues (2008) and Van Berkel (2009).
21. For some of the recent studies utilizing agent-based simulation in an eco-industrial context, see the work of Beck and colleagues (2008), Becka (2008), and Karlsson and Wolf (2008).

References

Andersen, M. S. 2007. An introductory note on the environmental economics of the circular economy. *Sustainability Science* 2: 133–140.

Beck, J., R. Kempener, B. Cohen, and J. Petrie. 2008. A complex systems approach to planning, optimization and decision making for energy networks. *Energy Policy* 36(8): 2795–2805.

Becka, J. 2008. A holistic approach to sustainability analysis of industrial networks. PhD thesis, University of Sydney, Sydney, Australia.

Boons, F. 2008. History's lessons:. A critical assessment of the Desrochers papers. *Journal of Industrial Ecology* 12(2): 148–158.

Chen, K., G. H. Jefferson, and I. Singh. 1992. Lessons from China's economic reform. *Journal of Comparative Economics* 16: 201–225.

Chertow, M.R. 2007. "Uncovering" industrial symbiosis. *Journal of Industrial Ecology* 11: 11–30.

Chertow, M. R. and D. R. Lombardi. 2005. Quantifying economic and environmental benefits of co-located firms. *Environmental Science & Technology* 39(17): 6535–6541.

Corder, G. 2008. *Developing local synergies in the Gladstone Industrial Area: Final project report*. Perth, Australia: Centre for Sustainable Resource Processing.

Dai, T. 2010. Two quantitative indices for the planning and evaluation of eco-industrial parks. *Resources, Conservation and Recycling* 54(7): 442–448.

Desrochers, P. 2002a. Cities and industrial symbiosis: Some historical perspectives and policy implications. *Journal of Industrial Ecology* 5(4): 29–44.

Desrochers, P. 2002b. Industrial ecology and the rediscovery of inter-firm recycling linkages: Historical evidence and policy implications. *Industrial and Corporate Change* 11(5): 1031–1057.

Desrochers, P. 2008. Did the invisible hand need a regulatory glove to develop a green thumb? Some historical perspective on market incentives, win-win innovations and the Porter hypothesis. *Environmental Resource Economics* 41: 519–539.

Ehrenfeld, J. R. 2005. Eco-efficiency: Philosophy, theory and tools. *Journal of Industrial Ecology* 9(4): 6–8.

Ehrenfeld, J. and N. Gertler. 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology* 1(1): 67–79.

Ekins, P. 2005. Eco-efficiency: Motives, drivers, and economic implications. *Journal of Industrial Ecology* 9(4): 12–14.

Fang, Y., R. P. Cote, and R. Qin. 2007. Industrial sustainability in China: Practice and prospects for eco-industrial development. *Journal of Environment Management* 83: 315–328.

Feng, J. T. 2003. Development and practice of eco-industrial linkages in Lubei Group. *China Population, Resources and Environment* 1: 110–112.

Geng, Y. and B. Doberstein. 2008. Developing the circular economy in China: Challenges and opportunities for achieving "leapfrog development." *International Journal of Sustainable Development & World Ecology* 15: 231–239.

Geng, Y. and J. Yi. 2006. Integrated water resource management at the industrial park level: A case of the Tianjin Economic Development Area. *International Journal of Sustainable Development & World Ecology* 13(1): 1–15.

Geng, Y., Q. Zhu, B. Doberstein, and T. Fujita. 2009. Implementing China's circular economy concept at the regional level: A review of progress in Dalian, China. *Waste Management* 29: 996–1002.

Gerschenkron, A. 1962. *Economic backwardness in historical perspective*. Cambridge, MA, USA: Belknap Press of Harvard University Press.

Gertler, N. 1995. Industrial ecosystems: Developing sustainable industrial structures. Master's thesis, MIT, Boston. http://dspace.mit.edu/bitstream/handle/1721.1/11556/33822653.pdf?sequence=1. Accessed 10 March 2011.

Gibbs, D., P. Deuz, and A. Procter, 2005. Industrial ecology and eco-industrial development. *Regional Studies* 39(2): 171–183.

Hardy, C. and T. E. Graedel. 2002. Industrial ecosystems as food webs. *Journal of Industrial Ecology* 6(1): 29–38.

Hashimoto, S., T. Fujita, Y. Geng, and E. Nagasawa. 2010. Realizing CO_2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. *Resources, Conservation and Recycling* 54(10): 704 – 710.

Huppes, G. and M. Ishikawa. 2005. A framework for quantified eco-efficiency analysis. *Journal of Industrial Ecology* 9(4): 25–41.

Jacobsen, N. B. 2006. Industrial symbiosis in Kalundborg, Denmark. *Journal of Industrial Ecology* 10(1–2): 239–255.

Jiang, K. 2009. Energy efficiency improvement in China: A significant progress for the 11th Five Year Plan. *Energy Efficiency* 2: 401–409.

Karlsson, M. and A. Wolf. 2008. Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry. *Journal of Cleaner Production* 16: 1536–1544.

Korhonen, J. and J. P. Snäkin. 2005. Analysing the evolution of industrial ecosystems: Concepts and application. *Ecological Economics* 52: 169–186.

Kurz, H. D. 2006. Goods and bads: Sundry observations on joint production, waste disposal, and renewable and exhaustible resources. *Progress in Industrial Ecology* 3(4): 280–301.

Lee, K. and J. A. Mathews. 2010. From Washington Consensus to BeST Consensus for world development. *Asia-Pacific Economic Literature* 24(1): 86—103.

Long, R. and X. Zhang. 2009. Negative entropy mechanism of the circular economy development countermeasures in mining area. *Procedia Earth and Planetary Science* 1: 1678–1685.

Lowe, E. A. 1997. Creating by-product resource exchanges: Strategies for eco-industrial parks. *Journal of Cleaner Production* 5(1/2): 57–65.

Lowe, E. 2001. The eco-industrial park handbook for Asian developing countries. www.indigodev.com. Mandaluyong City, Philippines: Asian Development Bank. Accessed 10 March 2011.

Mathews, J. A. 2009. China, India and Brazil: Tiger technologies, dragon multinationals and the building of national systems of economic learning. *Asian Business & Management* 8: 5–32.

Mathews, J.A., S. Kidney, K. Mallon, and M. Hughes. 2010. Mobilizing private finance to drive an energy industrial revolution. *Energy Policy* 38: 3263–3265.

McMillan, J. and B. Naughton. 1992. How to reform a planned economy: Lessons from China. *Oxford Review of Economic Policy* 8(1): 130–143.

MEP (Ministry of Environment Protection). 2009. *Annual progress report for national eco-industrial demonstration parks, 2008*. Beijing, China: MEP.

Mol, A. P. J. 2006. Environment and modernity in transitional China: Frontiers of ecological modernization. *Development and Change* 37(1):29–56.

Moriguchi, Y. 2007. Material flow indicators to measure progress toward a sound material-cycle society. *Journal of Material Cycles and Waste Management* 9: 112–120.

Nemerow, N. L. 1995. *Zero pollution for industry: Waste minimization through industrial complexes*. New York: Wiley.

Park, H.-S., E. R. Rene, S. M. Choi, and A. S. F. Chiu. 2008. Strategies for sustainable development of industrial park in Ulsan, South Korea: From spontaneous evolution to systematic expansion of industrial symbiosis. *Journal of Environmental Management* 87: 1–13.

Porter, M. E. and C. van der Linde. 1995. Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives* 9(4): 97–118.

Schwarz, E. J. and K. W. Steininger. 1997. Implementing nature's lesson: The industrial recycling network enhancing regional development. *Journal of Cleaner Production* 5: 47–56.

Shi, H., M. Chertow, and Y. Song. 2010. Developing country experience with eco-industrial parks: A case study of the Tianjin Economic-Technological Development Area in China. *Journal of Cleaner Production* 18: 191–199.

Sterr, T. and T. Ott. 2004. The industrial region as a promising unit for eco-industrial development: Reflections, practical experience and establishment of innovative instruments to support industrial ecology. *Journal of Cleaner Production* 12: 947–965.

Tan, R. and L. Bao. 2006. Constructing eco-industrial park: The road for Tianjin economic-technological development area. *Journal of US-China Public Administration* 3(2): 11–24.

Triebswetter, U. and D. Hitchens. 2005. The impact of environmental regulation on competitiveness in the German manufacturing industry: A comparison with other countries of the European Union. *Journal of Cleaner Production* 13(7): 733–745.

UNEP (United Nations Environment Programme) and SEFI (Sustainable Energy Finance Initiative). 2008. Public finance mechanisms to mobilise investment in climate change mitigation. www.sefalliance.org/fileadmin/media/sefalliance/docs/Resources/UNEP_Public_Finance_Report.pdf. Accessed 10 March 2011.

UNEP and SEFI. 2009. Private financing of renewable energy. http://sefi.unep.org/fileadmin/media/sefi/docs/publications/Finance_guide_FINAL.pdf. Accessed 10 March 2011.

UNFCC (United Nations Framework on Climate Change). 2007. Investment and financial flows to tackle climate change. http://unfccc.int/files/cooperation_and_support/financial_mechanism/application/pdf/background_paper.pdf. Accessed 10 March 2011.

Van Beers, D. 2008. *Capturing regional synergies in the Kwinana Industrial Area: 2008 status report*. Perth, Australia: Centre of Excellence in Cleaner Production, CurtinUniversity of Technology and Kwinana Industries Council (KIC).

Van Beers, D., G. Corder, A. Bossilkov, and R. van Berkel. 2007. Industrial symbiosis in the Australian minerals industry: The cases of Kwinana and Gladstone. *Journal of Industrial Ecology* 11(1): 55–72.

Van Beers, D., A. Bossilkov, and C. Lund. 2009. Development of large-scale reuses of inorganic by-products in Australia: The case study of Kwinana, Western Australia. *Conservation and Recycling* 53: 365–378.

Van Berkel, R. 2009. Comparability of industrial symbiosis. *Journal of Industrial Ecology* 13(4): 483–486.

Van Berkel, R. 2010. Quantifying sustainability benefits of industrial symbioses. *Journal of Industrial Ecology* 14(3): 371–373.

Van Berkel, R., T. Fujita, S. Hashimoto, and M. Fujii. 2009. Quantitative assessment of urban and industrial symbiosis in Kawasaki, Japan. *Environmental Science and Technology* 43(5): 1271–1281.

Xu, M., X.-P. Jia, L. Shi, and T.-Z. Zhang. 2008. Societal metabolism in Northeast China: Case study of Liaoning Province. *Resources, Conservation and Recycling* 52: 1082–1086.

Yu, C.-X., Wu, C.-Y., & Wang, W.-Z. 2007. 基于循环经济的中国鲁北生态工业模式选择 [Pattern selection of LuBei eco-industry of China based on circular economy.] *China Soft Science* 7: 135–140.

Yuan, Z. W. and L. Shi. 2009. Improving enterprise competitive advantage with industrial symbiosis: Case study of a smeltery in China. *Journal of Cleaner Production* 17: 1295–1302.

Yuan, Z. W., B. Ji, and M. Yuichi. 2006. The circular economy: A new development strategy in China. *Journal of Industrial Ecology* 10(1/2): 4–8.

Zhang, B., J. Bi, Z. Y. Fan, Z. W. Yuan, and J. J. Ge. 2008. Eco-efficiency analysis of industrial system in China: A data envelopment analysis approach. *Ecological Economics* 68(1/2): 306–316.

Zhang, H., K. Hara, H. Yabar, Y. Yamaguchi, M. Uwasu, and T. Morioka. 2009. Comparative analysis of socio-economic and environmental performances for Chinese EIPs: Case studies in Baotou, Suzhou, and Shanghai. *Sustainability Science* 4: 263–279.

Zhang, L., Z. W. Yuan, J. Bi, B. Zhang, and B. B. Liu. 2010. Eco-industrial parks: National pilot practices in China. *Journal of Cleaner Production* 18: 504–509.

Zhu, D. 1998.可持续发展呼唤循环经济 [Sustainable development appeals for cycle economy]. *Science and Technology Review* 9: 39–43.

Zhu, D. 2008. Background, pattern and policy of China for developing circular economy. *Chinese Journal of Population, Resources and Environment* 6(4): 1–6.

Zhu, Q. and R. P. Côté. 2004. Integrating green supply chain management into an embryonic eco-industrial development: a case study of the

Guitang Group. *Journal of Cleaner Production* 12: 1025–1035.

Zhu, Q., E. A. Lowe, Y.-A. Wei, and D. Barnes. 2007. Industrial symbiosis in China: A case study of the Guitang Group. *Journal of Industrial Ecology* 11(1): 31–42.

Zhu, Q., J. Sarkis, J. J. Cordeiro, and K.-H. Lai. 2008. Firm-level correlates of emergent green supply chain management practices in the Chinese context. *Omega* 36: 577–591.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: This supporting information presents graphs showing historical trends in China's energy intensity and resource efficiency.

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