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From an eco-industrial park towards an eco-city: a case study in Suzhou, China

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ABSTRACT

As eco-industrial park policies have been in place for years, many mature eco-industrial parks tend to acquire more than just industrial functions and become new urban districts. We investigated this development and conducted empirical research in Suzhou Industrial Park, to obtain insight in how a mature eco-industrial park influences if not leverages the development of an eco-city. To this end we inventoried and analyzed policy instruments and environmental infrastructures and deduced how in Suzhou Industrial Park these led to improved energy efficiency, reduced pollution and contributed to its eco-city development. Eco-efficiency and decoupling theory were used to evaluate the environmental performance relative to economic growth in Suzhou Industrial Park. Our results showed that relative decoupling of environmental performance and economic growth was realized for most eco-efficiency indicators, while non-decoupling and absolute decoupling occurred incidentally. This was caused by the deployment of strict regulatory and economic instruments (such as stricter environmental entry rules and requirements on sulfur dioxide emissions). Moreover, the increasing share of tertiary industry, urban service and residential activities also lead to this result. Thus, the experience in Suzhou Industrial Park reveals that an eco-industrial park may evolve into an eco-city development when it leads to an improvement of its environmental performance and a growth of tertiary industry, develops synergies between its infrastructures for industrial and residential areas and enhances the economic prosperity derived from its industrial sites.

1. Introduction

An eco-industrial park (EIP) aims to facilitate companies to exchange resource flows in order to reduce the environmental impact caused by industrial activities in an industrial cluster (Chertow and Ehrenfeld, 2012). In China, the national demonstration EIP program has been in force for over a decade. The program was launched in 2001 as an approach to remedy the environmental degeneration that resulted from the rapid industrialization in the national industrial zones from the 1980s onwards. So far, eco-transformation of the first-generation industrial parks has led to what could be labeled EIPs in terms of improving energy efficiency and pollution prevention (Geng and Zhao, 2009; Tian et al., 2013; Yu et al., 2014b; Zhang et al., 2010).

Then what would constitute the next step for eco-transformation of Chinese EIPs? As scholars have pointed out, Chinese EIPs are not just industrial areas, but they have also become industrialized towns or urban districts (Liu et al., 2012; Shi et al., 2012; Tian et al., 2013). Unlike the US model, an industrial park in China is often a complex that integrates industrial production and residential functions. When the first batch of national industrial zones was established in the 1980s, many of these development zones were located far away from their mother cities, which allowed them to be developed across a large acreage of land. Some residential buildings were built as auxiliary facilities for accommodating a large number of skilled workers. As more companies started their business in these industrial parks, more

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employees with their families settled down. This required the provision of medical care, education and commercial centers etcetera (Tian et al., 2012). Furthermore, in these industrial parks, the secondary and tertiary sectors[1] began to dominate the economy, which is a typical feature of urban economics and development (Arnott and McMillen, 2006). Another key indicator of initial urbanization is the share of tertiary industry. Tian et al. (2013) investigated 17 national demonstration EIPs in China and found that the proportion of tertiary industry exhibited notable growth, in some EIPs amounting to as much as 60%: 40% (secondary: tertiary). Thus, these industrial parks have shown clear signs of urbanization. The next logical step for eco-transformation of Chinese EIPs then would be to integrate urban and industrial functions to minimize energy consumption and pollution. As a consequence, the related planning, measures and assessment for environmental management need to simultaneously consider the industrial sites and the residential areas.

With respect to the environmental performance of a city, the concepts of eco-city and low-carbon city have been promoted in China to deal with the environmental consequences and energy consumption caused by rapid urbanization (de Jong et al., 2013a; Dong et al., 2013; Joss and Molella, 2013). An eco-city has been defined as a city that can minimize the demands on resources (like energy and water) and reduce waste (Roseland, 1997), in order to provide healthy living conditions. Several principles need to be considered to realize the goals of an eco-city, for instance, resource recycling and conservation, measures in industries to reduce pollution, accessible transportation, affordable and decent housing (Roseland, 1997). The concept of a low-carbon city has substantial overlap with that of an eco-city, as it focuses on the decoupling between urban economic growth and CO_2 emissions (Chen and Zhu, 2013). The principles of environment, land use, economy and social welfare in the urban planning for eco-cities need to be interpreted as a set of measurable indicators which can guide policy making and monitor policy implementation (Devuyst et al., 2013; Li et al., 2009). Besides, due to the complexity of cities, the realization of an eco-city requires coordination among all actors (e.g., local authorities, industries and citizens) (Button, 2002). Thus, it is better to involve the related departments to make joint planning and design indicators. In China, for the implementation of an eco-city program one often selects a district as pilot project. Examples are Sino-Singapore Tianjin Eco-city[2] in Binhai New district and Sino-Finnish Eco-valley[3] in Mentougou, Beijing. The policies regarding environmental management and industrial structure are first introduced in a pilot district where progress can monitored and demonstrated for a wider promotion of nation-wide urban eco-transformation (de Jong et al., 2013b).

In the literature, a few studies have appeared to date regarding the environmental aspects involved in a transition from industrial sites to eco-cities. Urban symbiosis has been elaborated to analyze Japanese eco-towns that use waste from cities as alternative raw materials or energy sources for industrial operations (Geng et al., 2010; Van Berkel et al., 2009). Dong et al. (2013) evaluated how industrial symbiosis in the industrial sites of Liuzhou City in China can facilitate low-carbon city construction. Renewable energy and industrial symbiosis were applied to the forestry industry to integrate the eco-development of two Swedish cities, Linköping and Norrköping (Baas, 2010). The progress of the circular economy at the regional level was reviewed in Dalian City by Geng et al. (2009), who analyzed the policy actions at the city level to encourage industries to reduce energy consumption and recycle waste. Furthermore, urban metabolism has been employed to analyze the flows of energy and waste generated in the technical and socio-economic processes that occur in cities (Kennedy et al., 2007; Simões and Marques, 2012; Wolman, 1965). The literature thus provides valuable knowledge about how to utilize resources in industrial sites to better serve their mother cities. It must be noted, however, that in the literature an industrial park is positioned as a city-component that is developed at a time when the city already has been established. As we have outlined above, in China the order of development is reversed: many industrial parks sparked the growth of what today have become small towns or urban districts. Thanks to preferential policies, effective administration and infrastructure development, these industrial parks develop much faster than those city-components. So instead of a city accommodating an industrial park, it is the industrial park that drives the development towards a flourishing new urban district. Furthermore, as industrial parks increasingly embark on eco-transformation, their influence on the eco-development of their mother cities has been expanding. Thus, when one seeks to implement environmental principles to transform industrial park and city in concert, how can the management of an industrial park incorporate, steer or even leverage the accompanying urbanization? The research to date does not provide answers to this question.

This study therefore aims to provide empirical foundations for understanding what conditions an eco-industrial park may provide for eco-city development. We intend to contribute to the literature of eco-industrial parks that reveal urban features. The structure of this article is as follows. Section 2 introduces the research methods and data collection. Eco-efficiency and decoupling are employed to unravel the relationships between environmental pressure and economic growth. Subsequently in Section 3, we present our empirical research in Suzhou Industrial Park (SIP) and we discuss the insights obtained from the case study. Apart from evaluating SIP's environmental performance through empirical data, we make an attempt to unravel the underlying reasons for our results. Finally, conclusions are drawn regarding the conditions that an EIP may provide to evolve into an eco-city. We anticipate the insights obtained to be useful for eco-transformation of industrialized areas accompanying urbanization.

2. Research methods and data collection

Established in 1994, Suzhou Industrial Park (SIP) was one of the earliest national demonstration EIPs. Currently, SIP has been making efforts to become a “new town” in Suzhou City (Shi et al., 2012; Wang et al., 2013b; Wei et al., 2009). SIP thus presents an interesting case to study the eco-transformation of an industrial park towards an eco-city.

After introducing the general context of SIP, we observe the institutional activities to elucidate what policy instruments SIP has employed and how these have been used to reduce energy consumption and avoid harmful environmental impact. Moreover, synergies among environmental infrastructures are investigated to reveal how the water and energy infrastructures are utilized to connect industrial and residential areas.

To evaluate eco-development in SIP, we would like to integrate environmental performance and economic growth. Several methods can serve to simultaneously consider environment and economy, such as eco-effectiveness and eco-efficiency. Eco-effectiveness points out that waste can be avoided through the redesign of products and the embedded system of industrial material flows

[1] In China, primary industry mainly refers to agriculture, including farming, animal husbandry, forestry and fishery; secondary industry includes mining and quarrying, production and supply of water, electricity, gas, manufacturing, and construction; tertiary industry includes all the other industries not included in the previous ones, mainly involving service sector.

[2] http://www.eco-city.gov.cn/.

[3] http://ecocity.fi/en/projects.

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(Braungart et al., 2007). It emphasizes environment-friendly design and production in companies. Eco-efficiency means "producing more economic value with less resources and less environmental influence" (Huppes and Ishikawa, 2005; Kuosmanen and Kortelainen, 2005). Initially it offered a concept for companies to maintain business profits in an environment-friendly way. Later, eco-efficiency indicators have been used to measure changes in regional and national environmental pressure (Seppäläa et al., 2005; Wang et al., 2011; Yu et al., 2013). Eco-efficiency indicators appear to be useful in environmental reporting because they can link information of environmental impacts to economic information in a comprehensive and consistent manner over periods of time (Van Caneghem et al., 2010). Therefore, we will use a set of eco-efficiency indicators (including energy, water and air) to reflect the regional environmental pressure during SIP's development.

Eco-efficiency is defined as:

$$\text{eco} - \text{efficiency} = \frac{\text{added economic value}}{\text{added environmental influence}} \tag{1}$$

This implies, for example, that the efficiency of energy consumption is the ratio between annual GDP and the amount of energy consumption. However, fast economic growth can lead to an apparent improvement in eco-efficiency, while the environmental impact keeps increasing (Wang et al., 2011). This is a shortcoming of eco-efficiency indicators. To remedy this, we adopt decoupling theory, which allows one to clearly evaluate the relation between environmental influence and economic growth. As the United Nations Environment Programme (UNEP) defines it, *decoupling* means "reducing the amount of resources used to produce economic growth and delinking economic development from environmental deterioration" (UNEP, 2011). *Relative decoupling* indicates that the environmental influence is increasing, but its growth rate is lower than that of economic growth. *Absolute decoupling* means the growth rate of environmental influence is zero or negative as the economic value increases (Wang et al., 2013a; Yu et al., 2013). Moreover, *decoupling indicators* of energy consumption and pollutant emissions can also be calculated, as a relative form of eco-efficiency, to present the extent of decoupling as follows (Lu et al., 2011; Wang et al., 2013a):

$$D = \frac{t}{g} \times (1 + g) \tag{2}$$

where D is the decoupling indicator; g represents the GDP's growth rate; t represents the decreasing rate of resource use per unit of GDP or waste emission per unit of GDP. For instance, the decoupling indicator of energy consumption, D_{energy}, is calculated as:

$$D_{energy} = \frac{t_{energy}}{g} \times (1 + g) \tag{3}$$

where t_{energy} is the decreasing rate of energy consumption per GDP. The same method can also be used to calculate the decoupling indicator of emission, D_{emission}. For instance, the decoupling indicator of wastewater discharge, $D_{\text{wastewater}}$, is calculated as:

$$D_{wastewater} = \frac{t_{wastewater}}{g} \times (1 + g) \tag{4}$$

where $t_{wastewater}$ is the decreasing rate of wastewater discharge per GDP.

Under the condition of a growing GDP, absolute decoupling occurs when $D \geq 1$; relative decoupling occurs when $0 < D < 1$; non-decoupling occurs when $D \leq 0$. The former two are acceptable, while the third one is an alerting situation. In addition, the larger D is, the less environmental influence is generated (Lu et al., 2011).

With these methods, we can evaluate SIP's eco-efficiency as the indicators to reflect the relationship between its economic development and environmental performance during eco-transformation. We have selected the indicators that cover the environmental impact of energy, water and air. The indicators include energy consumption and the emissions of five major pollutants: wastewater, chemical oxygen demand (COD), ammonia nitrogen (AN), sulfur dioxide (SO_2) and particulate matter (PM). This selection of indicators aligns with the requirements stated in the 12th Five Year Plan of Suzhou City and SIP, which pointed out the key pollutants that need to be monitored and controlled (SIP, 2011; Suzhou Municipality, 2012). When selecting the indicators we considered data availability and the continuity of the data set. The data were acquired from SIP's departments: the Administrative Committee (AC), Environmental Protection Bureau (EPB), the Economic, Trade and Development Bureau (ETDB) and the China–Singapore SIP Public Utilities Development Group (CSPU). The data on energy consumption and polluting emissions cover industrial and residential areas. Thus, the results of eco-efficiency calculated by GDP can reveal the environmental performance in the entire SIP region. We analyzed the eco-efficiency results to unravel the factors that may have led to these results for SIP. The definitions and the expressions of the variables of eco-efficiency are presented in the Appendix.

3. Case study

3.1. General context of SIP

Suzhou Industrial Park (SIP) was established in 1994 as a project of government-to-government collaboration between China and Singapore. Located in the eastern part of Suzhou City, SIP occupies a total area of 288 km^2, of which the China–Singapore Core Cooperative Zone (the main industrial site in SIP) covers 80 km^2. The total number of permanent residents had reached over 700,000 in 2012, including registered and non-registered population. Currently, approximately 25% of the land is industrial land, and 30% is residential and commercial land. The remainder is green space and water. The train from SIP takes 20 min to arrive in Shanghai and 1 hour to reach Nanjing. With a convenient transportation network, it is well connected with the nearby transportation hubs.

Benefiting from the collaboration model, SIP adopted knowledge from Singapore regarding urban planning, market economy, social services and management style (Wei et al., 2009). The land use and industrial layout strictly followed the original planning that integrated short-term and long-term goals. Thus, SIP's development avoided the confusion caused by revised planning and demolition. The knowledge from Singapore on planning and management ensured the enforcement of environmental quality since its establishment. SIP's GDP in 2012 reached RMB[4] 173.8 billion, representing 15% of Suzhou City's GDP. The two pillar industries (i.e., electronics and telecommunications, and precision machines) accounted for 47% and 20% of this GDP in 2012, respectively (see Fig. 1). With respect to EIP development, in 2001, SIP obtained the label of ISO14000 National Demonstration Zone. As the national EIP program was launched, SIP was approved as a pilot in 2004 and started to implement EIP planning in accordance with the national EIP development guideline. In 2008, SIP passed the evaluation and obtained the label as one of the first three National Demonstration EIPs (MEP, 2008). Currently, the energy

[4] RMB is the currency of China. 100 RMB is approximately equal to 16 US dollar.

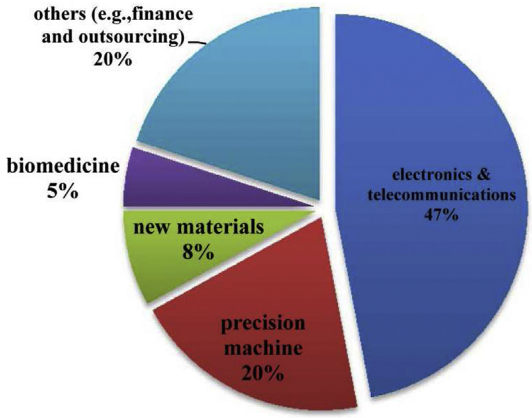

Fig. 1. The proportion of the industries in SIP by 2012.

consumption per GDP is 61% lower than the national level. The discharge amounts of COD and SO_2 are only one-eighteenth and one-fortieth of the national average, respectively (SIP, 2013b).

Signs of urbanization can be revealed by the proportion of tertiary industry and residential population (Arnott and McMillen, 2006). In 1994, the shares of primary, secondary and tertiary industry were 25.9%, 53.5% and 20.6%, respectively. As the development of industrialization and urbanization proceeded, the shares had changed to 0.1%, 62.2% and 37.7% in 2012. Fig. 2 indicates the proportion of the three sectors in the annual GDP and the number of registered inhabitants. It shows that secondary industry has been the pillar sector, but its proportion has been declining. By contrast, the share of tertiary industry has steadily increased. In 2015, the goal of tertiary industry is to increase to 44% of GDP (SIP, 2008). The residential population of SIP achieved a continuous growth and reached 392,000. The growth of tertiary industry and population implies that the demand for social services is rising. Indeed, SIP has incorporated urban functions for commercial and residential areas, which today make it resemble a small city and this gets beyond industrial production only. In 2008, SIP specifically proposed that the industrial park would commit itself to become a new city center of Suzhou City and accommodate comprehensive urban services such as financial and commercial centers, cultural tourism and exhibitions (SIP, 2008).

3.2. Institutional activities

The principles of environmental protection have been considered in planning and policy making since SIP was established. Table 1 structures the policy instruments for environmental issues. The first regulatory action in SIP's history was the Measures on Environmental Protection for Construction Projects in 1995 (SIP, 2001). After that, the regulations on hazardous waste and wastewater were issued in the late 1990s. These measures guided and supervised environmental performance during construction and industrial production in the early stage of SIP. Moreover, when the new companies or projects are recruited, the environmental impact and energy consumption are assessed by SIP's EPB to decide whether the project can be approved. SIP strictly enforces the rule of one-vote veto in accordance with the environmental and energy inspection. This implies that potential companies or projects shall be rejected as long as their environmental performance does not meet the requirements, no matter how much economic profit the project can generate. Without the approved environmental assessment, the business license will not be issued. From 1995 to 2012, around 400 projects were rejected due to the environmental entry rule, involving the investment of 3 billion US dollars. If the project is approved, as Fig. 3 shows, the construction of facilities is required to follow the principles of “three synchronization” [5] for pollution prevention and control. After the environmental inspection of construction, EPB will approve the operation and install real-time systems to monitor the pollutant emissions.

The regulatory instruments in Table 1 show that the requirements have become more stringent for both new and existing projects. Since 2007, the requirements of freshwater consumption and wastewater discharge for new projects have been required to conform to the national EIP standard. Meanwhile, some measures have clearly focused on eliminating the companies or industries that have intensive energy consumption or cause excessive pollution. For the existing companies in SIP, energy audits are mandatory and coal-fired boilers are forbidden, except for the co-generation plant. Moreover, in 2010, the range of mandatory energy audits has been enlarged to all companies the energy consumption of which is larger than 3000 tce/year. These regulations especially target the industries of paper making, electroplating and the production of printed circuit boards.

To reduce water consumption, a water quota pricing system has been used since 2007. A company the freshwater consumption of which exceeds the national EIP standard has to pay a rate that is 50% higher than the regular water rate. As to economic instruments for environmental protection in SIP, mainly funding is used as a reward after examining the performance rather than direct subsidies. A maximum of 10% of the actual cost can be awarded depending on the environmental assessment by SIP's EPB and Financial Bureau. The funding for energy saving can subsidize at most 20% of the investment in equipment or technology. Energy audit fees can be reimbursed for up to 50%. As the details of economic instruments show in Table 1, this funding gives clear directions to support the projects that can contribute to the goals of EIP development regarding pollution prevention and energy efficiency. Every year, the funding for environment and energy can support approximately 60 projects that involve 100 companies.

Apart from regulatory and economic instruments, voluntary approaches have been used in SIP. Since 2005, the labels of circular economy and environmental protection have been granted to the organizations and individuals that made progress on reclaiming water, waste recycling and environmental awareness. The organizations do not only include companies, but also schools and residential neighborhoods, in order to enhance the dissemination of eco-solutions. By the year 2012, around 200 organizations had obtained such labels. As da Cruz et al. (2014) pointed out, the actions for sustainable development (e.g., waste recycling) require industries, local authorities and citizens to coordinate and take responsibilities. Moreover, two non-government business associations are active with respect to environmental issues. SIP's Environment, Health and Safety (EHS) Association has been active since 2005 as an informal networking event organized by SIP's companies. In 2009, EHS Association was registered as a non-profit organization providing training and networking opportunities to follow up actions to accommodate environmental regulations and organize assessments, as well as giving feedback to SIP's EPB. So far, the EHS Association has attracted more than 200 companies from within SIP. Another spontaneous one is the low carbon business association that was initiated in 2010 by 36 companies from the energy sector. Apart from trainings and workshops, this association

[5] “Three synchronization” is the requirement of China's Ministry of Environmental Protection. It means the related environmental protection facilities must be simultaneously designed, constructed and operated together with the whole project.

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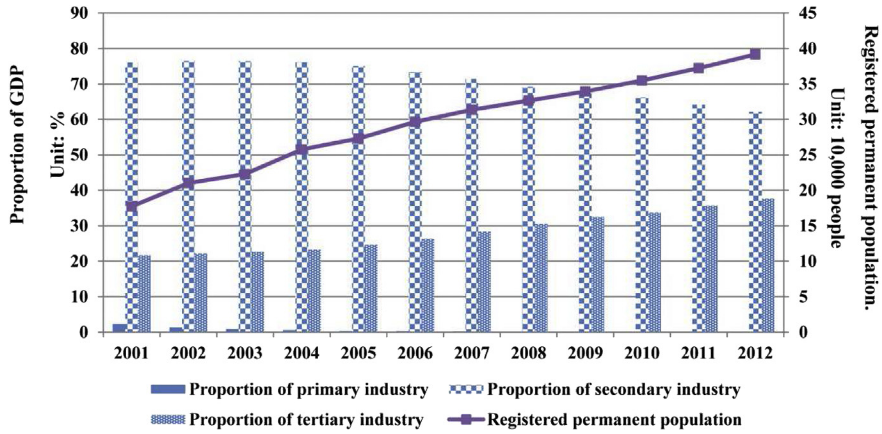

Fig. 2. Proportion of three industrial sectors in GDP and the registered permanent population in SIP. Data source: SIP's ETDB.

also provides consulting services for policies and technologies regarding new energy. In addition, in 2012, the first term of environmental information disclosure was launched by SIP's EPB in the 20 companies to voluntarily publish the information on resource consumption, types and amount of pollutants, waste disposal and treatment equipment.

3.3. Environmental infrastructure

All the public utilities in SIP are operated by CSPU whose business segments include water, sewage, natural gas, steam supply, power generation, environmental technology and energy services. Fig. 4 shows the centralized utilities of water, energy and waste that supply both SIP's industrial and residential areas. Two major groups of synergies are demonstrated in Fig. 4. One is the symbiosis among the plants of wastewater, sludge and cogeneration. The other one is the regional energy cascading of heating, cooling and electricity. The centralized wastewater plants can treat industrial and domestic sewage. The maximum capacity of the wastewater treatment plants is 350,000 tons/day. To reduce fresh water use, reclaimed water systems were launched in the No.1 and No.2 wastewater treatment plants. The two reclaimed water systems have a total capacity of 30,000 tons/day. The reclaimed water is mainly used as cooling water for the Dongwu Cogeneration Plant. However, the larger volume of treated wastewater implies that more sludge will be generated. Usually, the sludge is landfilled or dumped, a practice that is permitted in the absence of regulation on sludge treatment and disposal fees in China. As sludge is known to eventually contaminate groundwater, to avoid unsafe disposal, a sludge drying plant was built in 2011, right next to No. 2 Wastewater Plant and Dongwu Cogeneration Plant. The capacity of 300 tons/day in the first stage can completely treat all the sludge in SIP. As Fig. 4 illustrates, the wet sludge is processed to dried sludge that is mixed as fuel in Dongwu plant to generate electricity, which saves an energy equivalent of 12,000 tce/year. The ash from the incineration of sludge is used for producing construction materials.

Table 1
Policy instruments to promote EIP development in SIP. Sources: (SIP, 2001, 2005, 2007, 2008a, b). Note: tce is tons standard coal equivalent.

Policy instruments	Year	Content
Economic instruments	2007	Water quota pricing system.
	2008	Annual funding for environmental protection (Budget: 50 million RMB/year). Improvement of intensive pollutant companies; Regional ecological restoration; Technologies for pollution prevention and reclaimed water; ISO14001; Cleaner production audit; Monitoring and emergency response.
	2008	Annual funding for energy saving (Budget: 15 million RMB/year). Technology improvement; New products for saving energy; Applying clean or renewable energy (e.g., natural gas, solar energy, ground/water source heat pump); Elimination of the backward production capacity; Energy audit.
	2012	Annual funding for green building. Green building certificate; Applying renewable energy to buildings; Installing monitoring system for energy audit; Label of energy efficiency for buildings; Retrofitting existing buildings.
Regulatory instruments	1995	Measures on Environmental Protection for Construction Projects (on trial).
	1995	One-vote veto rule by environmental and energy inspection.
	1997	Prevention measures on hazardous waste (on trial).
	1997	Measures on supervision and management for wastewater plant on environmental issues.
	1999	Measures on wastewater discharge management.
	2007	Eliminate all coal-fired boilers except for the cogeneration plant.
	2007	Enhance the environmental entry conditions for new projects. • Freshwater consumption per IAV $\leq$9 tons/10^4 RMB; Wastewater discharge per IAV $\leq$8 tons/10^4 RMB; • Stop recruiting electroplating projects and other environmentally risky projects.
	2009	Mandatory energy audit for energy intensive consumers (energy consumption $\geq$ 5 kilo tce/year).
	2010	Stop recruiting chemical projects and eliminate backward chemical companies.
	2010	Mandatory energy audit for energy intensive consumers (energy consumption $\geq$ 3 kilo tce/year).
Voluntary instruments	2005	Label of circular economy demonstration organizations and individuals.
	2009	EHS (Environment, Health and Safety) association.
	2009	Training and workshops for cleaner production audit and energy audit.
	2010	Low carbon business association.
	2012	Voluntary environmental information disclosure.

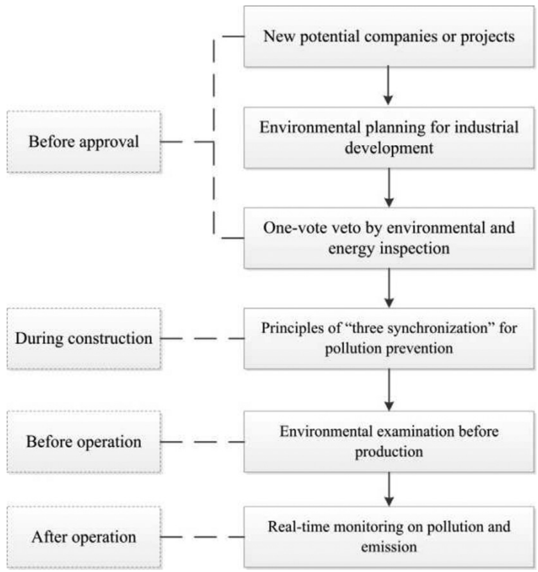

Fig. 3. Environmental inspection from project recruiting to project operation. Source: SIP's EPB.

The production of the construction material is around 10,000 tons/year. During the drying process, 90,000 tons/year of condensate is collected and sent back to the cogeneration plant, which saves water and heating costs amounting to 1 million RMB/year.

The cogeneration plants can supply steam to 90% of the SIP area. The two gas-fired cogeneration plants have a generating capacity of 360 MW and capacity for producing 560 tons/hour steam. Compared with the coal-fired plants, these two gas-fired ones can reduce SO_2 emissions by 1500 tons and ash by 300,000 tons annually. The let-down steam from Dongwu Cogeneration Plant is used to produce chilled water for district cooling. This non-electric air-conditioning project can decrease 1 to 2 degrees of the ambient temperature for the Moon Bay Business District (gross floor area of 1.1 hectare). Every year, the cooling center can save 3390 tce of energy, 8000 tons of CO_2, 70 tons of SO_2 and 70 tons of NO_X. In addition, through replacing the distributed air-conditioners, the district cooling can save 5×10^7 RMB/year in maintenance cost.

3.4. Results of environmental performance in SIP

3.4.1. Energy consumption and energy efficiency

As Fig. 5 shows, the total energy consumption kept growing to 4.45×10^6 tce in 2012, with an average annual growth rate of 10.3%. The energy consumption of 2012 was almost twice the quantity of 2005. Regarding the energy consumption by sector, the manufacturing industry accounted for the largest share, while its proportion had gradually decreased to 75.8% in 2010, 9% lower than that in 2005 (SIP, 2012). The energy consumption of service industry witnessed a notable increase and became the second largest share. From 2005 to 2010, its proportion in three sectors rose from 7.9% to 11.5%. The changes in the proportion of manufacturing and service industries indicate that the industrial structure in SIP has gradually changed. Moreover, another trend of growing energy consumption happened in the residential areas. In 2010, the residential energy consumption (mainly from buildings) took up by 7.1% (SIP, 2012). From 2005 to 2010, the average annual growth rate of residential energy consumption was 19.5%, which implies that energy consumption per unit of floor space has grown considerably.

Energy efficiency continued to improve (see Fig. 5) between 2005 and 2011, with an obvious growth in 2012. Compared with 2005, an increase of 36.6% was realized in 2012 and the annual growth rate was 4.6%. The decoupling indicator of energy consumption (D_{energy}) is calculated by equation (3). The results of D_{energy} (see Table 2) are all between 0 and 1. It indicates that SIP's energy consumption had experienced a relative decoupling from 2005 to 2012. In this period, the energy consumption increased but the growth rate was smaller than that of GDP. From 2006 to 2009, D_{energy} kept increasing. This implies that the growth rate of energy consumption was decreasing. Then the value dropped to 0.29 and 0.2 in 2010 and 2011. In 2012, D_{energy} rose to 0.53, the highest level during the seven year period.

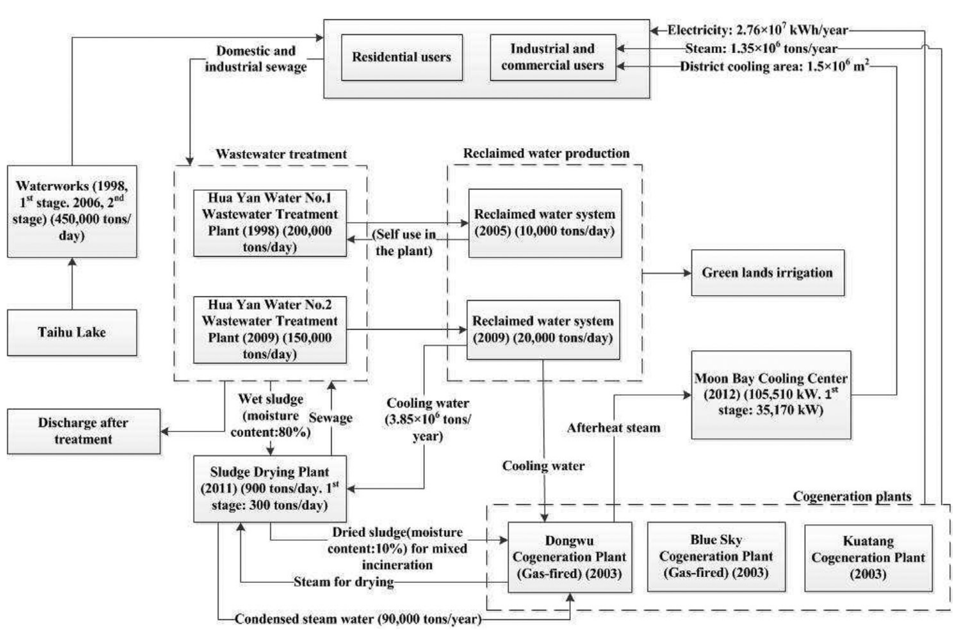

Fig. 4. The centralized public utilities in SIP, mapped in the year when the utility began its operations. Data source: (CSPU, 2011).

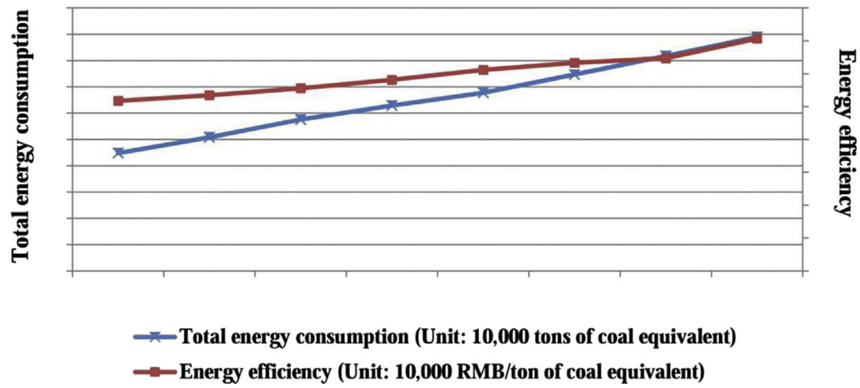

Fig. 5. Total energy consumption and energy efficiency of SIP from 2005 to 2012.

Table 2
Decoupling of energy consumption of SIP from 2005 to 2012. Note: GDP of 2006–2012 is in constant prices of 2005.

	GDP (10^8 RMB)	g (%)	Total energy consumption (10^4 tce)	Energy efficiency (10^4 RMB/tce)	t_{energy} (%)	D_{energy}
2005	580	–	224.15	25.88	–	–
2006	679	17.1	254.14	26.72	3.1	0.21
2007	799	17.7	287.64	27.78	3.7	0.25
2008	914	14.4	314.42	29.07	4.4	0.35
2009	1036	11.8	338.77	30.58	4.9	0.46
2010	1182	13.3	373.51	31.65	3.4	0.29
2011	1322	11.8	408.67	32.35	2.2	0.21
2012	1573	19	445.05	35.34	8.4	0.53

Data source: SIP's ETDB.

3.4.2. Environmental efficiency of water and air

In this section, we calculate the eco-efficiency of water and air, aligning the performance of five major pollutants (i.e., wastewater, COD, AN, SO_2 and PM). In order to plot the trends of total emissions and eco-efficiency, we have normalized the data, as illustrated in Fig. 6 illustrates.

The trends of total volumes are shown in Fig. 6 (a). The total volumes of wastewater and COD show increasing trends during the seven years, growing by 67% and 50% in 2012 compared with 2006. AN had a significant decrease of 60% after several fluctuations. The total emissions of SO_2 had a relatively steady decrease from 2127 tons in 2006 to 1387 tons in 2012. The annual decrease rate of SO_2 was 6.9%, while the emissions of PM show an upward trend.

The eco-efficiency of the five pollutants has been calculated by equation (1). Overall, the eco-efficiency of all the pollutants had increased in the seven years. As Fig. 6 (b) shows, the most notable improvement is SO_2. The eco-efficiency of SO_2 constantly increased and the amount of 2012 was over twice as large as in 2006. The eco-efficiency of AN peaked in 2008, and after a drop in 2009 it increased again. The eco-efficiency of wastewater and COD improved steadily with a slight decline in 2010. The efficiency of PM reached its lowest level in 2007 and then started to rise from 2008.

The decoupling indicators of emissions ($D_{emission}$) are also calculated through equation (2) (see Table 3). Among all the indicators, SO_2 had sustained decoupling from 2007 to 2012, as the $D_{emission}$ of SO_2 had been larger than 0 all the time. Moreover, SO_2 had an absolute decoupling for four years since 2008 and the value of $D_{emission}$ increased to 2.52 in 2010. The $D_{emission}$ of wastewater mostly achieved relative decoupling, indicating an overall improvement, although it had once non-decoupling status in 2010. The environmental influence of COD and AN were generally acceptable. COD only once had non-decoupling and otherwise either relative decoupling or absolute decoupling. The $D_{emission}$ of AN achieved absolute decoupling in 2008, then it dropped to non-decoupling, which reveals unstable environmental performance with respect to this indicator. PM had a non-decoupling in 2007 with the lowest indicator of −8.12, then it rose above 1. After another year of non-decoupling in 2010, the indicator stayed at relative decoupling.

3.5. Discussion

The case study has revealed how SIP improves its regional energy consumption and environmental management. Overall, the energy efficiency of SIP has improved as GDP grows, while total energy consumption has continued to rise. This can be attributed to three main factors. First, the industrial structure has been adjusted. The manufacturing industry has gradually given way to service industry that has much lower energy consumption while creating higher added value. This is steered by SIP's particular strategies on increasing the service industry and expanding its urbanization. Second, stricter policy instruments regarding energy efficiency have been implemented to strengthen the mandatory energy audits. Some chemical and electroplating companies have been moved out of SIP. 50 companies with energy consumption larger than 3000 tce/year had implemented the mandatory energy audits by 2011. As a result of their audits, 225 projects were carried out that reduced energy consumption by 80,000 tce (SIP, 2012). Third, the promotion of clean and renewable energy has been supported by funding and subsidies for industrial production as well as for public and residential buildings. These technologies are effective in improving energy efficiency, such as the Moon Bay district cooling center and the gas-fired cogeneration plants. In 2010, the share of clean energy increased to 78.6% (SIP, 2012). The installation of water/ground source heat pumps and solar water heaters is encouraged in the public and residential buildings. 80% of the new buildings will be green buildings by 2015 (Wang et al., 2013b). Currently, the added installation area of this clean energy in buildings can reach 450,000 m^2 every year (Wang et al., 2013b). All these factors contribute to the improvement of energy

Fig. 6. Total emissions (a) and eco-efficiency (b) of the main pollutants in SIP from 2006 to 2012. Note: The results have been normalized. Data source: SIP's ETDB.

Table 3
De-coupling of the main pollutants in SIP. Note: RD stands for relative decoupling. AD stands for absolute decoupling. ND stands for non-decoupling.

	Wastewater		COD		AN		SO_2		PM	
	$D_{emission}$	Evaluation	$D_{emission}$	Evaluation	$D_{emission}$	Evaluation	$D_{emission}$	Evaluation	$D_{emission}$	Evaluation
2007	0.06	RD	0.25	RD	0.68	RD	0.28	RD	−8.12	ND
2008	0.61	RD	1.13	AD	6.27	AD	1.97	AD	4.77	AD
2009	1.06	AD	0.65	RD	−10.71	ND	2.36	AD	1.40	AD
2010	−0.60	ND	−0.10	ND	4.21	AD	2.52	AD	−1.65	ND
2011	0.51	RD	0.58	RD	0.51	RD	1.27	AD	0.70	RD
2012	0.71	RD	0.67	RD	0.71	RD	0.58	RD	0.68	RD

efficiency and the decoupling between energy consumption and GDP growth.

The progress of eco-efficiency of water and air is made in the following ways. First, the end-of-pipe treatment infrastructures dramatically reduce the pollutants of COD, AN and PM. Second, industrial symbiosis between industrial facilities and residential areas were formed to improve the efficiency of water and energy. Moreover, the synergies among wastewater treatment plants, water reclamation facilities, sludge dried plant and cogeneration plants prevent pollution from sludge and also reduce wastewater discharge. Third, the regulatory and economic instruments have stimulated companies to improve their environmental performance. As we introduced in section 3.2, the stricter regulations target the energy-intensive and polluting companies especially in the industries of paper making and printed circuit boards. Meanwhile, funding has been provided to support companies to improve their environmental performance. For instance, Gold Huasheng Paper, one of the largest paper manufacturers in China, has invested 34 million RMB in building a water reclaiming system inside the company. This system has the capacity of 7000 tons/day and COD treatment facilities. This was a key project funded by SIP in 2010. Since the facilities were launched, Gold Huasheng Paper can reduce 2.6 million tons of wastewater discharge and 214 tons of COD annually. Through using the reclaimed water, this paper company can also save 25 million RMB per year from water and pollution fees. Among the performance of the five pollutants, the reduction of SO_2 emission was the most significant and it realized continuous decoupling from 2007 to 2012. This was achieved by forbidding

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coal-fired boilers and the support for using natural gas and other clean energy sources. Moreover, cleaner production audits have been launched in 26 companies since 2011, which has resulted in the reduction of 1.6 million tons of water consumption. Furthermore, 227 companies have obtained ISO14001 certifications by 2012. So far, SIP is the industrial park that has the highest density of ISO14001-certified companies among all the national industrial parks. Therefore, the eco-efficiency of water and air in SIP is improved by the centralized infrastructures as well as the policy instruments aiming to stimulate companies' environmental performance.

The eco-efficiency analysis of SIP has revealed that the portfolio of economic, regulatory and voluntary instruments is effective to decouple environmental pressure from economic growth. Like many national industrial parks in China, the eco-transformation is driven by the AC which uses top-down planning and a set of policy instruments to facilitate company participation (Yu et al., 2014a). The policy instruments incorporated the guideline of National EIP standards to assess the new projects and the existing companies, in order to improve the industrial environmental performance. Due to the enhanced environmental requirements, several manufacturing companies have been eliminated from SIP, leading to an industrial transformation. Meanwhile, service industries with high added value have been promoted, such as finance, outsourcing, research and innovation. In this process, the employment opportunities attract more employees, especially highly educated talents. More residents and commercial businesses have emerged, giving SIP more urban functions. Furthermore, the centralized energy and water infrastructures have been built according to EIP principles. SIP has expanded these infrastructures to simultaneously serve the residential areas, which provides physical conditions for eco-city development. EIP planning focuses on the environmental pressure caused by industrial activities. As urban functions emerge in industrial parks, the industrial and urban planning should be considered in combination. SIP's master plan between 2012 and 2030 has clarified the land use for residential areas, cultural facilities (e.g., library and youth center), schools and hospitals. Apart from the adjustment of industrial structures for high added value and low environmental impact, the goals of the planning also aim to provide a livable dwelling environment (SIP, 2013a). In addition, green buildings and clean technologies have been encouraged by economic instruments to improve the energy efficiency of residential and commercial areas.

All in all, EIP's development in SIP has provided a better foundation for eco-city development, in terms of the exploration of environmental and industrial policies and urban construction. We have observed that the eco-transformation in SIP has revealed the transition of an industrial park towards an eco-city. The measures issued by SIP's AC for environmental performance primarily concerned industrial pollution as SIP focused on manufacturing. As urbanization proceeds in SIP, pollution (e.g., water and air) from industrial sites draws more concern since these pollutants may impact negatively on residential areas. In addition, the energy consumption of buildings in the residential and commercial areas has become notable. Thus, the policy implementations of SIP have focused on integrating industrial sites and residential areas. Urbanization in an industrialized town may be a result of post-industrialization, but the resource conservation and pollution prevention need to be steered through policy instruments initiated by local authorities.

4. Conclusions

Our empirical research in SIP has demonstrated how an industrial park has been transformed to improve environmental performance and integrate its various urban functions. The eco-efficiency analysis indicates that economic growth can be decoupled from environmental impact through appropriate policy interventions. This benefits the process of eco-city development in terms of creating a win–win for economy and environment during urbanization in an industrialized town like SIP.

We hereby answer the research question: what conditions can an eco-industrial park provide for eco-city development? First, mandatory and strict regulations for energy saving and emission reduction can significantly improve the environmental performance in the whole region. Second, the adjustment of industrial structure reduces the presence of intensive energy consumers and polluters and stimulates the service industry with high added value. It is effective in matching economic growth with small environmental impact and to benefit the transition towards an urban economy. Third, an EIP has high quality infrastructures that can be utilized by residential areas, which is useful to improve the efficiency of regional energy and water use. Fourth, urban functions in an industrial park are initially driven by the industrialization that provides sufficient employment opportunities and economic growth. Therefore, such an industrialized town has substantial economic drivers, which avoids the shortcomings of “an empty city” in some brand new eco-cities that lack industrial activities (Caprotti, 2014). However, there are some limitations in our research. We obtained the research findings from the case study of SIP. Similar to other national industrial parks, SIP has preferential policies and more competitive companies, which has made it a fast-growing region. Especially, the collaboration with Singapore brings SIP more efficient administration and enforcement. Other ordinary industrial parks may not be capable to effectively enforce the related policies. Nevertheless, the insights for steering eco-transformation can still shed some light on analyzing the possibilities of an EIP to become an eco-city.

EIPs and eco-cities show considerable overlap in terms of their concepts and environmental indicators. They both emphasize resource conservation, pollution prevention, efficient waste treatment and recycling. EIPs target the environmental impacts from industrial production, while eco-cities incorporate a wider range of goals to provide healthy living conditions and good social welfare to citizens. As more Chinese EIPs have become complexes of industrial production and residential areas, the development of an industrial park requires us to consider how industrialization and urbanization can be integrated. Urban functions should not be just the auxiliary facilities of industrial sites. Furthermore, industrial parks can also improve their endogenous capacity through such urbanization by reducing their dependency on external capital and technology. Thus, the goal of urbanization in industrial parks should aim at the agglomeration of capital, talents and innovation to enhance the comprehensive development, in order to propel their industries. This transformation is based on the advantages of an EIP, which paves the way for an eco-city.

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Appendix. Definitions of variables of eco-efficiency

Efficiency of energy consumption is the ratio between GDP and the total amount of energy consumption with the unit of 10,000 RMB/ton of coal equivalent. It is defined as:

$$E_{energy} = \frac{\text{GDP}}{\text{total energy consumption}}$$

Eco-efficiency of wastewater is the ratio between GDP and the discharge amount of wastewater with the unit of RMB/ton. It is defined as:

$$E_{wastewater} = \frac{\text{GDP}}{\text{total wastewater discharge}}$$

Eco-efficiency of COD is the ratio between GDP and the discharge amount of COD with the unit of 10,000 RMB/ton. It is defined as:

$$E_{COD} = \frac{\text{GDP}}{\text{total COD discharge}}$$

Eco-efficiency of AN is the ratio between GDP and the discharge amount of AN with the unit of 10000 RMB/ton. It is defined as:

$$E_{AN} = \frac{\text{GDP}}{\text{total AN discharge}}$$

Eco-efficiency of SO_2 is the ratio between GDP and the discharge amount of SO_2 with the unit of 10000 RMB/ton. It is defined as:

$$E_{SO_2} = \frac{\text{GDP}}{\text{total } SO_2 \text{ discharge}}$$

Eco-efficiency of PM is the ratio between GDP and the discharge amount of PM with the unit of 10000 RMB/ton. It is defined as:

$$E_{PM} = \frac{\text{GDP}}{\text{total PM discharge}}$$

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