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(産業共生を計画・評価する分析手法に関する研究：鉄鋼産業を含む産業集積地区を対象に）

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Summary

Industrial symbiosis (IS) is a core concept of “industrial ecology”. It encourages the material and energy flows circulate in the industrial and urban systems, so as to reduce the consumption of virgin material, fossil fuels, and mitigate the generation of waste and pollutants. Industrial symbiosis provides a system innovation to fight for a series of environmental challenges like the climate change, sustainable urban development and so on, especially for industrializing countries. It provides solution from network optimization perspective. To make a quantitative analysis on the industrial symbiosis is important to generalize the IS project, verify its effects and support the policy making, while to date, quantitative analysis is rather few.

Under this circumstance, this doctoral dissertation aimed to conduct a planning and quantitative evaluation on industrial symbiosis with case study on steel plant industrial complex in China, which had been under rapid economic growth and industrialization. Two typical industrial cities in China were selected as case studies.

This paper was organized as follows:

Chapter 1 presented the background of this research. Industrialization had brought both prosperity and environmental challenges to human beings. The concept of industrial symbiosis and its application as urban symbiosis provided new solution to address the challenges. Especially, to generalize and transform the industrial symbiosis concept to developing countries, which were under rapid industrialization and urbanization, was proved to be good idea. However, research on planning local industrial symbiosis for them and quantitative evaluation to verify the effects of industrial symbiosis implementation was relative few. Therefore, it was important to conduct the planning of local industrial symbiosis and develop integrated evaluation model to assess the effects of planned industrial symbiosis in typical developing country. With this consideration, this research chose China as case study. The research objectives and dissertation structure was introduced.

Chapter 2 reviewed the development of the theory, practice and analytical methodologies in

the research field of industrial symbiosis. It was found that, on the whole, industrial symbiosis was still an emerging research field. In the aspect of project practice, developed countries had promoted a series of successful projects, and the application of industrial symbiosis had brought both environmental and economic benefits to them. However, in developing countries, there was still a lot of room to enhance the promotion of industrial symbiosis. In the field of analytical methodologies, material flow analysis (MFA), life cycle assessment (LCA) and input-output analysis (IOA) had become mature tools, however, to extend their application in micro level and developing countries which lacked data, modification and integration was needed. Conducting case studies in developing countries was necessary to verify the effects of IS, so as to provide useful information for the decision making process. However, to date, there had been a lack of both case studies in developing countries and integrated modeling studies in the literatures.

Chapter 3 compared industrial symbiosis promotion in China and Japan. It was found that even though both the two countries had promoted “sound material-cycle society” related strategy, the development stage was different. In Japan, industrial and urban symbiosis was promoted like Kawasaki eco-town, and regional symbiosis was implemented. While to China, development stage was still focus on cleaner production and the eco-industrial park, to promote industrial and urban symbiosis, as well as regional symbiosis would be focus in the next promotion stage. Based on the review on Japanese case, experiences related to industrial symbiosis were learned and transformed to this case study.

Chapter 4 focused on the data acquisition. Innovative survey procedure was designed to collect local industrial symbiosis data in Jinan and Liuzhou city, local industrial symbiosis database was constructed including technical data, company input-output data, economic data, emission factors and general regional socio-economic data. Main findings in this chapter were the industrial symbiosis development condition in Jinan and Liuzhou could present two levels: national advanced level with more synergies and primary urban symbiosis, and local level with focusing on cleaner production and bulky waste recycling. Even though Liuzhou had the similar industrial system as Jinan, a lot of industrial symbiosis opportunities were not uncovered.

Chapter 5 conducted the integrated model development. Material and energy flow analysis, process based LCA and hybrid input-output model was integrated to assess the planning of industrial symbiosis. The main findings and contributions were that: through the model integration, it resolved the bottleneck of process based LCA and IO-LCA application in the industrial symbiosis evaluation and lack of scenario analysis in China.

Based on the data acquisition and model development, **chapter 6** and **7** presented two case studies. In **chapter 6**, network analysis and assessment on the symbiosis in the national pilot project in Jinan city was made. Results highlighted extinguish environmental benefit. In total, more than 4 million ton raw material and 1.5 million ton coal equivalent (tce) energy was saved, and more than 4 million ton waste was reduced. Considerable CO_2 reduction was achieved through the implementation of industrial symbiosis. 3944.05 ktCO_2/y was reduced in total. Material and energy

symbiosis reduced CO_2 emissions by 3792.42 and 151.62 ktCO_2/year respectively. In addition, as an advanced national pilot project, Jinan's experience could be transformed into local cases.

In **chapter 7**, based on the study in Jinan city, planning and quantitative assessment for industrial symbiosis in Liuzhou city was presented. Two main findings were highlighted:

(1) Considerable environmental benefits were achieved. There were dramatic carbon mitigation effects. Compared with BAU, planned industrial and urban symbiosis could contribute to the CO_2 reduction by 1104.96 ktCO_2/y. Waste plastics recycling, waste tire recycling and biomass utilization presented great CO_2 mitigation in the lifecycles. They reduced 39.59, 39.92 and 845.89 ktCO_2/y respectively. Scenario analysis by 2015 highlighted that industrial symbiosis was able to help the local city realize co-benefit, reduced CO_2 emissions and air pollutants together. IS provided an extra mitigation measure beyond traditional technological development and structure adjustment.

(2) On the other hand, results emphasized a need of trade-off thinking. Coal flying ash recycling reduced 11.40ktCO_2/y, but meanwhile, it also increased 827.55 tCO_2/y from second energy consumption. As a cost of constructing the industrial symbiosis, emissions from transportation increased by 2246.61 tCO_2/y. In detail, with implementation of waste plastic recycling, waste tire recycling, coal flying ash recycling and biomass utilization, CO_2 emissions from transportation increased by 29.05, 58.10, 140.69, and 1948.42 tCO_2/y, respectively. This finding highlighted a future research need on optimizing the symbiosis and transportation network, and made technology shift to reduce second emissions.

Finally, in **chapter 8**, policy implications related to the generalization and extension of industrial symbiosis in China, as well as supporting policies to enhance the promotion of industrial symbiosis were proposed and discussed. Based on the planning in the case studies, the future concerns on the developing energy symbiosis in the case cities were discussed. With smart design, waste heat from the factories could be utilized more efficiently. Utilize the concept of IS to support the transit thinking on China's industrial policy was important, like the improvement on the factories location, freight network, and technical shift. Conclusion of the main findings in this work and future concerns were drawn in the final part of this chapter.

The main findings of this research would be critical for China and other developing countries' future industrial and regional planning policy, and shed a light on the future low-carbon development in developing countries in Asia.

Key words:

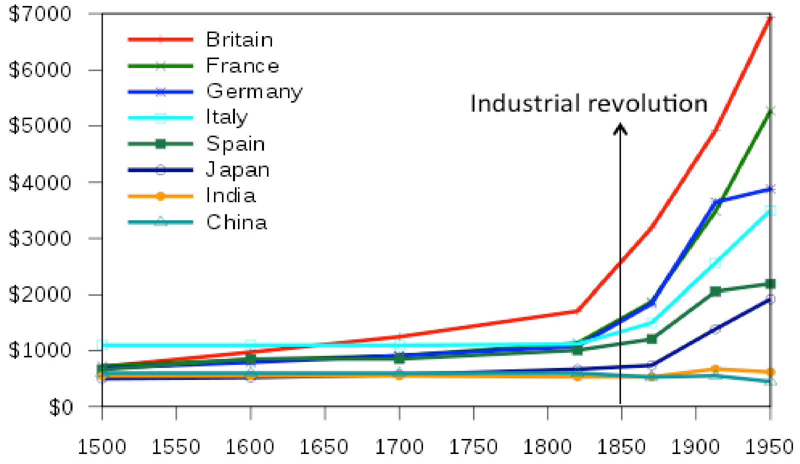
Industrial symbiosis; Industrial and urban symbiosis; Hybrid LCA model; Scenario analysis; China

Content

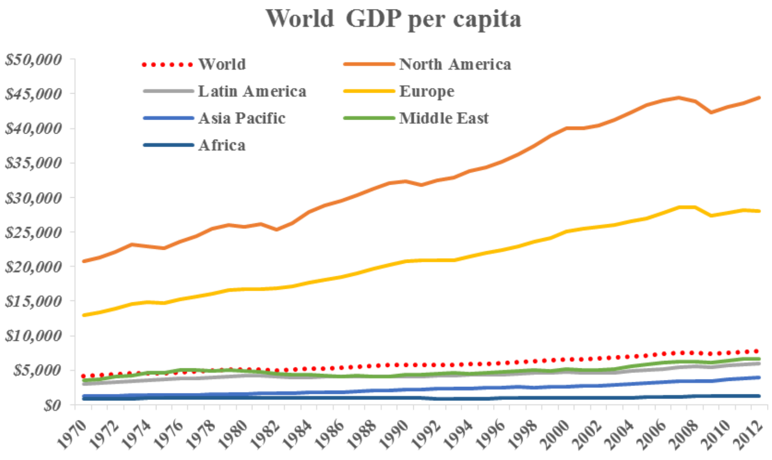
1.Research Background

1.1 Background

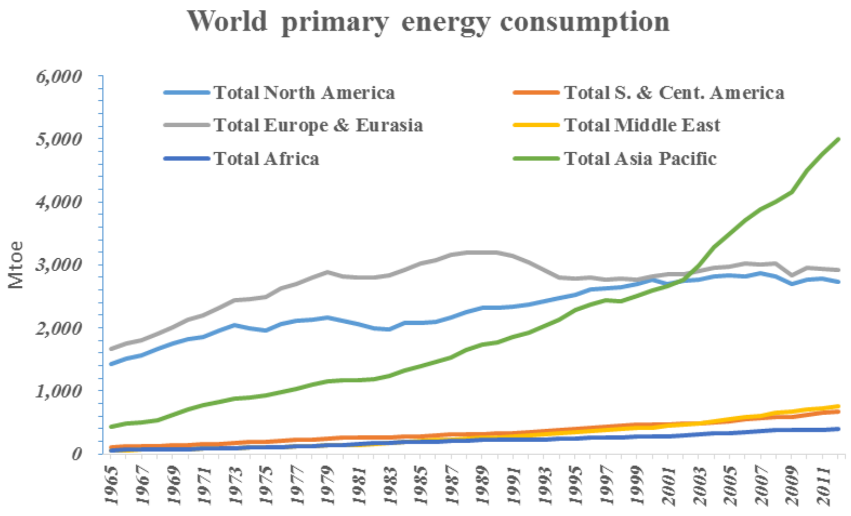
There is no doubt that the global industrialization trend has brought the prosperity of human society, e.g. global GDP has been increased significantly after the industrial revolution (*Figure 1-1 (a)*). Rapid industrialization has played a role as the main driver for economic growth (income increase; job creation, poverty reduction, and so on), and accelerating the global development. However, meanwhile, it also causes a series of environmental problems, like resources depletion, environmental pollution and climate change (Geng and Doberstein, 2008; van Berkel et al., 2007; Xu, 2009). Shown as *Figure 1-1*, in the past decades, under the rapid industrialization and economic growth, energy consumption and accordingly CO_2 emissions had dramatically increased, especially for rapid developing transitional economy, e.g. Asia Pacific regions.



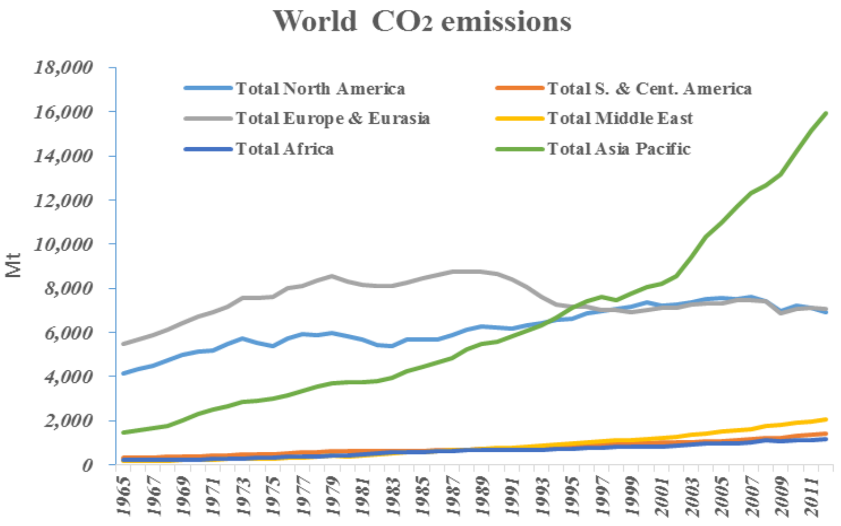
(a) Rapid GDP per capita increase after industrial revolution
Source: revised by the author based on: http://commons.wikimedia.org/wiki/File: Maddison_GDP_per_capita_1500-1950



(b) World GDP per capita in the past decades



(c) World energy consumption in the past decades



(d)World CO_2 emissions in the past decades

Figure 1-1 Global change of GDP per capita, energy consumption and CO_2 emissions, 2005 USD
Source: World Bank, 2013; BP energy statistics, 2013

Apart from the economic growth, industrialization is also intertwined with the urbanization process, acts as one key factor affecting the sustainable urban development. Particularly, cities concentrating on industrial development, e.g. heavy industrial cities, resource based cities and cities located with integrated industries, would face series pollution generated by industries. Solutions are needed for sustainable urban development, so as to reduce environmental impacts and improve living environment (Hayashi, 2010). To coordinate industry and urban is one key point.

The idea of **industrial symbiosis (IS)**, which is under promotion in a number of developed countries, like European countries, Japan, US and Korea, provides a systematical approach to green the industry and coordinate the relationship between industry and urban. **IS** is a system innovation that integrating industrial process and natural process, to reconcile the expanding conflicts among them (Chertow, 1998, 2000; Ehrenfeld and Gertler, 1997). It is defined as a relationship, in which two or more previous unrelated industries exchange their materials, energy and/or by-products in the system. Through the cooperation, a collective benefit greater than the total sum of the individual benefits without a symbiosis could be generated (Chertow, 1998, 2000). In this way, IS provides an opportunity for industries and nearby communities to improve their eco-efficiency (Chertow, 1998, 2000; Mirata and Emtairah, 2005). In addition, IS could be applied in the form of urban symbiosis, which is defined as a specific opportunity arising from the geographic proximity of industrial and urban areas (Chen et al., 2011; Geng et al., 2010; Van Berkel et al., 2009). In the application of urban symbiosis, societal waste could be innovatively utilized into the industries and reduce the related energy consumption and pollutants.

The hypothesis of the application of industrial symbiosis is shown as *Figure 1-2:* Industrial symbiosis and urban symbiosis could enhance the resource efficiency through increasing the exchange of material/energy flows in the industrial process and between industries and urban. It provides a way to optimize the material/energy flow network, so as to reduce resource consumptions and emissions, and coordinate industries and urban.

With such merits, generalize and transform the industrial symbiosis idea is particularly fit to developing countries, which are under rapid industrialization and urbanization. For those countries, how to coordinate the relationship of urban and industry becomes gigantic topic for their sustainable development. Find a smart way to build a harmonious relationship between urban and industry is necessary. Under this philosophy, there are two-level commissions: (1) greening the industries; (2) constructing a smart and efficient system to link the industry and the urban area. IS would provide such solutions in two points: (1) through resource circulation, to "green" the industries; (2) reorganize the linkage between industries and cities, change it into more environmental friendly format.

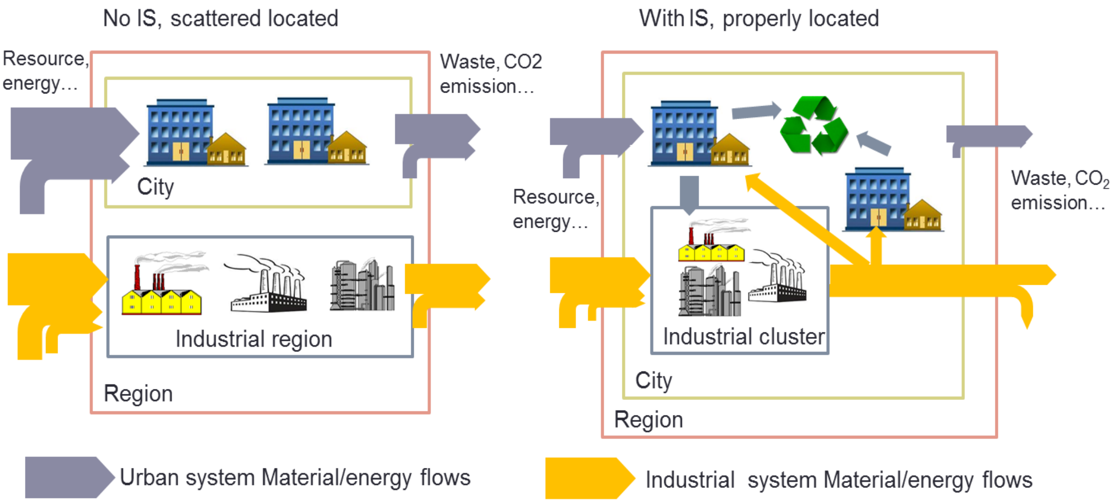


Figure 1-2 Flows optimization by industrial and urban symbiosis

Furthermore, applying and verifying IS in China would be meaningful for the IS generalization in developing countries. China is famous for its “world factory”, especially process industry like the iron/steel industry. Industries bring huge energy consumption and carbon dioxide (CO_2) emissions (*Figure 1-3*). Take iron/steel industry as an example, China’s total production of crude steel had grown from 95.36 million tons to 567.84 million tons, from 1995 to 2009, overtaking Japan as the world’s largest steel producer in 1996. China’s share on the world steel production had leaped from 12.68% in 1995 to 46.39% in 2009[1]. Meanwhile, as an energy intensive industry (EII), the surging resource/energy consumption and pollutants emissions were serious. In 2009, the CO_2 emission from Chinese iron/steel sector accounted to 1.17 billion tons[2], shared 16.29% of Chinese total CO_2 emission(Zeng et al., 2009), nearly equal to total Japanese CO_2 emission(1.22 billion tons in 2009[3]) and 50% of the world’s steel industry CO_2 emission(Liu and Gallagher, 2010). Thus it is important to apply IS.

In addition, China presents another feature as typical developing countries: the challenge of urbanization. With accelerating economic growth and urbanization, China already has more numerous and larger cities than ever before. In 2010, the urban population in China has increased to more than 660 million, with an urbanization rate of 49.68% (*Figure 1-4*). These numbers are expected to up to 850 million and 60.00% according to Chinese government’s estimation[4]. It indicates an emerging concern of sustainable urban development in China (Chen et al., 2013; NBS, 2011; UN, 2012).

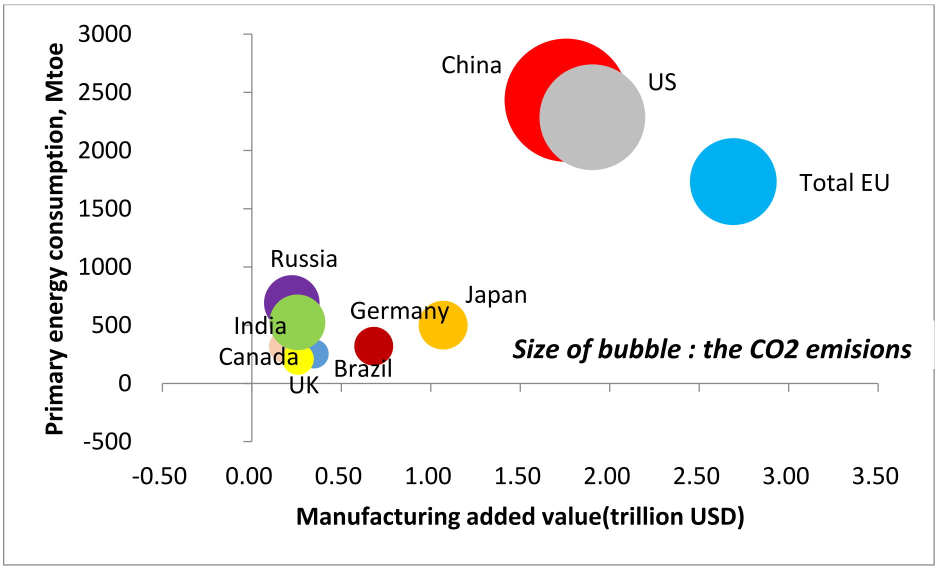


Figure 1-3 Energy consumption, CO_2 emission and manufacturing added value in selected countries in 2010
Data source: BP energy statistics, 2011; UN 2011.

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[1] World steel association, Steel Statistical Yearbook

[2] Data source: CO_2 emission from Chinese iron/steel sector is calculated from the consumed energy type.

[3] Data source: BP statistics, 2010.

[4] http://www.china.org.cn/china/2012-05/04/content_25299433.htm

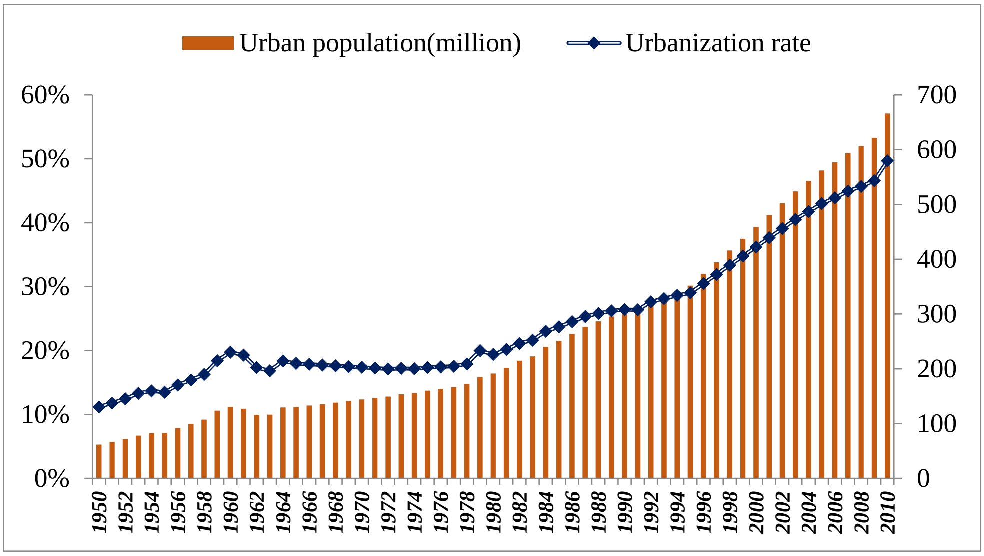

Figure 1-4 China's urbanization rate and urban population, 1950-2010
Data source: China Statistical Yearbook

Compared with post-industrial countries, China suffers from both lower resource efficiency and recycling and reuse ratio. It was reported that in 2006, China consumed 15% worldwide primary energy, 30% crude steel and 50% cement, while the GDP only took 5.5% of global one. In 2008, the industrial waste discharge was as high as 1.9 billion tons, while the overall recycling and reuse ratio for resource was only 35%, 20% lower than the international advanced level (Dong, 2011). With this circumstance, promotion of IS to build circular society would be necessary.

Based on the above, to conduct a study on the industrial symbiosis with case study in China would be meaningful. To support generalization and verification of IS, "planning" and "evaluation" are two important topics. To enlighten the policy implications in developing countries, select typical industrial cities in China is helpful. Currently, there is rather few IS planning case studies on this topic outside developed countries, and even fewer evaluation studies. Therefore, there is a research gap on the lack of IS projects' information and proper modeling approach to support such research in developing countries.

Under this circumstance, this study would conduct a comprehensive planning and quantitative assessment on industrial symbiosis, with case study in steel plant industrial complex in China. This research would make IS planning in typical iron/steel dominated industrial cities in China, and develop hybrid LCA model to make evaluation, so as to verify the effects of IS. The findings would be beneficial to the future industrial and urban policy implications in China and developing countries.

1.2 Objectives and originalities

- **Objectives and research scheme**

With this background, this study focuses on the planning and quantitative evaluation on IS, and its policy implication in China, which is under surging industrialization and urbanization, with three focuses:

- Planning IS: investigate and plan local IS in iron/steel industrial complex in typical industrial cities in China. Propose a solution for better utilization of industry, to enhance the eco-efficiency of industrial and urban system in China.
- Evaluation and scenario design: construct hybrid LCA to evaluate the life cycle impacts of the planed IS, so as to verify the effects of IS. Set IS scenario analysis up to 2015, to support local policy making in future.
- Policy implications: based on the case study and its results, this research discusses how to generalize and extend IS to forward China's future industrial and urban policy implications, to support the regional sustainable development. Supporting policies for IS promotion is further proposed and discussed. .

With the above objectives, research scheme is summarized in *Figure 1-5*. The central research question is how to enhance the eco-efficiency of industrial system and how to properly utilize the industries to address some urban challenges. In this study, the concept of "industrial symbiosis" (IS) and its application as "industrial and urban symbiosis" acts as new solutions to address the above questions. To make simplification, we would use the terminology "industrial symbiosis" in most times. With new solutions, this research would use several approaches to resolve the proposed questions:

First of all, **project survey** approach is the basis for database construction and case study. We conduct the investigation in technology level, industrial process level and industrial cluster level, so as to uncover the opportunities of industrial symbiosis planning, and contribute to the integrated industrial symbiosis database construction.

Then, ***evaluation model*** would be important for the verification of IS application. It could provide critical information for the improvement of planning and related policy implications.

Furthermore, based on the analysis on local condition and industrial features, ***design for the local industrial symbiosis*** is made, so as to plan the industrial symbiosis in the case cities.

Finally, ***case studies*** could verify the planning and help to the planning generalization. This study conducts a case study in typical industrial cities with life cycle assessment and scenario analysis. To the best of our knowledge, to date, very few integrated planning and evaluation study is made in China. Thus this study is very meaningful.

With the above approaches, the main outcomes of this research include: data survey and the construction of local IS database (it is the basis for case study); hybrid LCA model for evaluation (provides analytical tool); local IS planning in steel plant industrial complex and the life cycle evaluation and scenario analysis on it (to verify the effects of planning); finally, based on the results of the case study, policy implications are proposed and discussed to address concerns on future sustainable industrial and urban development in China and other developing countries.

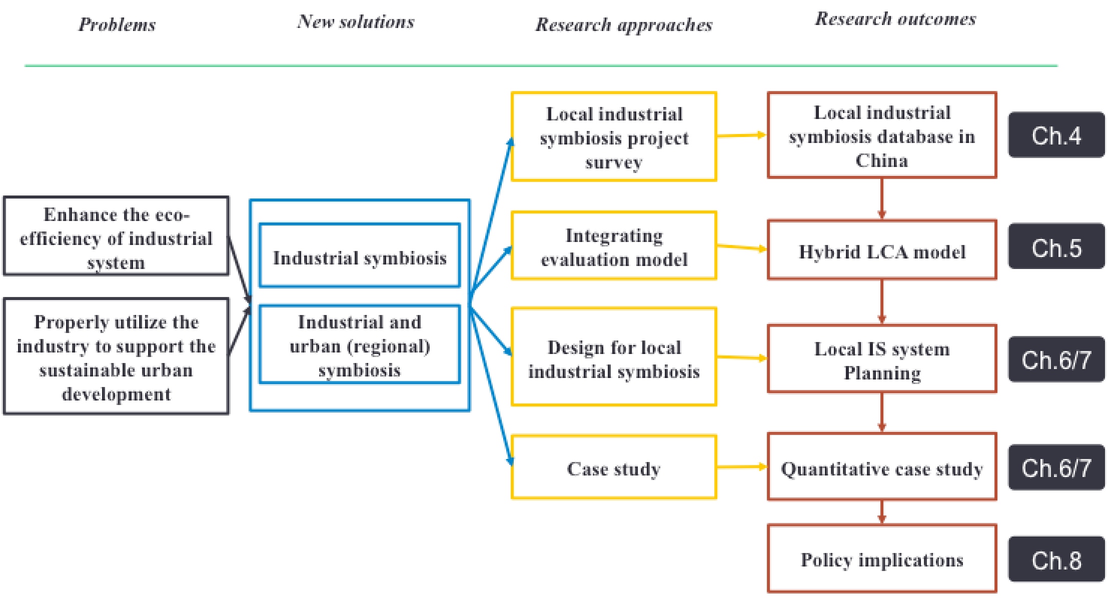

Figure 1-5 Research scheme

- **Originalities**

According to the above research questions, approaches and outcomes, this research would provide original contributions to the following aspects:

- Evaluation methodology: Revise traditional LCA model and establish a hybrid LCA model fits to data scarcity condition. Design IS scenarios and conduct scenario analysis on the IS planning, and apply in China's local case study, providing supporting information for policy makers.
- Database construction: Design innovative survey procedure and collect first hand data from the local projects in China, and construct the database with detail IS inventory data.
- Policy implementation: Propose utilize IS to improve the regional industrial layout in China. Combined with the quantitative evaluation and international comparison, propose policy innovations to support the promotion of IS in China. The experiences gained in China would be beneficial to other developing countries.

1.3 Dissertation structure

Under this background and research objectives, the structure of my dissertation is organized in *Figure 1-6*: **Chapter 1** introduces the background of this research as well as the research framework and originalities. **Chapter 2** conducts a comprehensive review on the theories, case studies and methodologies. **Chapter 3** makes the international comparison on the industrial symbiosis promotion in China and Japan, to identify the proper IS design ideas that can be utilized in China. In **Chapter 4**, industrial symbiosis projects and cases in China are investigated with survey procedure, first hand data is collected and local database is conducted. Then, in **Chapter 5**, integrated evaluation model is established. Based on these, **Chapter 6** and **7** presents two case studies: (1) makes assessment on a national pilot project in Jinan city; and (2) based on the study in the national project, conducts planning and evaluation on the local industrial symbiosis in Liuzhou city. Finally, **Chapter 8** discusses the policy implications and concludes this work.

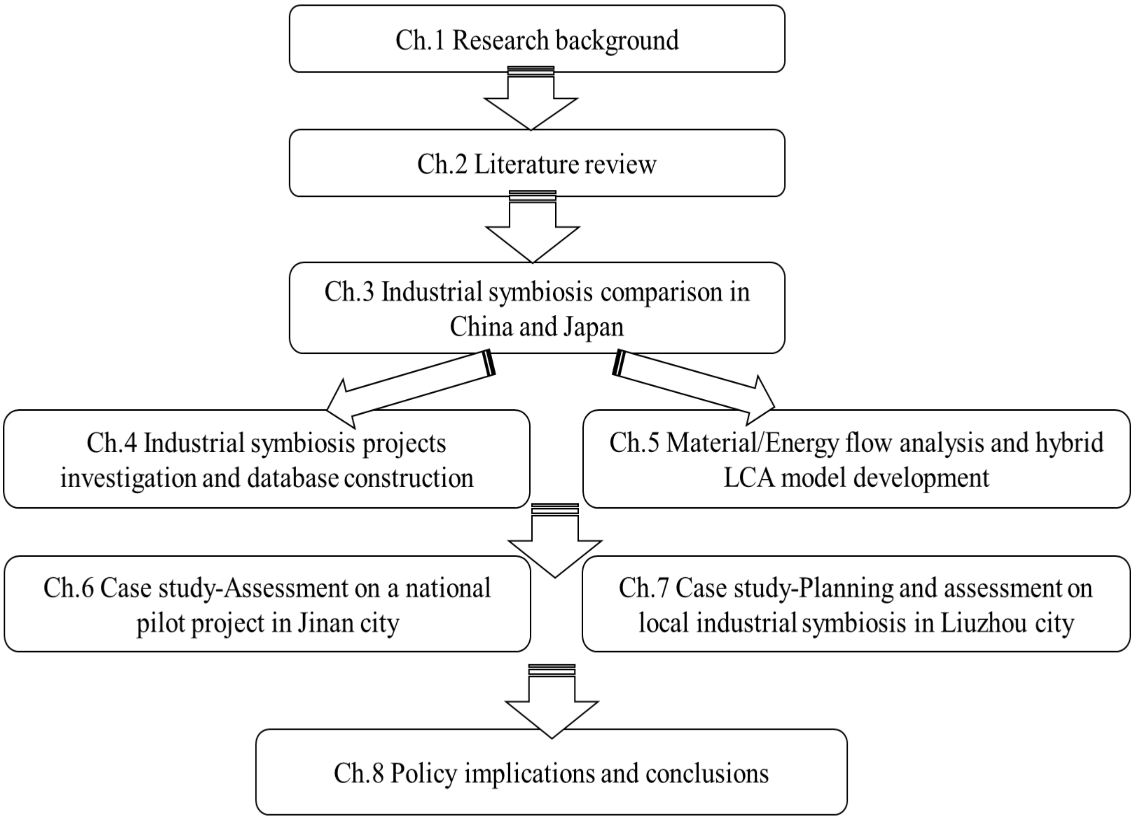

Figure 1-6 Dissertation structure

2.Literature review

This chapter makes a comprehensive review on the theory development of industrial ecology and industrial symbiosis; related modeling approaches to quantify the industrial symbiosis; as well as international practice.

2.1 Review on the theory of industrial ecology and industrial symbiosis

Industrial symbiosis is the core concept in this study, and it is also one of the core components of ***"Industrial Ecology"***. This section would make a review on the related concept and theory development.

2.1.1 Industrial ecology

The theory of industrial ecology was developed to provide a new conceptual framework to understand how industrial systems had impacts on the environment (Huber, 2000; Lowe, 1993). Its conception could trace to the terminology of "Industrial Metabolism" (IM) proposed firstly by Robert Ayres (Ayres, 1989) and the word of "industrial ecology" had become popular in 1989 with a Scientific American article by Robert Frosch and Nicholas E (Allenby, 1992; Diwekar and Small, 1998; Lowe, 1993; R.Ayres and L.Ayres, 2002). They presented that ***"why would not our industrial system behave like an ecosystem, where the wastes of a species may be resource to another species? Why would not the outputs of an industry be the inputs of another, thus reducing use of raw materials, pollution, and saving on waste treatment?"*** (Frosch and Gallopoulos, 1989). Such new developed framework acted to identify the environmental impacts of products and processes associated with industrial systems, and further implemented strategies to reduce the impacts, so as to achieve the goal of sustainable development. It was a new methodology to identify the interactions of physical material flows, and interrelationships both within and between industrial and ecological systems(Allenby, 1992; R.Ayres and L.Ayres, 2002).

The widely cited and acknowledged definition on "Industrial Ecology" came from Robert White (White, 1994), the former president of the US National Academy of Engineering. He summarized based on several sources and elements by defining industrial ecology as ***"the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources"***((R.Ayres and L.Ayres, 2002), pp4.) . It could be seen as an evolution of environmental protection, from end of pipe pollution control to the system thinking and optimization (*Figure 2-1*). In international society, the concept of "Industrial Ecology" was also promoted as various policy realms, like the "3R" in Germany, "Sound material-cycle society" in Japan, and "Circular Economy" in China.

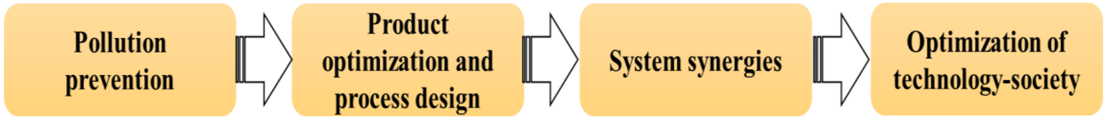

Figure 2-1 IE as an evolution thinking

Industrial ecology makes quantification on the material and energy flows in the system, and modeling how the industrial processes could serve to modern society function. From a system perspective, industrial ecology focus on (R.Ayres and L.Ayres, 2002) :

- Industrial metabolism and material and energy flow analysis;
- Analyze the flows and the interactions with each other from a life cycle perspective,
- Modeling the system.

2.1.2 Industrial symbiosis

Industrial symbiosis can be seen as one core practice of the philosophy of IE. The concept of Industrial Symbiosis (IS) provides a system innovation to enhance the resource efficiency. IS refers to a relationship that industries exchange materials, energy and/or by-products in a mutually beneficial way and improve the resource utilization (materials, energy, water) through closing the loops (Chertow, 2000; Jacobsen, 2006). As an extended concept of IS, urban (and/or regional) symbiosis refers to a specific opportunity arising from the geographic proximity of urban and industrial areas(Chen et al., 2011; Geng et al., 2010; Van Berkel et al., 2009), could innovatively utilize the urban wastes into industries and reducing the related environmental impacts (). Especially, some urban refuse could be utilized by the nearby industry and in return, industry could provide the urban with living necessity like heat. Under such a concept, urban and industry could be connected harmoniously and the resource consumption and pollutants emissions could be reduced accordingly. Scheme of industrial symbiosis and its application as industrial and urban symbiosis is shown in *Figure 2-2* and *Figure 2-3.*

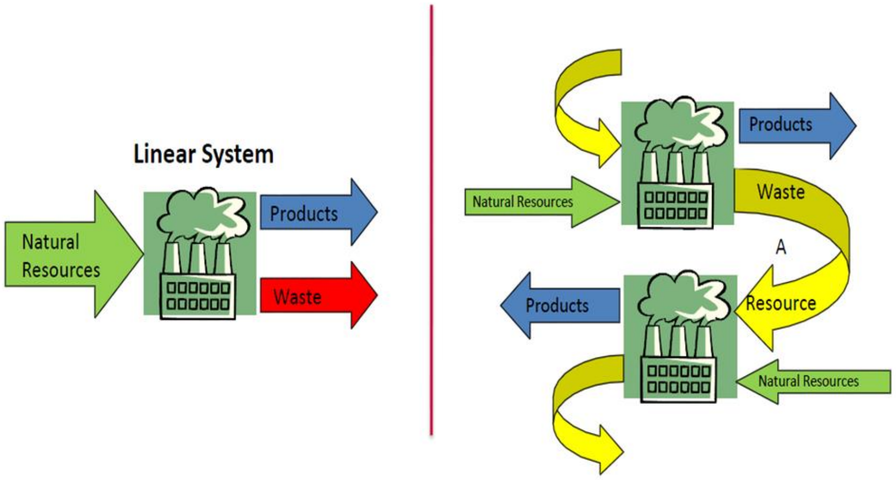

Figure 2-2 Schematic image of industrial symbiosis

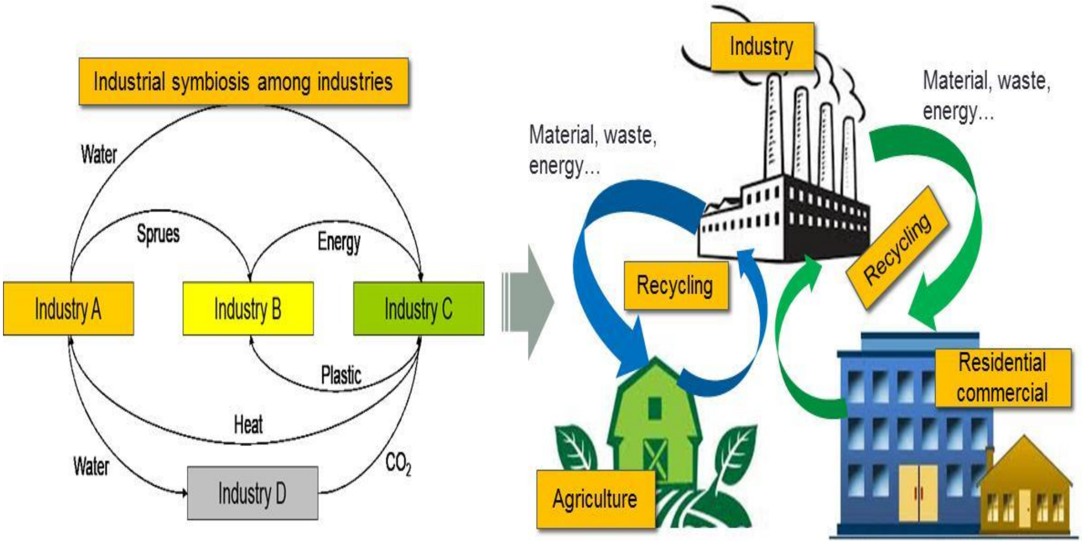

Figure 2-3 Industrial symbiosis and its application as industrial and urban symbiosis

As system innovation, IS had been globally promoted. *Figure 2-4* summarized the development of IS and the related practice. There was an evolution for the development of concept of IS. In the 1970s, the environmental protection issues became popular (Huber, 2000), and since 1972, the Kalundburg eco-industrial park in Denmark was constructed and gradually became well known(Jacobsen, 2006). Nowadays, it was the most famous industrial symbiosis practice in the world. In the 1980s, the life cycle assessment (LCA) was widely applied, which marked that focus had transformed from traditional end of pipe technology to pollution prevention and system/product design (Diwekar and Small, 1998; Hertwich et al., 2000; R. Ayres and L. Ayres, 1996). In 1989, the milestone was the birth of "Industrial metabolism" (Allenby, 1992; Ayres, 1989; Frosch and Gallopoulos, 1989), and then in 1994, the concept of "Industrial ecology" was formed. It meant a new discipline had been established. Under this discipline, a number of national projects had been promoted. The famous practices included: "eco-industrial park (EIP) program" in US, since 1995 (Côté and Cohen-Rosenthal, 1998; Gibbs and Deutz, 2005)； "eco-town project" in Japan, since 1997 (Moriguchi, 2000; Van Berkel et al., 2009). In 2000, as the other milestone, the concept of "Industrial symbiosis" was formally proposed by Professor Chertow in US (Chertow, 2000, 2007). Since then, diverse IS practice had been conducted, in the form of EIP, regional symbiosis and circular economy, as well as eco-industrial development (EID). Much more countries participated, e.g.UK (in 2000, it released the national industrial symbiosis project-NISP, focusing on regional waste recycling) (Costa et al., 2010; Jensen et al., 2011; Mirata, 2004), Korea (from 2005, it had conducted the national EIP project under the national strategy of "Green Growth", focusing on heavy industrial clusters)(Behera et al., 2012; Park et al., 2008b), and China (in 2001, launched the national EIP project, and the circular economy became national strategy)(Bai et al., 2014; Tian et al., 2014; Zhang et al., 2010).

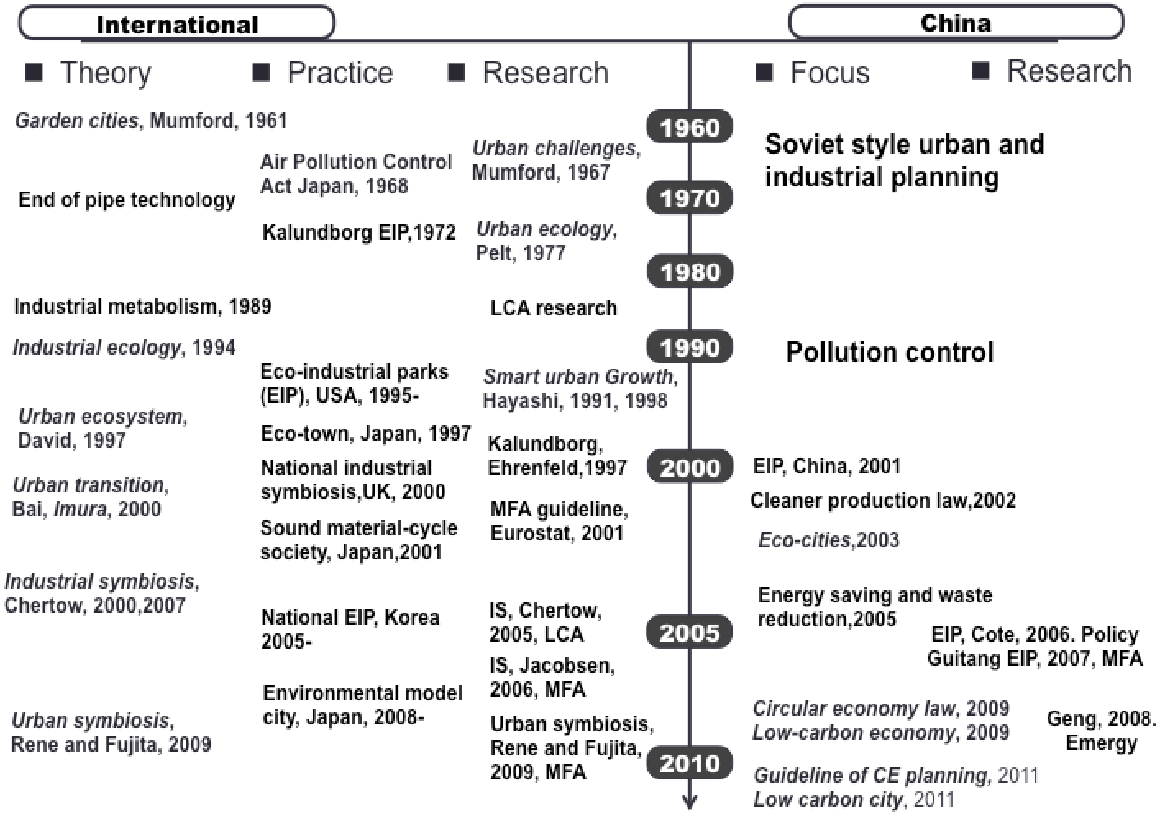

Figure 2-4 Development of industrial symbiosis theory and related practice

Significant environmental and business benefit was gained through IS, through saving the virgin materials, mitigating waste generation and reducing the costs by using wastes and by-products, as well as the cascading use of energy and water, and infrastructure share. A numerous case studies had verified the benefits of IS: the most famous one: Kalundborg, Denmark (Jacobsen, 2006), The eco-industrial parks and the industrial complex in Puerto Rico, USA (Chertow and Lombardi, 2005); “eco-town project” in Japan; National industrial symbiosis project in United Kingdom (Costa et al., 2010; Mirata, 2004), Kwinana and Gladstone, Australia (van Beers et al., 2007), and “circular economy pilot”, China (Zhang et al., 2010). Particularly, the promotion of IS could significantly reduce the carbon emissions at industrial cluster level (Hashimoto et al., 2010; Van Berkel, 2010) and city level (Geng et al., 2010; Jacobsen, 2006).

On the whole, after decades’ development, the number of case study on IS has been increasing since 2005, mainly in developed countries (Ehrenfeld,1997; Jacobsen, 2006; Chertow, 2005; Rene and Fujita, 2009). There is a trend with more quantified case studies than descriptive studies. However, for developing countries like China, case studies are still rather few and mainly semi-quantified (Zhu, et al., 2007; Shi, et al., 2010).

In the past decade, the “industrial symbiosis” had pasted its way from the concept evolution, definition formation, national practice, to the specific local practice. With technology and mind change, industrial symbiosis has extended to engage in more concerns of sustainability.

The emerging field includes:

- **From industrial symbiosis to urban/regional symbiosis**: The basis of IS was recycling of resource and waste. At the beginning, the spatial scale of IS was limited to industrial cluster, the main activities were the resource exchange among clustered factories. Based on the industrial symbiosis, urban and regional symbiosis was proposed and developed, to optimize the resource management in a larger spatial scale. Such idea was extremely beneficial to the harmonious relationship between industries and urban.
- **Emerging IS activities like the heat exchange**: Traditional IS focused on the bulky waste recycling and material exchange, like the slag utilization between iron/steel and cement company, gypsum recycling and utilization between power plant and cement company, and so on. With the technology advancement and requires of increasing environmental concerns, more types of waste could be utilized, especially the energy, corresponding to the concerns on climate change. Compared with solid waste, waste heat is much more difficult to utilize due to its instability and high cost on the pipeline construction. As a result, the more efficient utilization of waste heat needs more advanced technologies, smarter symbiosis design and supporting policy on the infrastructure.

2.1.3 Eco-industrial park

The other concept highly related to the industrial ecology and industrial symbiosis is "eco-industrial park (EIP)". It could be seen as the real practice of 'industrial symbiosis' in the estate format (Côté and Cohen-Rosenthal, 1998; Gibbs and Deutz, 2005). The so-called "eco-industrial park (EIP)", is defined as an industrial park, in which, the companies cooperate with each other and with the nearby urban areas, in an attempt to save virgin material, reduce generation of waste and pollution, and reduce cost through infrastructure sharing. It is a solution to increase the economic gains and improve the environmental quality (Côté and Cohen-Rosenthal, 1998; Oh et al., 2005). Industrial symbiosis and Eco-industrial parks had been undertaking globally. Up to 2013, May, 167 cases had been reported[5]. Best EIPs practices were in EU, USA, Japan, South Korea, as well as emerging economy like China. The supporting mechanisms included self-organized and national initiatives.

The purpose of this research is not to make in-depth analysis to distinguish the concept of industrial ecology, cleaner production, industrial symbiosis and EIP. We would use the word industrial symbiosis at the most condition, on behalf of the thinking of industrial system design and the construction of industrial and urban system.

2.2 Review on methodologies in the field of industrial ecology

After more than two decades' development, industrial ecology has gradually formed its basic methodologies. The mainstream approaches include material/substance flow analysis, life cycle

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[5] Source: www.ecoindustry.org

assessment and input-output analysis. They are powerful tools to analyze and assess the social and industrial system. In addition, some other mathematical and economic tools could also contribute to industrial ecology, e.g. cost-benefit assessment could effectively evaluate the IS project. This section conducts a comprehensive review on these methodologies, so as to pave a basis for further model integration and case study.

2.2.1Review on Material flow analysis (MFA)

One key objective of industrial ecology is to optimize the flows in the network so as to enhance the material efficiency and reduce the environmental impacts. Therefore, material flow analysis (MFA) is one of the most basic and mature tools in industrial metabolism analysis and industrial ecology (Cleveland and Ruth, 1998; R. Ayres and L. Ayres, 1996).

MFA is a method to analyze material flows, i.e. chemical elements, compounds, materials or commodities in a whole system (R.Ayres and L.Ayres, 1996). It bases on material balancing representing the law of material conservation and provides insights into the industrial system. The main contribution of MFA to industrial symbiosis is that: it provides standard tool and indicators to trace the flows (material, energy and water) in the system, so as to serve to the diagnosis of environmental problems, to support planning of improvement, and to control results of management measures (Brunner et al., 1994; Eurostat, 2001).

MFA could be applied on several spatial scales (Brunner and Rechberger, 2004), including national entities (Hashimoto and Moriguchi, 2004; Hoffrén et al., 2000), regional or local level (Brunner et al., 1994), urban systems (Barles, 2009; Broto et al., 2012) and industrial areas (Sendra et al., 2007). Most widely applied is economy-wide material flow analysis, and it already become standard approach for national accounts, with the help of the promotion by Eurostat (Eurostat, 2001, 2007, 2009). *Figure 2-5* and *Table 2-1* shows the standard framework and derived indicators.

After decades of development and standardization, the general trend of MFA development is narrowing down the scale, as well as integrated with other tool, like the input-output model, life cycle assessment, to trace consumption side flows and emissions or footprints (Schaffartzik et al., 2014). EW-MFA had become standard tool to quantify national material accounts, lots of countries and regions had published their MFA results, like EU countries (Hoffrén et al., 2000), Japan (Moriguchi, 2001), US (WRI, 2008), China (Wang et al., 2012a; Xu and Zhang, 2007) and so on. Particular, Eurostat published methodological guideline for the EW-MFA and established database (Eurostat, 2001, 2007, 2009). City level MFA become popular and there are several studies applied MFA approach to quantify the IS benefit in industrial clusters (Berkel et al., 2009; Schmidt, 2010). Due to the data availability of certain materials or product flows at regional level, studies at the regional and industrial park levels are still limited compared with national studies and few standard method has yet to be developed (Sendra et al., 2007).

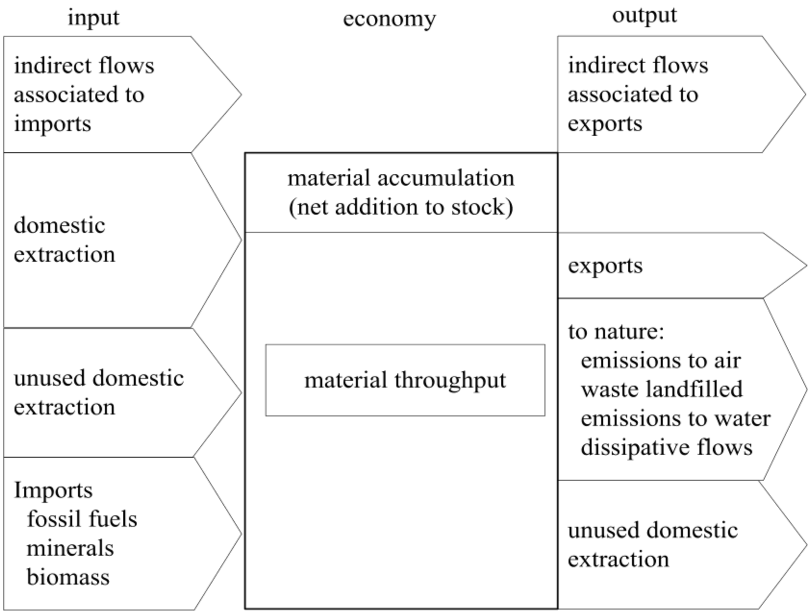


Figure 2-5 Framework of Economy-Wide MFA

Source: (Eurostat, 2001).

Table 2-1 Key indicators of MFA

Indicators	*Definition*	*Expression*
DMI (10^4 t)	Direct material input	Domestic Extraction (DE) plus imports from other systems
TMR(10^4 t)	Total material requirement	DMI and hidden flows and plus unused materials
DPO(10^4 t)	Domestic processed output	Waste and emissions to the eco-environment
Inputs intensity (t/capita)	Direct material input per capita	DMI per capita
Emission intensity(t/capita)	Wastes & emissions per capita	DPO per capita
Resource output efficiency(10^4CNY/t)	Economic output per unit of resource consumption	GDP per unit of DMI

Former quantitative studies on the assessment of IS mainly based on the quantification of material exchange in the IS (Berkel et al., 2009; Chertow and Lombardi, 2005; Jacobsen, 2006) and life cycle assessment (Eckelman and Chertow, 2009; Hashimoto et al., 2010; Mattila et al., 2010). For the former, it was a comparison of the principal material and/or energy flows in the symbiotic scenario compared to the standalone operation of each company. Exclusion of resource use and environmental impact that occurred as trade-off from the IS caused limitation. Such limitation could be improved by life cycle assessment, but the data is much more difficult to gain. From this point, found a proper integration is important.

In addition, one focus of this research is heavy industries like iron/steel industry and the industrial cluster. As an integration of MFA approach in factor level and industrial cluster level, a new realm as the material and energy flow analysis (MEFA)(Haberl et al., 2004) could effectively the process material account and the potential of heat recovery and carbon emission mitigation in individual steelmaking plant (*Figure 2-6*), to resolve the coupled complexity of material and energy flows when it is measured in enterprise level. In iron/steel processing, substance property and material flow was coordinated in terms of time, temperature and spaces (Siitonen et al., 2010). Iron and carbon flows are the main forms of material flow and energy flow. The changes in the system like the technology innovation or energy supply structure adjustment could be reflected through the changes of the material flows. And the material flows would further affect the energy flows. From this perspective, an energy flow analysis combined with the material flow analysis was necessary and effective and a hybrid material/energy flow analysis (MEFA) attracted international research interests (Schiller, 2009; Suh, 2005) Most studies focused on macro level, such as (Herva et al., 2012; Schiller, 2009). Some research also conducted in technology level (Rodr ǵuez et al., 2011) and factory level (Teresa Torres et al., 2008). However, on the whole, the research on the iron/steel industry was relative few, especially for the factory level. (Michaelis and Jackson, 2000) applied the MEFA for historical analysis on UK's iron and steel industry. But the research was not suitable to apply in company level. Hu (Hu et al., 2010) integrated the material flow analysis method to analyze the energy flow of iron and steel plant in China. But no energy saving and residual heat recovery potential was quantified.

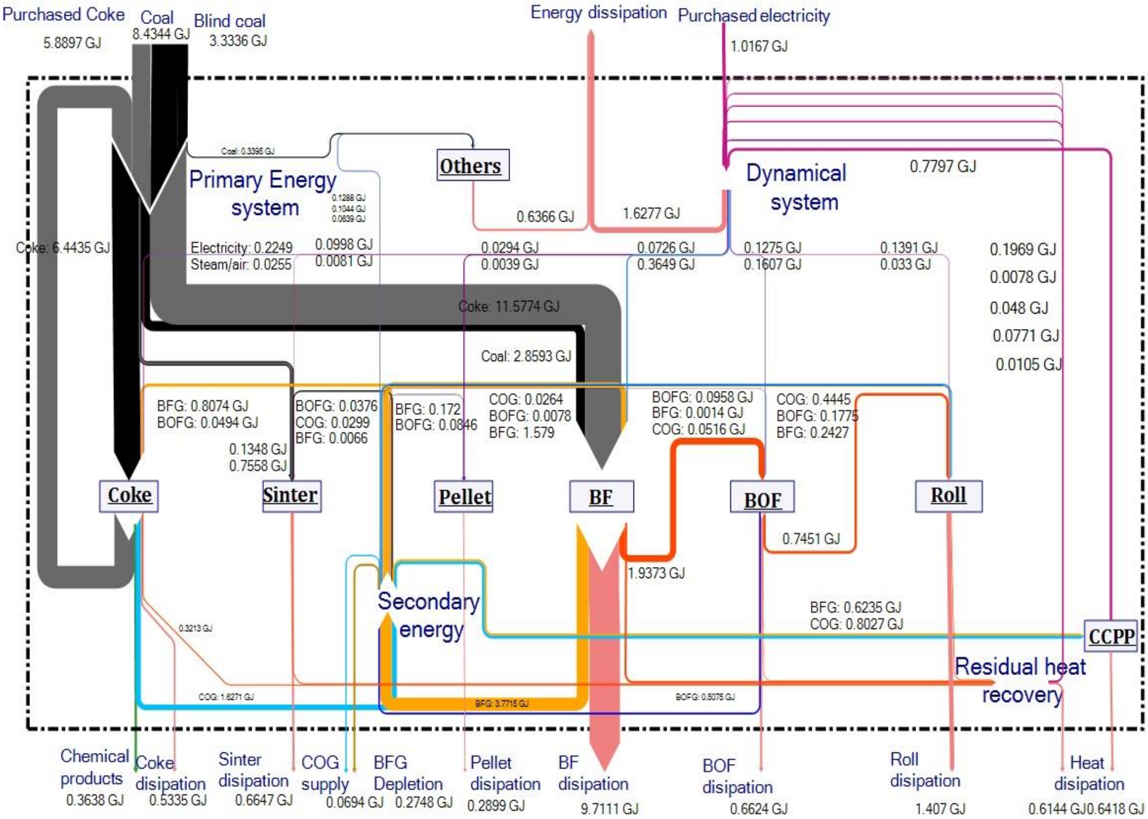


Figure 2-6 Energy flow chart in a typical iron/steel factory by MEFA.

Source: author's paper: (Zhang et al., 2013a)

2.2.2 Review on Life cycle assessment (LCA)

The other typical IE tool is Life Cycle Assessment (LCA). LCA is a systematical analytical tool to evaluate on the environmental impacts of product, and/or service system, focusing on all its life cycle stages, which is from resource mining to the end of life (Geng et al., 2010; Soratana and Landis, 2011). The general concept of Life cycle assessment is shown in *Figure 2-7*. LCA could provide an adequate instrument for environmental decision support.

LCA was widely applied as important method for evaluating environmental impacts of certain waste management (Laurent et al., 2014a; Laurent et al., 2014b). Detail literatures included: LCA researches on the environmental impacts of certain waste treatment and recycling, like the waste food recycling (Cellura et al., 2012), waste glass recycling (Blengini et al., 2012) , waste papers recycling (Liang et al., 2012; Wang et al., 2012b), PET bottles recycling (Song and Hyun, 1999) and waste to energy approaches (Tunesi, 2011; Vázquez-Rowe et al., 2014). LCA was applied to evaluate the potential impacts of different waste treatments and disposal approaches (Cherubini et al., 2009; Liang et al., 2012). LCA was also applied on the evaluation on the implementation of certain treatment method or certain facility on different spatial scales (Cherubini et al., 2009; Khoo et al., 2010; Rigamonti et al., 2013). In most of the above studies, the LCA methodology was applied to evaluation the possible consequences of waste management strategies, through setting up series of scenarios representing various options (Abiola et al., 2010; Marvuglia et al., 2013). With the LCA analysis, the total environmental impacts like the fossil fuel consumption, CO_2 emission, as well as life cycle economic cost could be calculated. From this perspective, LCA would be very useful to set the IS scenario and make environmental evaluation, as industrial symbiosis was highly related waste management. However, to date, LCA research on industrial symbiosis had been rather few, mainly due to the research boundary and data availability (traditional process based LCA required a large volume of inventory data, which was usually unavailable in less developed countries).

Figure 2-7 Concept of Life cycle assessment

Consider this circumstance, to utilize the advantage of LCA, like setting the decision scenarios and the philosophy of life cycle impacts, and modify it to fit to certain boundary and data availability would be contributable to IS research. In this way, hybrid LCA, e.g. combined with input-output model would be a good choice (Aurangzeb et al., 2014; Meylan et al., 2014). In the case of hybrid LCA, there is much more China related cases, but most focus single waste recycling, the method is usually with combination with input-output modeling (Liang et al., 2013; Liang et al., 2012).

2.2.3 Review on Input-output analysis (IOA)

The input–output model (IO model) was mature and power tool which could effectively present the interactions between different sectors of national and regional economies, developed by Wassily Leontief (1905–1999) in 1936 (Giljum S. and Hubacek, 2009; Leontief, 1936). From the unit perspective, it could be divided into monetary input-output model, physical input-output model and hybrid one (Giljum S. and Hubacek, 2009).

Compared with traditional monetary input-output model, hybrid input-output model could be an effective tool to simulate different industrial symbiosis patterns at city level. Compared with material flow analysis, hybrid input output model has advantages in calculating the inherent relationship between material flows and economic flows, reflecting the interconnection between sectors (Liang and Zhang, 2013). Compared with life cycle assessment which focusing on technology level, input-out model fits to the analysis on meso-level, and the data is more available in China (Liang et al., 2010; Xu et al., 2008).

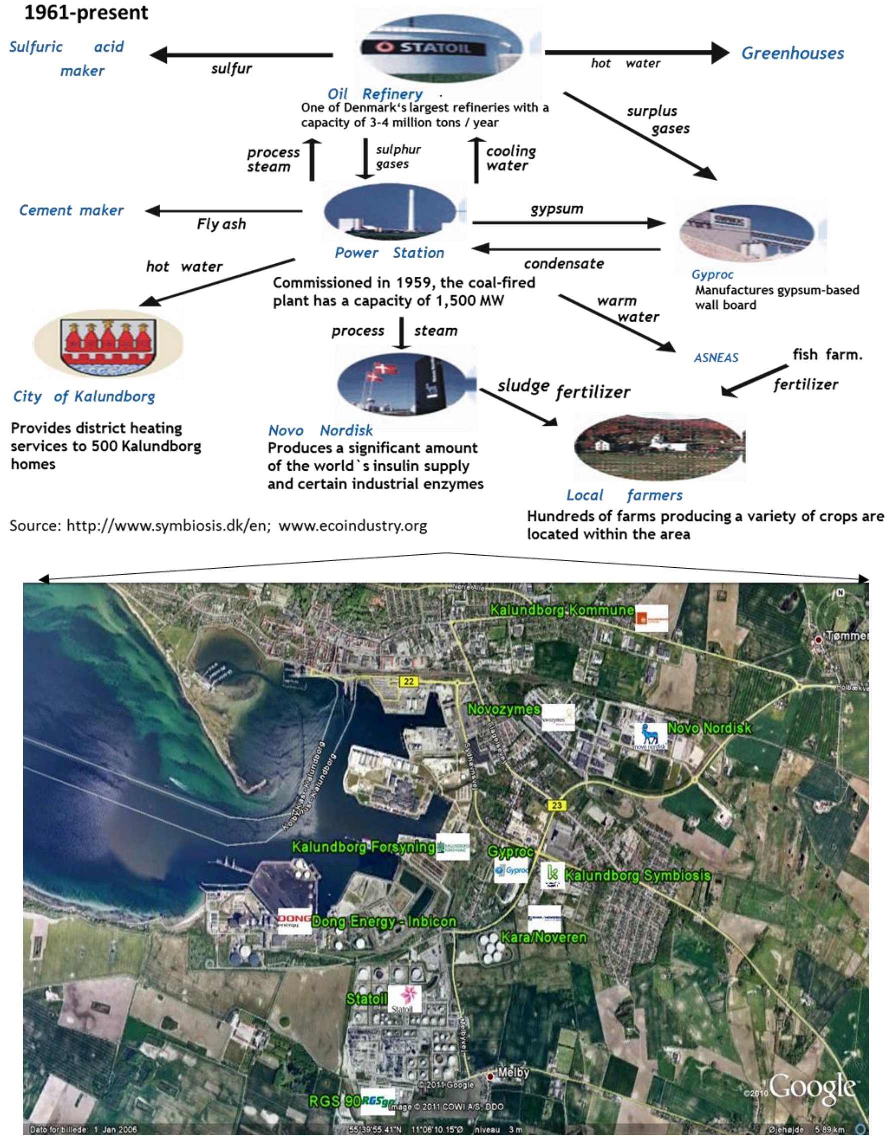
A number of previous works about using input-output model in environmental study fields (Giljum S. and Hubacek, 2009; Liang et al., 2010) had been done, but few focused on the industrial symbiosis topic. An improved hybrid physical input and monetary output model (HPIMO) to assess how industrial symbiosis and waste recycling could contribute to energy saving and pollutants mitigations, could be a contribution to analytical tool development. In such revised hybrid model, for the inputs, the energy resources were presented in standardized energetic units, the output was presented in monetary units, and air pollutants were presented in mass units. The model could quantitatively represent the correlations between economic sectors by monetary input output table (MIOTs), presenting the interactions between the environmental and the economic system(Liang and Zhang, 2013). In this way, how the performance of the system, in terms of environmental and economical, could be simulated and interpreted by changing those parameters according to the scenarios settings.

2.3 International industrial symbiosis practice

Typical International practices in IS were reviewed in detail, so as to enlighten the planning of IS in this research.

(1) Kalundburg, Denmark

Kalundburg is the most famous IS practice in the world. *Figure 2-8* shows its symbiosis network and the map. Kalundburg locates the northwest coast of Zealand, little more than 100km from Copenhagen. It has 16500 residents. The most well-known example of Industrial Symbiosis is here. In the IS network, intensive collaboration between companies and between industries and urban areas, are presented: in terms of solid waste exchange, examples include fly ash and desulfurization gypsum from power station could be used by cement company and construction material companies (to produce board). Sludge from the pharmaceutical company could be utilized to produce fertilizer. Particular, energy source is exchanged: Excess steam from the power plants is supplied to the refinery company and the pharmaceutical company. Hot and warm water is supplied to urban residents and farm (Domenech and Davies, 2011; Jacobsen, 2006).



Source: http://www.symbiosis.dk/en; www.ecoindustry.org

Figure 2-8 The industrial symbiosis practice in Kalundburg, Denmark

Source: https://maps.google.com.hk

(2) Emerging IS focusing on energy symbiosis

Apart from some traditional industrial symbiosis, due to energy and climate change concerns, energy related symbiotic activity is very important. Growing energy costs and enormous waste heat loss support recovery of waste heat as a promising and cost effective option to reduce worldwide industrial energy consumption (IEA, 2010). Waste recovery and reuse also provide financial savings, help reduce of CO_2 and NO_x emissions, and aid innovation through quality improvement of processes and products. Besides one company's internal improvement of excess heat recovery, IS provides waste heat exchange between companies. In academia, practices of IS for heat or energy were reported for the existing synergy, and estimated environmental and economic benefits (Park et al., 2008a).

Several successful energy symbiosis practices are conducted in Europe and Korea, focusing on the industrial complex and industry-district heating system (detail as below). In addition, there have been several studies of industry-district heat network (Finney et al., 2012; Kapil et al., 2012). But on the whole, energy symbiosis is an emerging field with few published reports, and deserves attention. Several world-class practices including:

- **In Kalundborg, Denmark**. As introduced, it is the most famous example of IS. With development, some new symbiosis has been developed. Shown as *Figure 2-9*, excess steam from the power plants is supplied to the refinery company and the pharmaceutical company. Hot and warm water is supplied to urban residents and farm (Jacobsen, 2006). In this way, it contributes a lot on the fossil fuel saving and carbon mitigation.

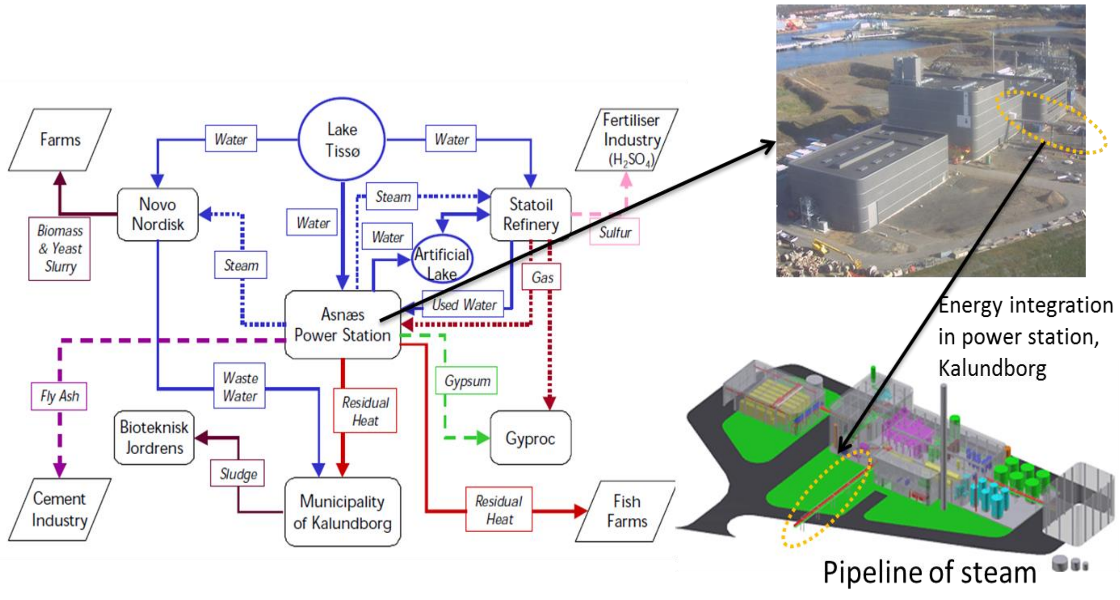


Figure 2-9 Heat supply network in Kalundburg

Source: revised by the author based on the information of official website of Kalundburg: www.symbiosis.dk/en

- **Excess heat utilization in Sweden**: the industrial excess heat utilization in District Heating (DH) networks is developed to reduce the consumption on primary energy and mitigate the CO_2 emissions accordingly. In the project, to help mediate the stakeholders, a third party access (simplified as TPA) proposal to deliver excess heat from industry to DH grids is under consideration (Broberg et al., 2012). Through a top-down investigation, it is estimated that the potential industrial excess heat production in Sweden is as high as 9 TWh/year (Cronholm et al., 2009). The result highlights a high potential of waste heat utilization.
- **Waste heat and steam exchange in industrial clusters in Korea**: a waste heat utilization network exists in several national eco-industrial park programs, like the Ulsan and Yeosu National Industrial Complexes, where the steam and waste heat is exchanged among refineries, power plants, and petro-chemical companies. Particularly, there is a pioneer project to exchange the CO_2 and steam between zinc factory and a paper and pulp factory (*Figure 2-10*). Both material and energy symbiosis is realized: steam from the zinc factory to the paper and pulp mill could utilized as energy source for the manufacturing process, while the CO_2 from the zinc factory could be utilized as material for the alkalized process in the paper and pulp making procedure. In this way, double mitigation on CO_2 is realized: (1) direct CO_2 mitigation through directly utilizing it; (2) second mitigation though utilizing the waste heat to reduce fossil fuels consumption (Park and Behera, 2014; Park et al., 2008b).

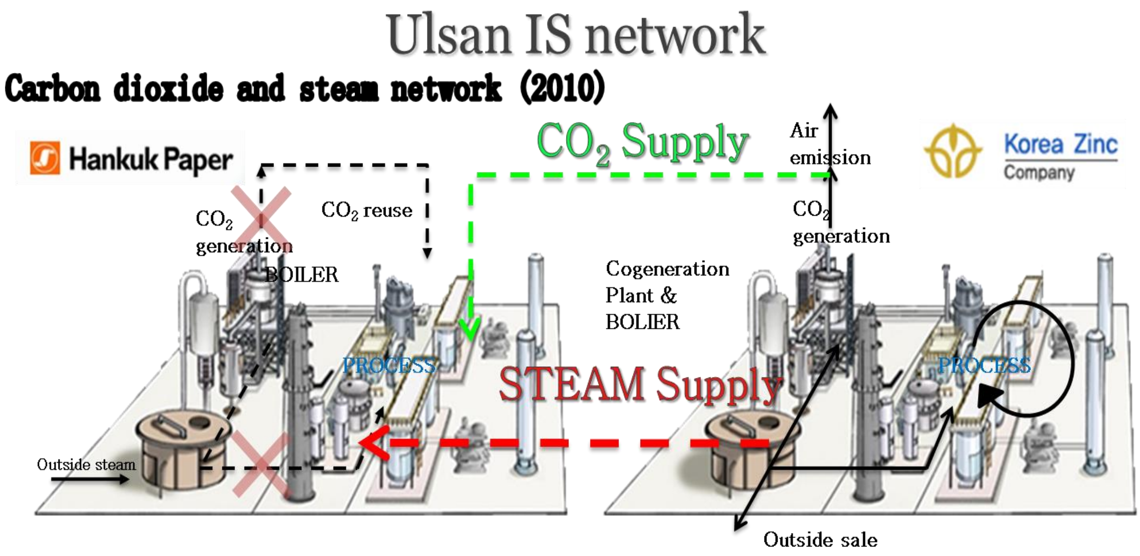


Figure 2-10 Heat utilization in Ulsan, Korea

Source: Professor Marian Chertow, Yale University. Presentation - US Business Council for Sustainable Development. July 17, 2013.

- **The symbiosis between agriculture and households**: apart from the waste heat exchange between factories and between industries and residential areas, several emerging practices of integration of industry and agriculture for heat exchange are reported. (Andrews and Pearce, 2011) presents an advanced case to waste heat exchange between a flat glass manufacturing plant and a nearby tomato greenhouse. Results highlights that the waste heat system is significantly more economical to operate than purely using the natural gas. With heat exchange, both environmental and economic gains are achieved. A similar case is reported in a Carbon Capture and Sequestration (CCS) project in Rotterdam, Netherlands, shown as *Figure 2-11*, where there is 300,000 tons/year of organic CO_2 from a petroleum company supplied to a nearby greenhouse. According to the calculation, the project can save 95 million cubic meters of natural gas and reduce CO_2 emissions by 170,000 tons every year (Rotterdam-Climate-Initiative, 2011). What is more, the products in the greenhouse are with high market value.

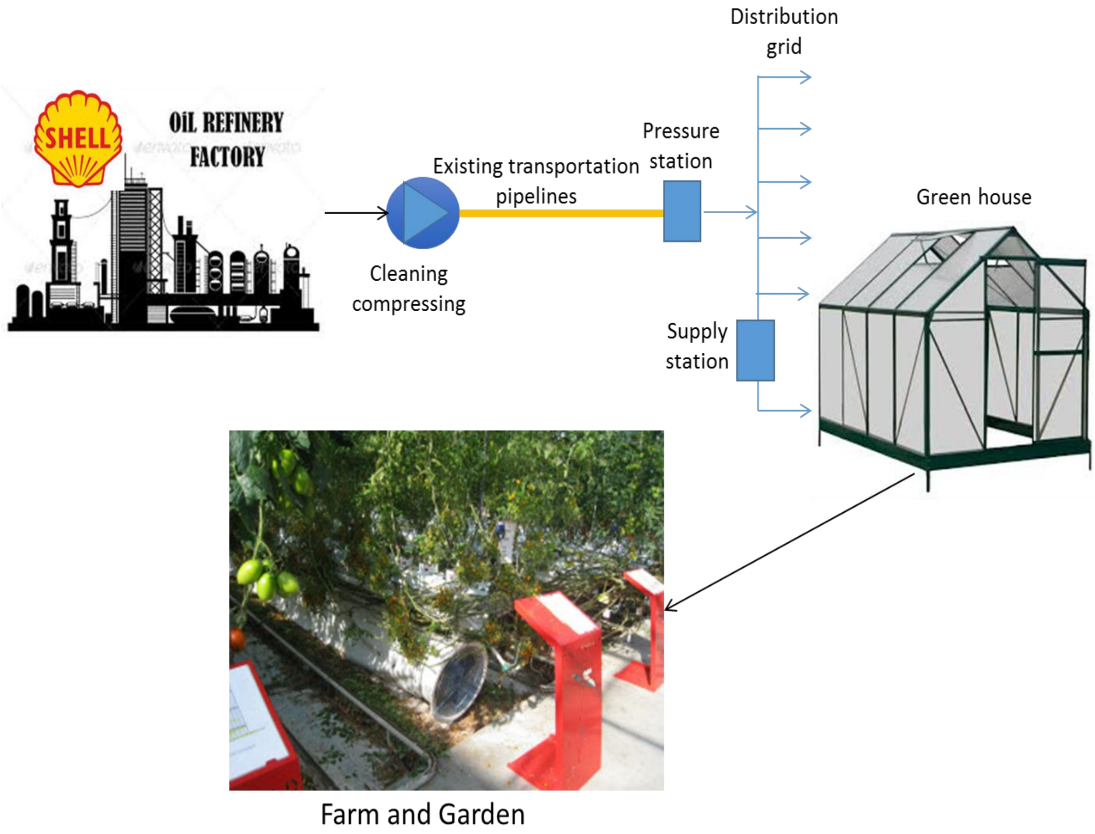


Figure 2-11 Heat to farm and CCS project in Rotterdam, Netherlands

Source: Rotterdam-Climate-Initiative, 2011

2.4 Summary

This chapter reviewed the development of the theory, practice and analytical methodologies of industrial symbiosis. On the whole, industrial symbiosis was still an emerging research field. In the field of project practice, developed countries had promoted a series of successful projects, and the application of IS had brought both environmental and economic benefits to them. However, in developing countries, there was still a lot of room to enhance the promotion of IS. In the field of analytical methodologies, MFA, LCA and input-output had become mature tools, however, to extend their application in micro level and developing countries which lacked data, modification and integration was needed. Conducting case studies in developing countries was necessary to verify the effects of IS, so as to provide useful information for the decision making process.

Based on the above reviews, the originalities of this research were summarized in three aspects:

- Data survey: first hand symbiosis projects in local cities of China was surveyed and database was constructed. It would contribute to the current statement of IS data scarcity in China.
- Analytical methodology development with model integration: hybrid LCA was established integrating process based LCA and environmental input-output model, to quantify the life cycle impacts of IS. Scenario up to 2015 was designed and evaluated to support local future policy making. This would supplement the statement of lack quantified case study and scenario analysis on IS in China.
- Finally, in policy implementation aspect, no research discussed to use IS to improve regional industrial layout and support urban development; Thus this research contributed to the IS policy implementation through innovative discussion on utilize IS to coordinate industry and urban, and used IS to improve regional industrial layout.

3.Industrial symbiosis comparison in China and Japan

This chapter conducts reviews on China's promotion on industrial symbiosis; then compares with the eco-town project in Japan, to summarize the advanced experience of Japan and future concerns on the industrial symbiosis promotion in China.

3.1 Review on industrial symbiosis practice in China

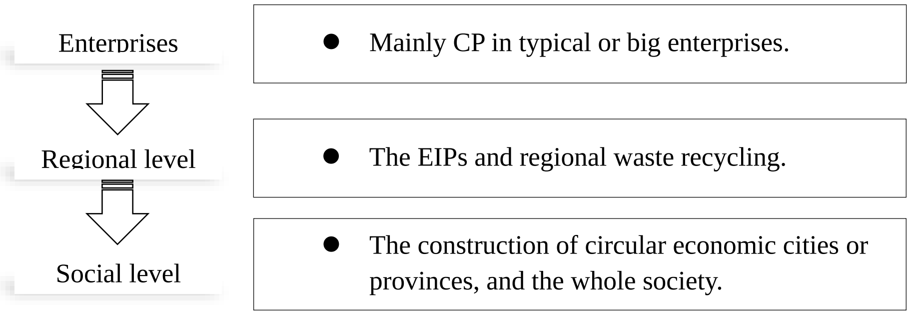
In China, the strategy of industrial symbiosis has been implemented in the form of national policy of "circular economy". Thus this section would make a review from the perspective of circular economy promotion in China.

3.1.1 Overview

The concept of a circular economy (CE) has been first raised by the British environmental economists Pearce and Turner in their book "Economics of Natural Resources and the Environment"(Pearce and Turner, 1990). In this book, they emphasized that the traditional linear economy was developed with no consideration on recycle, which only treated the environment as a waste reservoir (Geng et al., 2009; OECD, 2009). The starting point of CE's implementation was in Germany (in 1996, enacted the "Closed Substance Cycle and Waste Management Act") and then, in Japan (in 2002, enacted the "The Basic Law for Establishing a Recycling-Based Society").

In 1999, the concept of CE was introduced into China, and since 2000, China began to promote the CE strategy under the charge of National Development and Reform Commission (NDRC) and State Environmental Protection Agency (SEPA, later it became MEP, Ministry of Environmental Protection). Especially, since 2005, CE has been promoted in national wide. Up to 2010, 27 pilots cities and provinces were nominated by NDRC, 36 national pilots EIP was nominated by MEP (Dong, 2011). After 2010, CE promotion in China had gone into a new stage, from a macro level into constructing the Chinese CE model. In 2010, NDRC released the "Guideline for CE planning" (Zhang et al., 2010).

CE is promoted in three levels in China (*Figure 3-1*), including cleaner production (CP) in enterprise level, industrial substance reuse and recycling and EIP in regional level, and creating a recycling oriented society in social level.



- Mainly CP in typical or big enterprises.
- The EIPs and regional waste recycling.
- The construction of circular economic cities or provinces, and the whole society.

Figure 3-1 Three levels of circular economy promotion in China

In the promotion of circular economy, EIP is a main format.

- **CE**: focus on “reduce, reuse and recycle” of resource, and harmonious relationship between economic system and environmental system. A little different from the “3R” in Germany and Japan, in China, as the economic development is important, thus the national policy maker want to integrate the “3R” into their economic development model. Therefore, the scope of CE in China is not only focus on environmental protection, but also economic development.
- **EIP**: in China’s governmental documents, "eco-industrial park" is defined as a new type of industrial estate that is built upon the principles of cleaner production, circular economy and industrial ecology. An eco-industrial park pursues closed-loops of materials, energy cascading, and minimization of wastes by interconnecting different enterprises through material and energy flows, establishing resource sharing and symbiotic exchange of by-products, so that the wastes or byproducts of one company can become the raw materials and energy supply of another company, and forming the recycling networks of "producers-consumers-decomposers" in industrial ecosystems. In China, the EIPs are mainly transformed or planned from two types: “industrial parks” and “economic/technology (or high-tech) developing zones”.

A little different from other countries, EIP is promoted in two different forms in China. **One is chiefly charged by NDRC, belong to the one part of National Pilot Circular Economy Zone Program” (NPCEZP); the other is chiefly supported by MEP, named “National Pilot EIP program” (NPEIPP).** Their relationship is summarized in *Figure 3-2*.

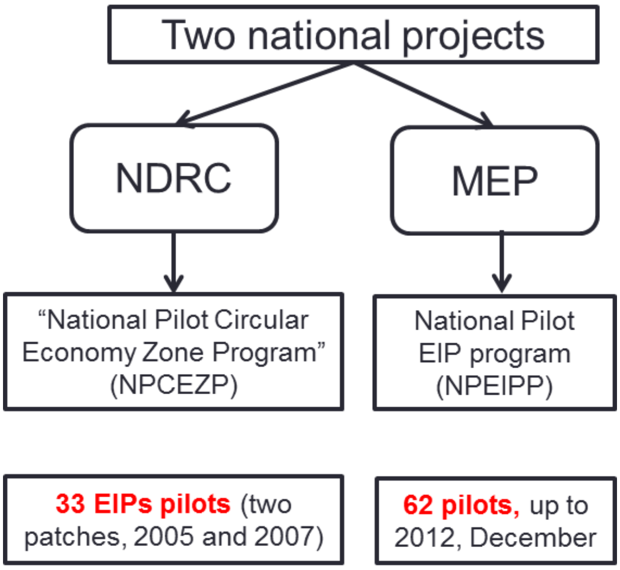


Figure 3-2 China’s eco-industrial park program

3.1.2 National pilot CE zone program (NPCEZP)

To promote the CE strategy, the government released the “National Pilot Circular Economy Zone Program” (NPCEZP) since 2001. The so-called “CE zone” included different geographical levels, like companies in key industry, parks, cities and provinces.

NPCEZP was firstly charged by State Environmental Protection Agency (now it becomes MEP, Ministry of Environmental Protection). In 2004, the National Development and Reform Commission (NDRC) was appointed by the State Council to take charge of promoting CE. In 2005 and 2007, two lists of NPCEZP are released by NDRC.

(1) Organization and management

Six governmental sections had taken part in the NPCEZP. NPCEZP is chiefly run by NDRC, with the cooperation of MEP, Ministry of Science and Technology (MOST), Ministry of Finance (MOF), Ministry of Commerce (MOC), and National Bureau of Statistics (NBS). The reason that why MOST and MOC attend was that in China, the NPCEZP included the “Economic and technology developing zones” and the “High tech developing zones” (OECD, 2009; Su et al., 2013). The pilot list was released by the NDRC, and the management was made by a leading group consist of the above six agencies.

(2) Number and type of Pilots

Two pilots’ lists were released in 2005 and 2007. *Table 3-1* summarized all the types and numbers of the pilots. In the two lists, there were 33 EIP pilots (including industrial parks and economic/technology developing zones).

3.1.3 National pilot EIP program (NPEIPP)

(1) Organization and management

NPEIPP began from 2000 and was chiefly charged by SEPA (In 2008, SEPA became MEP), with the cooperation of the MOST and MOC. The reason for the inclusion of MOST and MOC was described as above, some EIP in China was transformed from High-tech Development Zones and Economic and Technology Development Zones, which were the primary forms taken by Chinese industrial parks(Shi, 2010; Zhang et al., 2010). The important policies were summarized in *Figure 3-3*.

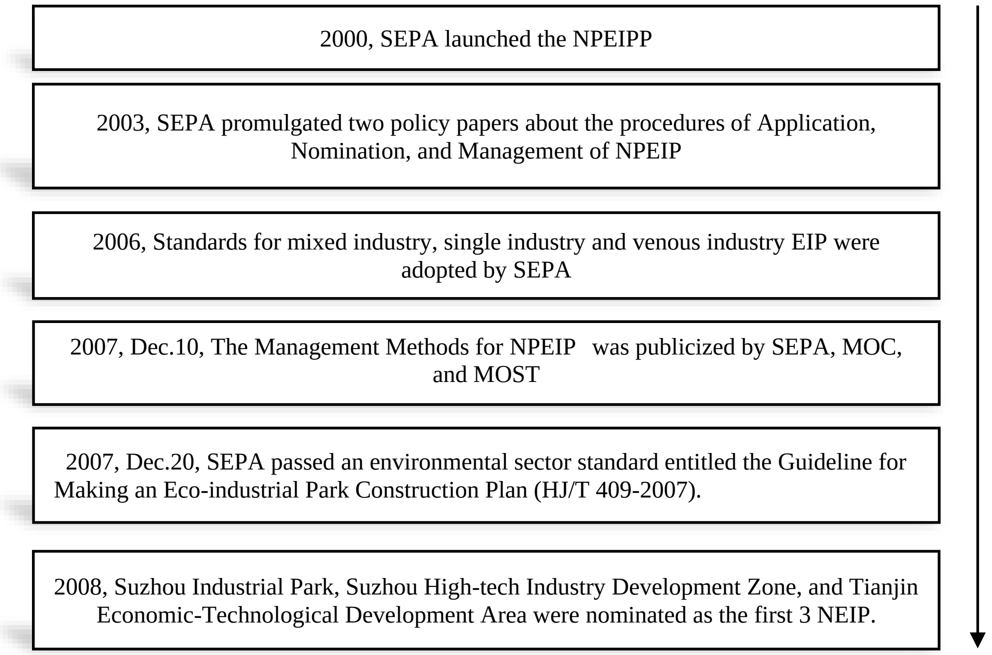
The development of NPEIPP included three stages: First of all, began the eco-industrial park planning, then, implemented the EIP and finally, conducted the assessment and nomination procedure, passing them to become a NEIP.

In the current practices, the first planning stage aimed to take for two or three years for the parks, which had already undertaken series of eco-industrial development practice and obtained an environmental management certification (e.g. ISO 14001) for the entire industrial park. The second stage EIP implementation aimed to last for four to six years.

Table 3-1 Two batches of NPCEZP lists

The first batch, 2005		**The second batch, 2007**	
Key industry	**Number of company**	**Key industry**	**Number of company**
Iron/steel	5	Iron/steel	5
Non-ferrous	8	Non-ferrous	5
Coal	5	Coal	6
Power generation	3	Power generation	2
Chemicals	12	Chemicals	5
Construction material	3	Construction material	2
Light industry (textile, paper, etc)	6	Light industry	17
Key field	**Number of parks or company**	**Key field**	**Number of parks or company**
Resource reuse/recycle	6	Resource reuse/recycle	8
Metal reuse/recycle	6	Metal reuse/recycle	3
Waste electronics /tires/ battery /package reuse/recycle	5	Waste electronics/tires/ battery /package reuse/recycle	6
Parks	**Number**	**Parks**	**Number**
Industrial park	7	Industrial park	13
Economic/technology developing zone	6	Economic/technology developing zone	7
City/province	**Number**	**City/province**	**Number**
City	7	City	13
Province	3	Province	4
Total	**82**	**Total**	**96**

Source: China Circular Economy Statistical Yearbook.



2000, SEPA launched the NPEIPP

2003, SEPA promulgated two policy papers about the procedures of Application, Nomination, and Management of NPEIP

2006, Standards for mixed industry, single industry and venous industry EIP were adopted by SEPA

2007, Dec.10, The Management Methods for NPEIP was publicized by SEPA, MOC, and MOST

2007, Dec.20, SEPA passed an environmental sector standard entitled the Guideline for Making an Eco-industrial Park Construction Plan (HJ/T 409-2007).

2008, Suzhou Industrial Park, Suzhou High-tech Industry Development Zone, and Tianjin Economic-Technological Development Area were nominated as the first 3 NEIP.

Figure 3-3 Milestone policies for NPEIPP

(2) Number and type of Pilots

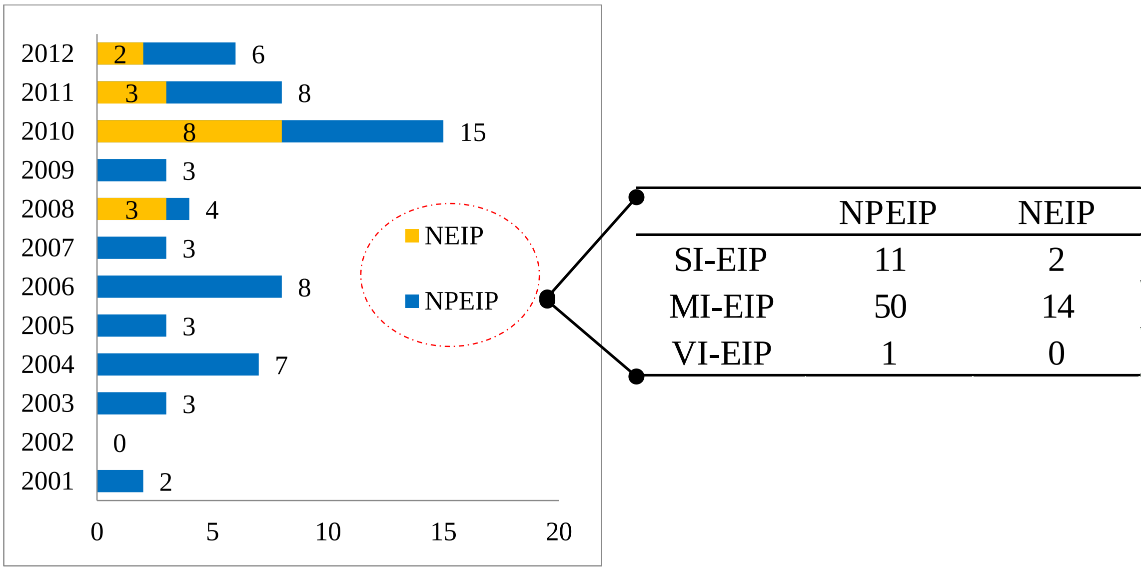
Different from the NPCEZP, in the NPEIPP, there are three types of EIPs.

- **Single industry EIP**: The clustered companies belong to one main industry, such the iron/steel EIP, coal industry EIP, and so on.
- **Mixed industry EIP**: The clustered companies belong to different industries. This type of EIP is mainly transformed from the "Economic and Technology development zones" and the "High-tech development zones", like Dalian Economic and Technology development zones and so on.
- **Venous industry EIP**: focus on venous industry.

Since the first NPEIP was approved in 2001, up to 2012, December, 62 NPEIPs had been approved by MEP, of which, 16 past the assessment and officially nominated as NEIP. Shown as *Figure 3-4*, much members of the NPEIPP were mixed industry EIP. Only one was venous industry EIP, which located in Qingdao, Shandong province.

As to the single industry EIP, it included one iron/steel EIP, one sugar industry EIP, one aluminum industry EIP, one coal mining industry EIP, and several chemical industry EIPs. It was noted that although in the EIP projects, there were two national projects, 12 EIPs belonged to both of the lists.

Finally, based on the review on the CE and EIP pilot projects in China, we could conclude that more than half of the pilots were in key industries. It demonstrated that in current statement, CE promotion in China still focused on the cleaner production in enterprises of key industries, and primary symbiosis among industrial cluster.



	NPEIP	NEIP
SI-EIP	11	2
MI-EIP	50	14
VI-EIP	1	0

Figure 3-4 Number of EIP pilots

Note: SI-single industry; MI-mixed industry; VI-venous industry

Source: http://kjs.mep.gov.cn/stgysfyq/m/201302/t20130222_248379.htm, in Chinese. The author collected and analyzed the data.

3.2 Industrial symbiosis promotion in Japan

With similar heavy industries, and developed social system, Japan provides a good example for comparison and learning.

In Japan, the most important industrial symbiosis practice is the Eco-Town Project. The “Eco-Town” Project in Japan was promoted by the collaboration of several ministries: the ministry focusing on economic development: Ministry of Industrial Trade and Industry (simplified as MITI. It later changed into the Ministry of Economy, Trade, and Industry in year 2001, simplified as METI), and the ministry in charge of environmental issues: Ministry of Environment in Japan (MOE), in the year of 1997. The overall target of the eco-town project is to promote the Zero Emission Society at local and national levels, focusing on establishing new environmental cities/towns and implementing advanced resource and waste recycling related technologies (GEC, 2005; METI, 2006). The project had been promoted from 1997 to 2006, and in total, there are 26 eco-towns had been approved in national wide. *Figure 3-5* shows the locations of eco-towns.

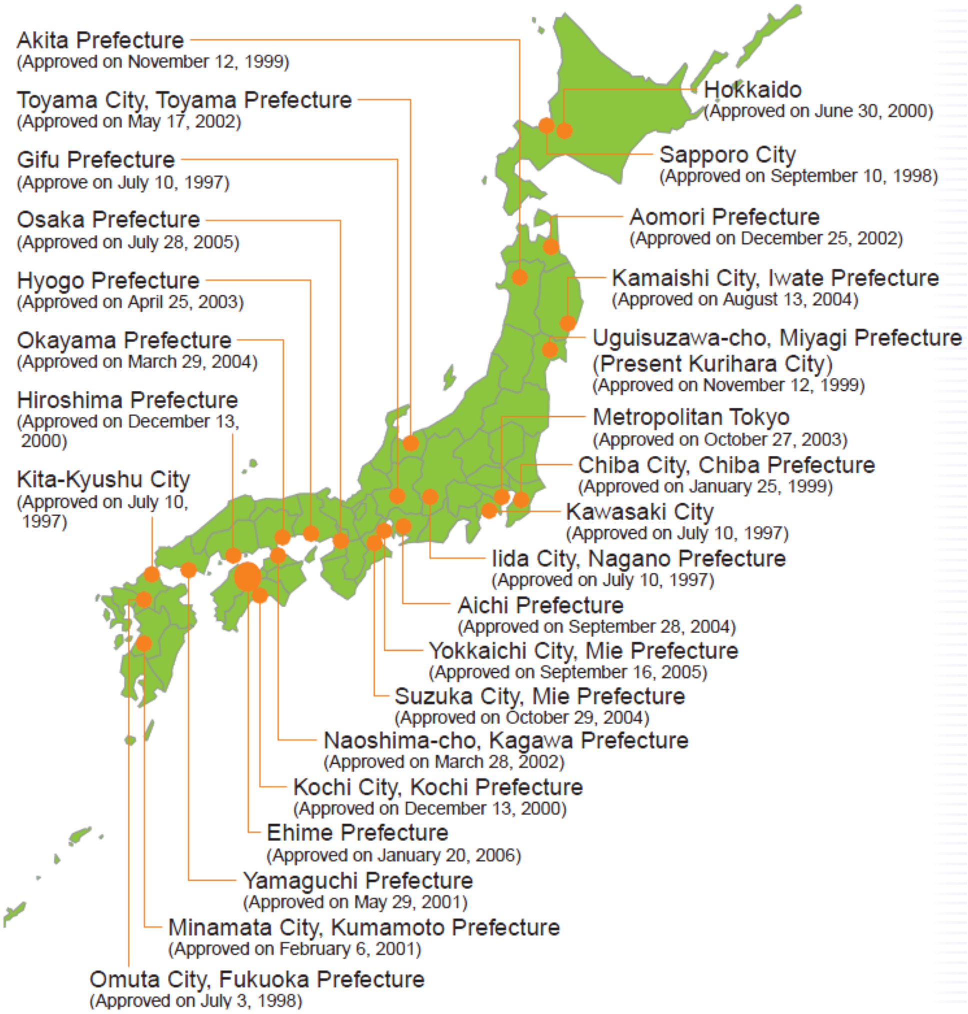


Figure 3-5 Map of approved eco-towns, up to 2006.

Source: (METI, 2006)

In the projects, several objectives were focused: (1) one purpose was to stimulate local economy through the promotion of series of emerging environmental industries (like municipal waste recycling companies) which took advantage of the industrial capabilities in each region; (2) to make system innovation, established integrated symbiosis systems involving industry, the public sector, and consumers, to realize creating a resource-recycling society in a given region (Ohnishi et al., 2012; Van Berkel et al., 2009).

As to the management mechanism, eco-town combined bottom-up and top-down procedure. METI and MOE made the collaboration, and METI provided support to mainly hardware technology such as engineering technology, and MOE provided support to software technology such as the system planning and database construction (*Figure 3-6*). Local company, and citizens actively took participate.

The features of eco-town projects include: (1) it focuses on environmental technologies promotion and integrated waste management, with the aim of utilizing environmental technologies and recycling system to enhance the eco-efficiency; (2) In the pursuit of making the industrial clusters more sustainable through the symbiosis; (3) strong legislation on waste management and recycling, shifting the market towards a sound material-cycle society; (4) Intensive subsidies on the recycling facilities from Japanese government provides financial support, so as to improve the waste recycling and environmental efficiency. In detail, approximately 1.65 billion USD was invested in 61 innovative recycling projects, with an average government subsidy of 36%; (5) through legislation and financial support, stimulate the environmental business and market (Hashimoto et al., 2010; Ohnishi et al., 2012; Van Berkel et al., 2009).

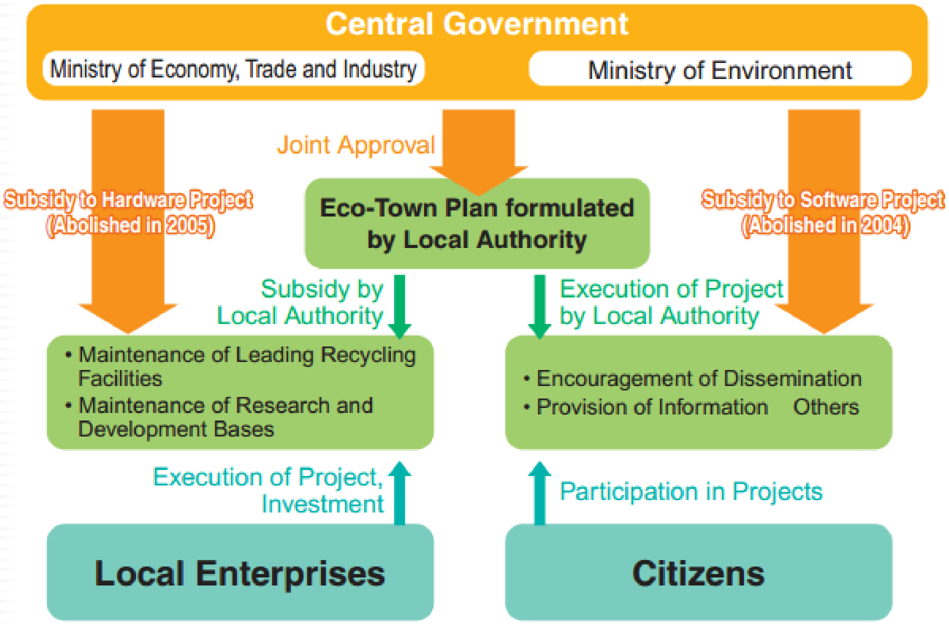


Figure 3-6 Management mechanism of eco-town project

Source: (METI, 2006)

One of the best promotions in eco-town project was waste reuse/recycling and industrial symbiosis. Promoting for 10 years, considerable environmental and economic benefit had been achieved. Among them, two eco-towns are the most famous, Kawasaki eco-town and Kitakyushu eco-town. The former focuses on heavy industries cluster and industrial symbiosis, while the latter is famous for the venous industry.

- Industrial and urban symbiosis in Kawasaki eco-town (*Figure 3-7*): The authors' group has conducted research in Kawasaki for nearly 10 years and we make a review mainly based on our previous publications(Dong et al., 2013b; Hashimoto et al., 2010; Ohnishi et al., 2012; Van Berkel et al., 2009). Industrial symbiosis in heavy industries clustered area and urban symbiosis between industrial and urban area is the merits of Kawasaki eco-town. With planning and coordination, several industrial and symbiosis activities have taken place between local industries and the city government, and the JFE Steelworks and DC Cement have driven the symbiotic developments in Kawasaki. Not only industrial waste like slag, but also urban refuse like plastics are recycled and reused in factories to reduce raw material and fossil fuels.
- Kitakyushu eco-town: industrial symbiosis is also the main theme. But a little different from Kawasaki eco-town, there are more venous industries and less heavy industries in Kitakyushu, like PET recycling companies, automobile dismantling companies and so on. Intensive recycling significantly reduces natural resources consumption and carbon emissions (*Figure 3-8*).

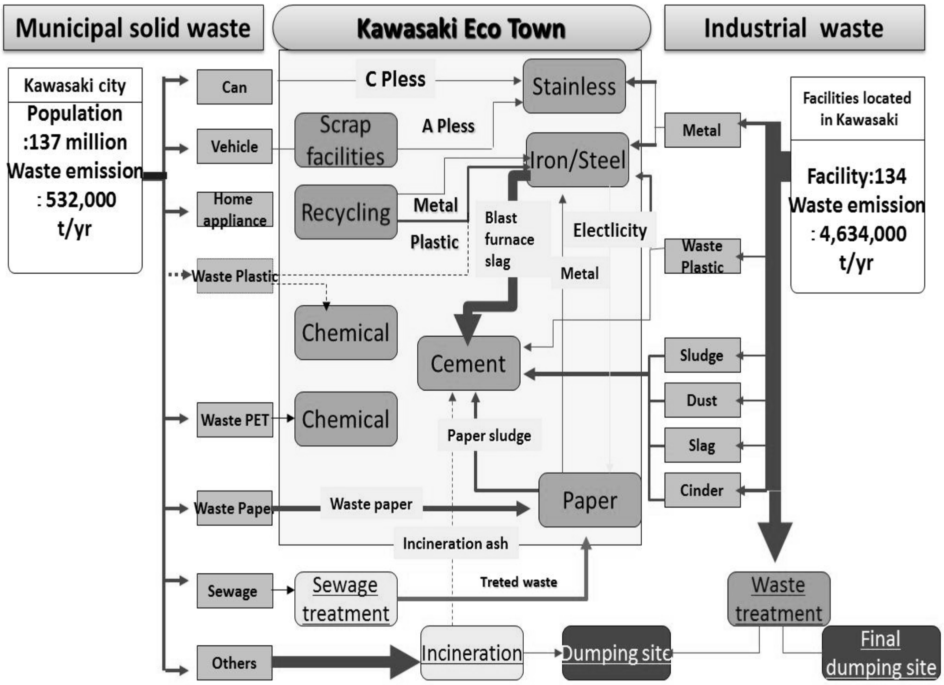


Figure 3-7 Synergy networks in Kawasaki city

Source: author's paper: T.Fujita, et al., 2014.

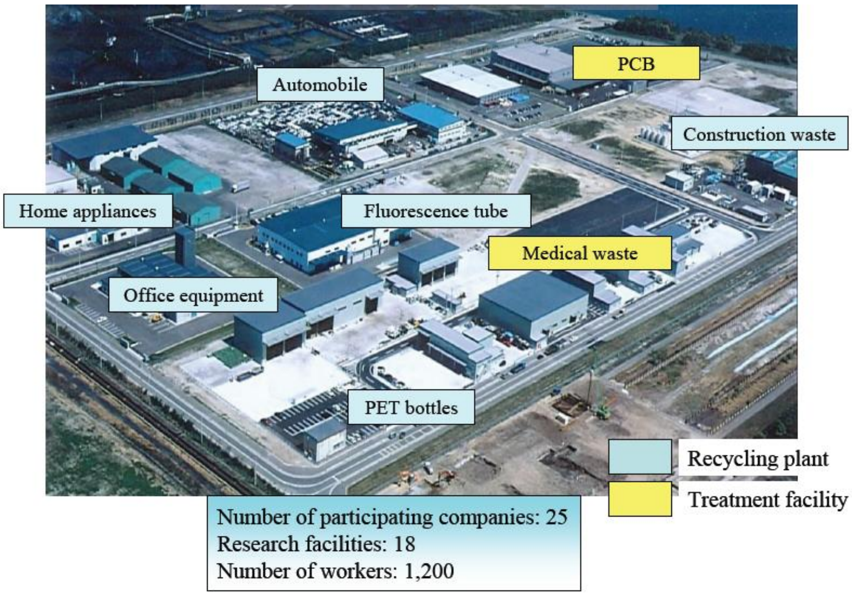


Figure 3-8 Real practice in Kitakyushu city, Japan
Source: http://www.city.kitakyushu.lg.jp/english/file_0040.html; Dr Fujimoto: Actions toward creation of a low-carbon society in Kitakyushu City, Japan

3.3 Comparison of IS promoting policies between China and Japan

China and Japan has similarity in many socio-economic context: manufacturing and heavy industries like iron/steel played an important role in the national economy; both countries promote the circular economy and low carbon strategy as national policy. With this circumstance, a comparison on national wide policy and specific local industrial symbiosis in China and Japan is meaningful, so as to investigate the inner socio-economic reasons behind the promotion on industrial symbiosis in China.

Both China and Japan have a national target on "Sound material-cycle society" and "low-carbon society". We firstly conduct the comparison on national wide strategy and promoting polies (*Table 3-2*).

Further, the same and difference of the "Circular society related policy" of the two countries are compared and summarized in *Table 3-3*. Compared with Japan, China is still in the "technology" stage, which focuses on technical advancement, cleaner production. Thus in the future, large scale system innovation and construction of regional symbiosis would be critical.

Table 3-2 Summary of Japanese and Chinese policies on "Sound material-cycle society" and "circular economy"

	Japanese "Eco-town"	**China's "circular economy"**
Year	Waste management policy	Circular economy related policies
1991	-Amendment of Waste Management and Public Cleaning Law -Law for the Promotion of Effective Utilization of Resources	-Focus on pollution control strategy -Promotion of end of pipe technologies on SO_2 reduction, waste water pollutants reduction, and so on.

1992	-The Earth Summit	
1993	-Basic Environment Law	
1995	-Law for Promotion of Sorted Collection and Recycling of Containers and Packages	
1997	-Amendment of Waste Management and Public Cleaning Law	
	- Eco-town subsidy program	
1998	-Law for Recycling of Specified Kinds of Home Appliance	
1999		-Idea of “circular economy” is introduced into China
2000	-Basic Laws for Establishing a Recycling Based Society -Law Concerning Recycling of Materials from Construction Work -Low concerning the Promotion of Recycling Food Cyclical Resources -Amendment of Law for the Promotion of Effective Utilization of Resources -Green Purchase Law	-National Development and Reform Commission had begun to promote circular economy, mainly focus on the technologies transformation and policy publication.
2001		-National eco-industrial park project had begun, promoted by MEP, China.
2002	-Law Concerning Recycling Measures for End-of-life Vehicles - Biomass Nippon Strategy	-Launch of 【Cleaner Production Promotion Law】
2003	-Amendment of Waste Management and Public Cleaning Law	
2004	-Amendment of Waste Management and Public Cleaning Law	
2005		-First batch of “national circular economy pilot”. -Promotion of “Energy conservation and waste reduction policy”.
2006	-Amendment of Law for Promotion of Sorted Collection and Recycling of Containers and Packages	
2007	The Cool Earth Action Plan	-Second batch of “national circular economy pilot”.
2008	-Second Basic Laws for Establishing a Recycling Based Society	
2009		-Launch of 【Circular Economy Promotion Law】, State Council and NDRC
2011	-New-generation eco-town project, MOE, Japan	-Launch of 【Circular Economy Technology Inventory】, NDRC

Source: revised from author’s paper: (T. Fujita, et al., 2014), (Ohnishi, et al., 2014) and (Dong, 2011).

Table 3-3 Comparison of Japan and China on its “circular society related policy”

	Japan	***China***
Basic strategy	Sound material-cycle society	Circular Economy
National planning	Eco-town project, by METI and MOE, 1997-2006	Circular Economy pilot project, NDRC Eco-industrial Park, MEP
Spatial scale		Three spatial level:

	To form a regional symbiosis	✓ Cleaner production and material exchange inner company (current); ✓ Industrial symbiosis and EIP (begin to promote since recently year) ✓ Regional symbiosis and sound material-cycle society
Regional collaboration	Lot	Few
Quantitative evaluation	Focus on material flow analysis and life cycle assessment	Focus on MFA oriented indicators

Source: revised from author's paper: (Ohnishi, et al., 2014) and (Dong, 2011).

3.4 Comparison from IS network perspective

After the national policies comparison, we select three specific cases for comparison: Jinan and Liuzhou in China (which are also the case areas in this study) and Kawasaki Eco-town in Japan. Their current reported IS networks are compared. In the case studies, more IS would be investigated for Jinan and Liuzhou. Jinan is the capital of Shandong province, and Liuzhou is the industrial center of Guangxi province. Both Jinan and Liuzhou have a ten million scale iron/steel enterprise. Kawasaki is one of the first and the best-known eco-town projects, locates near Tokyo, Japan and is the heavy industries clustered area with a four million scale iron/steel plant. The location information is shown in *Figure 3-9*.

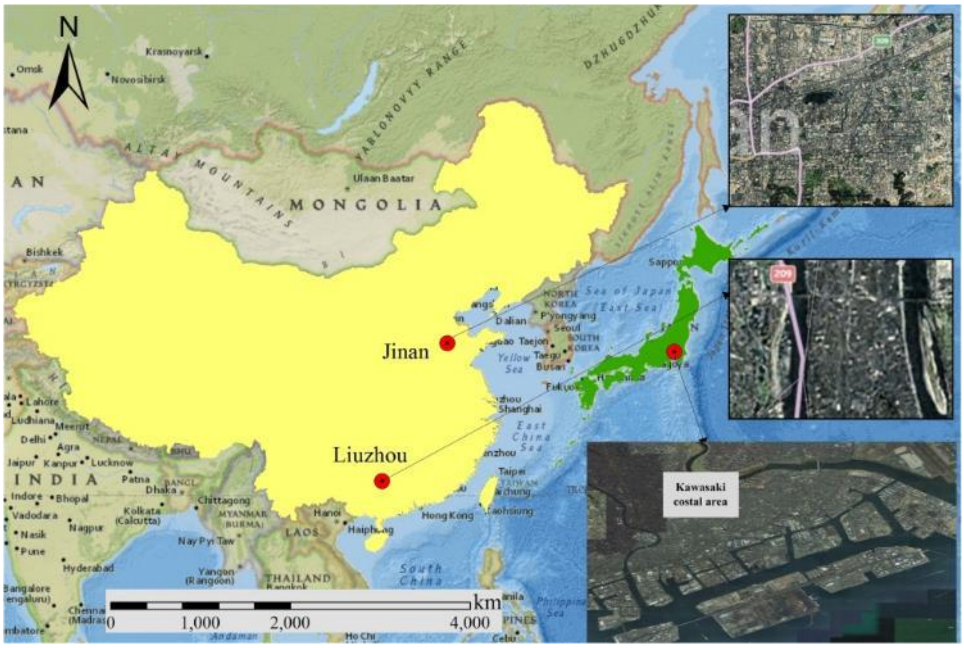


Figure 3-9 Geographic location of cases in Kawasaki, Jinan and Liuzhou

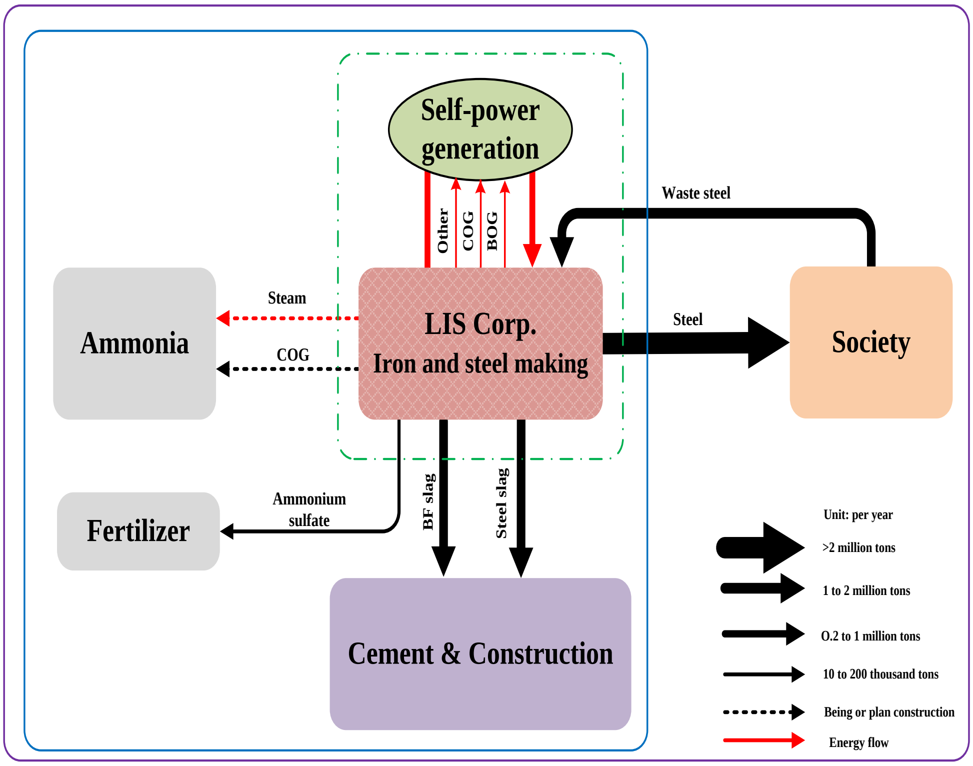
The selected cases present three development stages of IS promotion. In the case of Liuzhou, there is only bulk solid waste exchange, which is the traditional IS activity. In Jinan case, it presents an advanced case of China. The linkages between industrial sectors and between industry and community are formed. And in the case of Kawasaki, it presents an even more diverse industrial symbiosis that urban symbiosis is formed.

The current formed industrial symbiosis was analyzed for three cases. Comparison was shown in *Figure 3-10*.

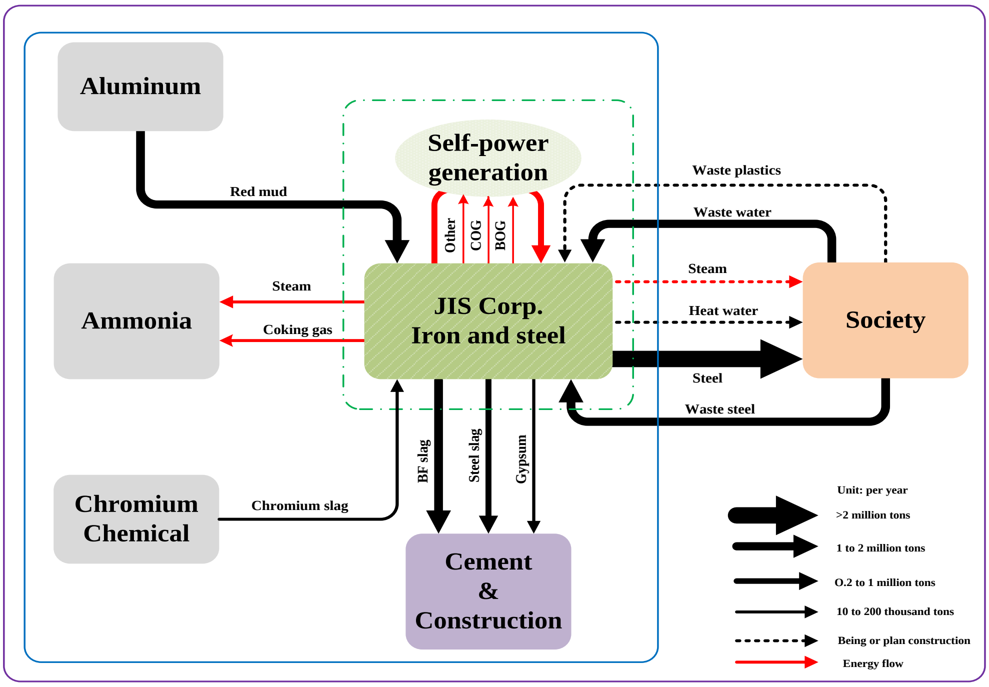
(1) *Figure 3-10 (a)* showed the current symbiotic network in Liuzhou case. There were three symbiotic activities were identified, mainly were traditional material or energy exchange, including BF slag reused to produce slag powder, BF/steel slag utilized by cement and construction industry, byproduct from the desulfurization process utilized to produce fertilizer. Recently a new energy exchange chain that providing coke oven gas and steam to chemical industry (producing ammonia) was under construction. It was noted that although the central steel company (Liuzhou iron/steel, LIS) made a great progress in energy conservation and emissions reduction, it had little symbiotic linkage with the other industrial or social community.

(2) *Figure 3-10 (b)* presented the current symbiotic network in Jinan case (the hub is also steel company, Jinan iron/steel, JIS). Among the industrial companies and the community, 9 symbiotic links were formed till now, and 3 were in planning or construction. 7 symbiotic links were between industries, and 2 linked waste steel and waste water from urban community with iron/steel plants. Over 10 million materials was exchanged in the whole symbiosis network, including traditional exchanged materials as waste steel, BF slag, waste water, but also new materials through the technology innovation such as gas and steam provided for nearby industries and community, red mud and chromium slag from heavy chemical industry, by-product utilized by cement and construction industry, etc..

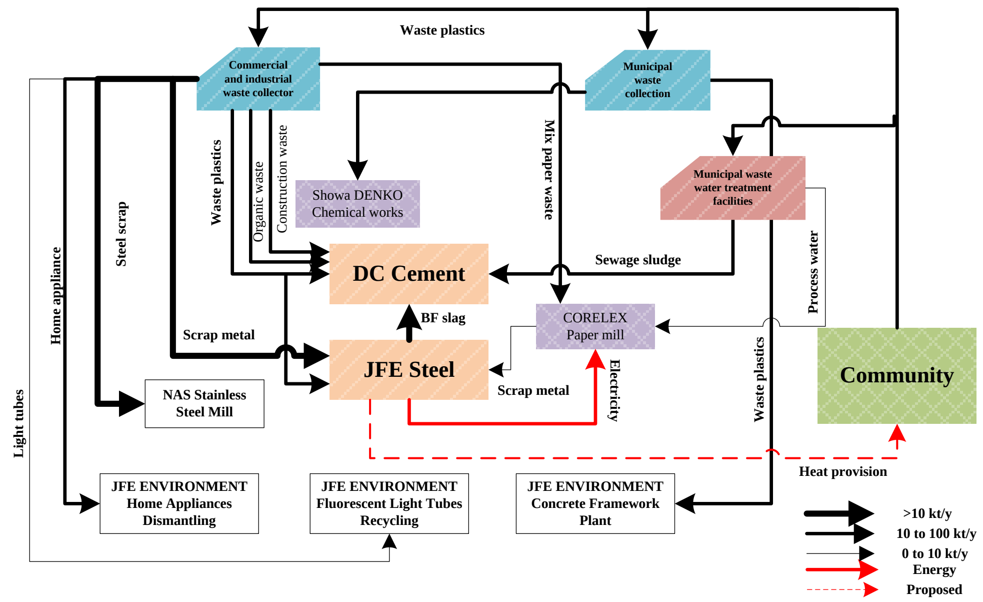
(3) *Figure 3-10 (c)* showed the industrial and urban symbiosis in Kawasaki. with IS planned, several linkages between urban and industrial system have formed between local industries and the urban areas, some key companies like JFE Steelworks and DC Cement have actively promote the symbiotic developments in Kawasaki (Berkel et al., 2009), recycling waste plastics as reductant for blast furnace was 50kilo ton/y, with an investment of 2744MJPY, 50% was subsidized by the government. Main symbiotic activities include: From industry to industry: BF slag was exchange as clinker substitute between steel and cement plant; industrial waste heat source could be provided to factories like the paper mills. From urban to industry: a. waste plastics are recycled into steel plant to act as the coke substitute in the furnace; waste steel is recycled into steel plant to act as semi-products; municipal waste water treatment sludge could be utilized as fuels in the furnace of steel and cement plants.



(a) IS in Liuzhou



(b) IS in Jinan



(c) IS in Kawasaki eco-town

Figure 3-10 Network comparison on the iron/steel centered industrial symbiosis in three cases

The comparison results presented that even though the features of the industrial areas (such the industries located) were similar, the features of the IS, such as the numbers of the synergies, the complexity of the network and the exchanged material/waste was diverse in the three cases. The symbiosis selected in China was with the features of large number and scale, but the types are single, the substance exchange types were homogeneous, mainly bulky industrial waste or by-product, and the geographical level was mainly inside the company or the industrial parks; While Kawasaki presented a symbiotic network in more complex form and broader geographical level. The formed industrial and urban symbiosis could enlighten us to plan new industrial symbiosis in Chinese cases.

While Chinese large scale industry generated huge quantity of exchanged waste and/or byproduct, the lack of symbiosis stability results in the single type and waste resource underuse. Currently there was lack of standardized recycling technologies and products in China, which increased the difficulty of substance exchange among different sectors. In addition, the flows of exchanged substance were unstable, the supply and demand could not be matched as a result. For example, the technology like using waste plastics in BF furnace often faced the problem of the different content and fluctuated quantity of waste plastics, and as a result, the Chinese iron/steel company could not apply this technology in reality.

Different socio-economic development stage was one key factor. Unlike Japan, both China’s industrial system and related supply demand chain was unstable under rapid growth stage. Various emerging activities would affect the stability. Under such instability, it is understandable that some bulky waste would be in priority to exchange.

Furthermore, “software technology”, which mainly included waste management system and regulations, played an important role in regional symbiosis. While in this point, China had a long way to go. The reason that in China IS was mainly in the form of bulk solid waste exchange was that such an exchange form required more the technological and economic feasibility than the information and organization feasibility. Because under the condition with different labor cost, technology barriers and waste market, China’s waste recycling system lacks specialization and stability, as a result, the quality and quantity of waste or product could not be guaranteed; The information of substance exchange was usually unavailable, making it more difficult form urban symbiosis. On the contrast, the successful urban symbiosis in Kawasaki required a lot in management and information system to guarantee the stable substance flows. In management aspect, Kawasaki established the innovative municipal waste management system in which a group of industrial and commercial waste collectors acted as key stakeholders, while LIS and JIS mainly depended on industrial organization like industrial society. In information aspect, Kawasaki established information platform through which the information about substance exchanges was shared with each participant with the help of government and the third party, while in LIS and JIS, the information share platform was established through merchants and investment. The options for the companies were limited.

To improve the problems of system stability and the lack of standard technology/products, it was required the promotion of circular economy technology and industrial linkage technology. Circular economy technology and product standard, as well as quality standards for the input material as guidance for waste generators should be established so as to guarantee the stable product and waste flows. To improve the immaturity of waste management system and regulation system, on the one hand, in order to establish a stable and innovative municipal solid waste management system needed to establish, public or commercial collectors needed to be encouraged to participate in the waste collection and recycling. On the other hand, the third party should be made to coordinate the stakeholders of the symbiosis. For sharing information between the industries or companies, the establishment of information platform was important. For the regulation system improvement, waste management legislation considering extended responsibility of the companies should be launched and implemented widely.

3.5 Summary

This chapter reviewed the industrial symbiosis promotion in China and Japan, and compared its promotion condition in China and Japan from national policies perspective and specific cases perspective. Results highlighted that: compared with Japan, China’s industrial symbiosis was still in the stage of bulky industrial solid waste exchange, mature industrial and urban symbiosis was not formed yet. The Kawasaki eco-town in Japan had showed an advanced industrial and urban symbiosis, which could enlighten the planning in this case study.

4.Industrial symbiosis projects investigation and database construction

This section presents the case selection, survey procedure design, investigation on companies and technologies information, as well as database construction.

4.1 Case selection

Case selection criteria: in this study, it makes two case studies: firstly, would investigate a national pilot industrial symbiosis, then based on the experience of the national pilot project and the investigation of technologies and synergies opportunities, a comprehensive planning and evaluation on one local industrial symbiosis is conducted. In this way, we could generalize the industrial symbiosis from national pilot to local area. The whole case selection criteria is shown in *Figure 4-1*.

Under this design, two cases are particular selected with similar industrial features:

- Case 1: one industrial symbiosis in Jinan city, national circular economy pilot. The center is one iron/steel dominating industrial park. To date, a relatively advanced industrial symbiosis are formed and some more are under planning.
- Case 2: local industrial symbiosis in Liuzhou city. It is local project, in an iron steel centered industrial park. Not mature industrial symbiosis is formed. This study would conduct a comprehensive planning and evaluation for it.

The location of Jinan city and Liuzhou city, and their main industries are shown in *Figure 4-2*. Detail information would be introduced in next section.

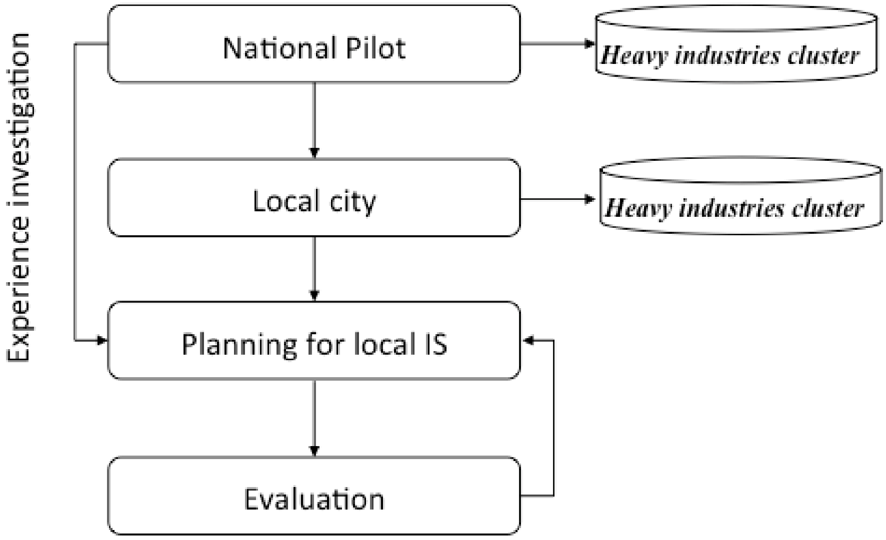
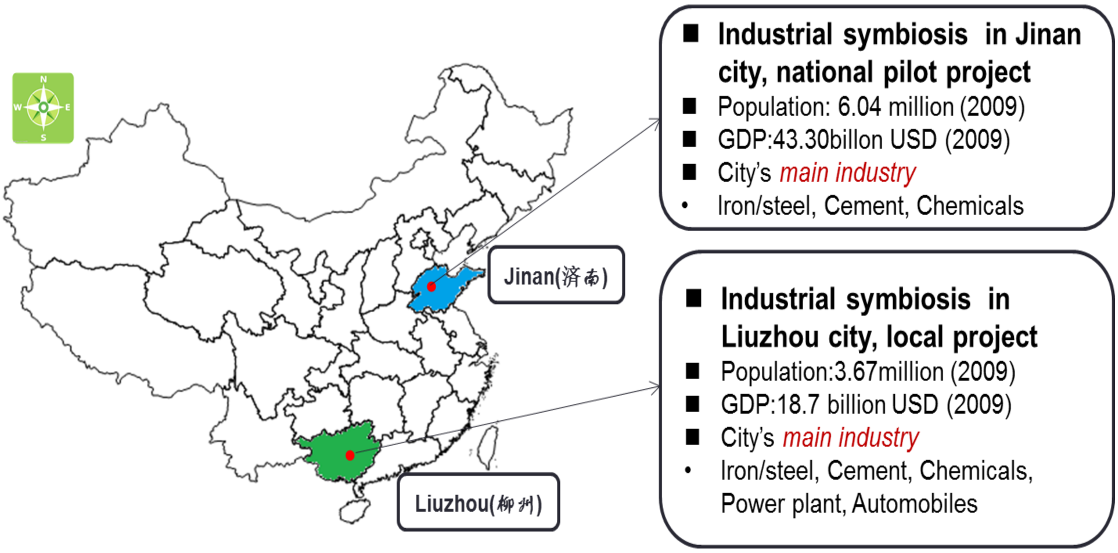


Figure 4-1 Case selection criteria



- **Industrial symbiosis in Jinan city, national pilot project**
- Population: 6.04 million (2009)
- GDP:43.30billon USD (2009)
- City's *main industry*
- Iron/steel, Cement, Chemicals

- **Industrial symbiosis in Liuzhou city, local project**
- Population:3.67million (2009)
- GDP:18.7 billion USD (2009)
- City's *main industry*
- Iron/steel, Cement, Chemicals, Power plant, Automobiles

Figure 4-2 Case selection and their locations

4.1.1 General information of Jinan case

Jinan city is the capital of Shandong province (the third largest province in China in term of GDP), with a population of 6.04 million (3.50 million in urban). In 2008, the GDP of Jinan was 300.60 billion CNY (43.3 billion USD). As one of the most important enterprise in Jinan, Jinan iron/steel group corporation (simplified as JIS in this research) located in eastern urban area of Jinan. After 2005, its total production of crude steel overtook 10 million tons, ranking the 7th in china, which was the world's 11th largest iron/steel enterprise in 2008[6].

4.1.2 General information of Liuzhou case

Liuzhou city is the industrial center in Guangxi province, southern China (*Figure 4-3*), with an area of 18 thousand km^2 and a population of 3.67 million in 2009[7]. The manufacturing industry generated more than 40% of the total city GDP in 2009. Iron and steel industry and automobile industry are the key industrial sectors in Liuzhou, with fractions of 13.82% and 26.93% on the added industrial value respectively, as well as 53.61% and 1.32% on the total industrial energy consumption in 2009, respectively. Specifically, there is millions ton scale iron/steel plant named Liuzhou iron/steel integrated corporation (simplified as LIS) locates in Liuzhou circular economy industrial park (Liuzhou CEIP). In 2009, its total production of crude steel was 8.18 million ton. In the industrial area, around the iron/steel plant, there are cement companies and chemical companies located. Such industrial condition provides high potential to form industrial and urban symbiosis.

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[6] Source: China Iron and steel Industry Statistical Yearbook, 2009.

[7] Source: Liuzhou statistical Yearbook, 2010.

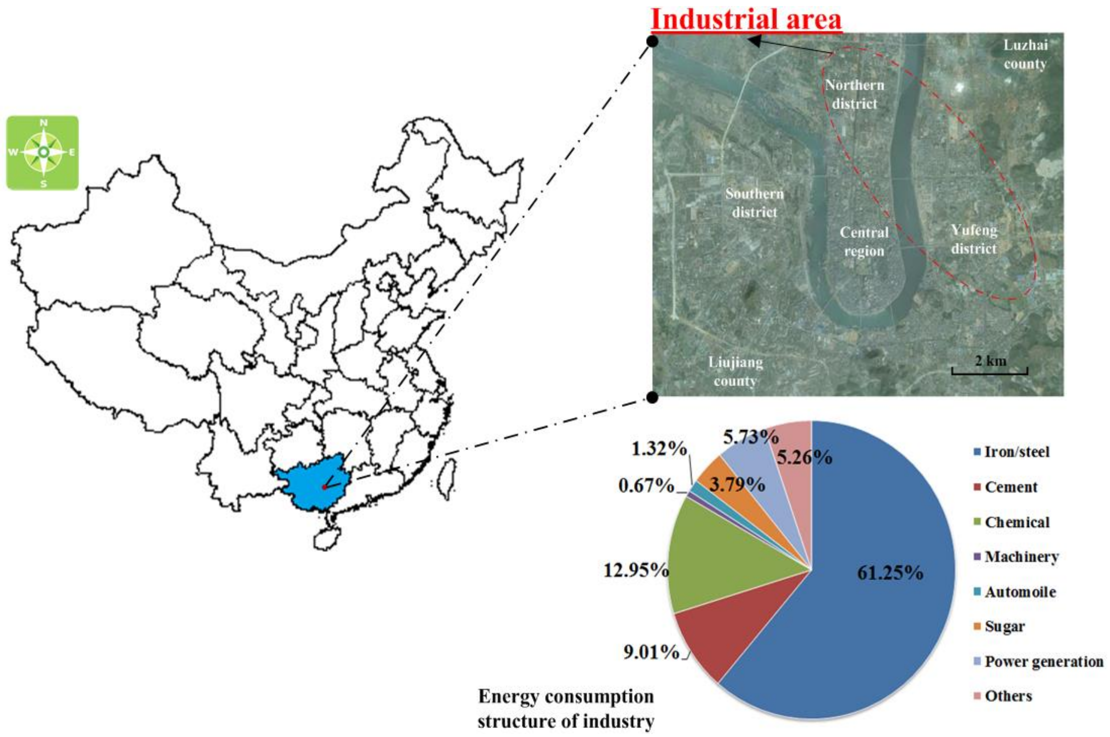

Figure 4-3 Location of Liuzhou city

4.2 Technology and projects investigation

As the basis for further planning for IS and its evaluation, the related technologies and projects are intensively investigated and data are collected. The general category includes:

- Basic information for the key company;
- Cleaner production technologies;
- Industrial symbiosis linkage and recycling technologies;
- Information on the synergies between companies.

The following sections would introduce the survey process and the detail information gained from the survey.

4.2.1 Survey procedure design

To collect first hand data, which is usually very difficult to be available, an innovative and integrated survey procedure is designed and conducted. The survey process is summarized in *Figure 4-4*. The participants include institution, central and local governments, as well as local companies. Hundreds of survey sheets are distributed, and on-site investigation is made. An integration of top-down and bottom-up process, as well as the collaboration among government, academic institute and local companies is key point.

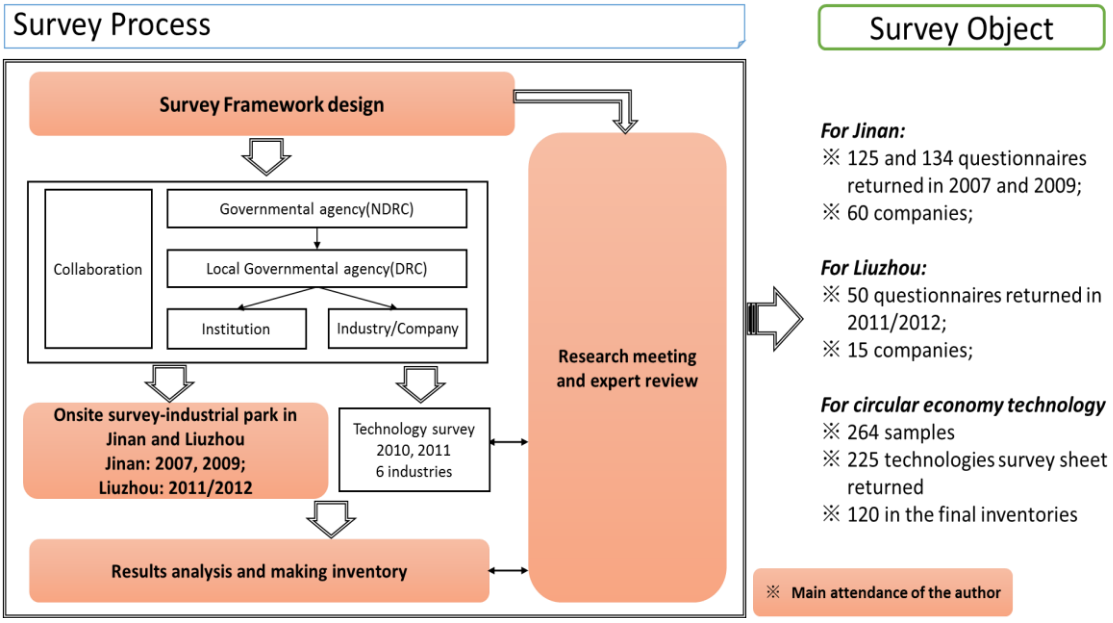

Figure 4-4 Survey process

The survey for the companies and technologies are mainly based on three projects:

- 【National Science and Technology Supporting Project on "Cleaner production and circular economy technology and demonstration", 2006-2011】. The object is Jinan city, focuses on one national iron/steel industrial park. It is also the national circular economy pilot. Lead by National Development and Reform Commission (NDRC).
- 【National Science and Technology Supporting Project on "National 12th five year circular economy technology inventory", 2009-2011】. The object is circular economy technologies survey in national wide in key industries (iron/steel, cement, chemicals, textile, non-ferrous metal, etc). Lead by National Development and Reform Commission (NDRC).
- 【12th five year planning for energy conservation and low-carbon transformation in Liuzhou city, 2011-2012】. The object is Liuzhou city, focuses on the local industrial park. Lead by Liuzhou city Development and Reform Commission, and CCID consulting company under Ministry of Industrial and Information, China (MII).

As to the detail survey procedure, Jinan city and Liuzhou city, as well as key companies in them, are intensively investigated.

For Jinan: the data mainly came from on-site survey to the companies. In 2007 and 2009, two large scale surveys were conducted: with the collaboration of local government and the companies, 125 and 134 completed questionnaires were returned. In the survey process, 60 companies including iron/steel company; cement plant; ammonia companies were interviewed. Apart from this, some data was collected from the technical report from the companies and the author analyzed them. Based on this, inventory data was made and 2009 was as reference. The types of data were mainly input-output data of material/energy consumptions for the company, waste emissions and the material and waste exchange, cost information, and general local socio-economic information (Dong et al., 2013b).

For Liuzhou: one of the author attended the "12th five-year plan for the energy conservation in Liuzhou city" in 2011 and 2012, they made a survey for 15 companies in the Liubei industrial area, included the iron/steel company, chemical company, cement company, power generation company, etc. The survey data mainly included the material/energy inputs/outputs for the company, waste emissions and the material and waste exchange. The baseline year for Liuzhou city was 2010.

Furthermore, the survey on the circular economy technologies in key industries is conducted, which could provide technical basis for the industrial symbiosis planning. Two large scale surveys were conducted in 2011 and 2012, in 6 industries including iron/steel industry, cement and construction industry; petroleum and chemical industry; non-ferrous metal industry, textile industry and related soft-ware technologies. Based on survey, very new and local data is collected compared with past works.

4.2.2 Investigation on key companies and projects

Key companies are particularly investigated. The key companies in the two cases are two iron/steel companies. They are also the hubs of the current and future planed industrial symbiosis. A detail review on the two companies and the related technologies and projects are made.

Jinan iron/steel group corporation ***(simplified as JIS)*** locates in eastern urban area of Jinan city, it is a typical long product steel plant. In 2005, its total crude steel production was around 10 million tons, ranking the 7th in china, and the world's 11th largest iron/steel company in 2008[8]. From 1995 to 2009, JIS had promoted industrial symbiosis strategy in three stages: (1) focused on energy conservation and cost reduction with the improvement manufacturing process. This happened in the 1990s. The main measures included improving the raw material quality and enhance the efficiency of manufacturing processes. (2) focused on cleaner production, in the period of 2001 to 2005. In this stage, the main measures included technology upgrading and manufacturing process parameter optimization. It is noted that a series of energy recovery technologies had been implemented, including the dry coke quenching(CDQ) equipment launched in 1999(2×70t/h) and 2007(100t/h and 150t/h), which was able to recover the sensitive heat from hot coke, Combined Cycle Power Plant (CCPP) technology for power generation with low and medium calorific value gas from the blast furnace in 2004, Top gas Recovery Turbine (TRT) power generation technology in 2005, etc. With the implementation of these technologies, the comprehensive energy consumption per ton steel had decreased by 33% from 1998 to 2008 (Dong et al., 2013b) (*Figure 4-5*).

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[8] Source: China Iron and steel Industry Statistical Yearbook, 2009.

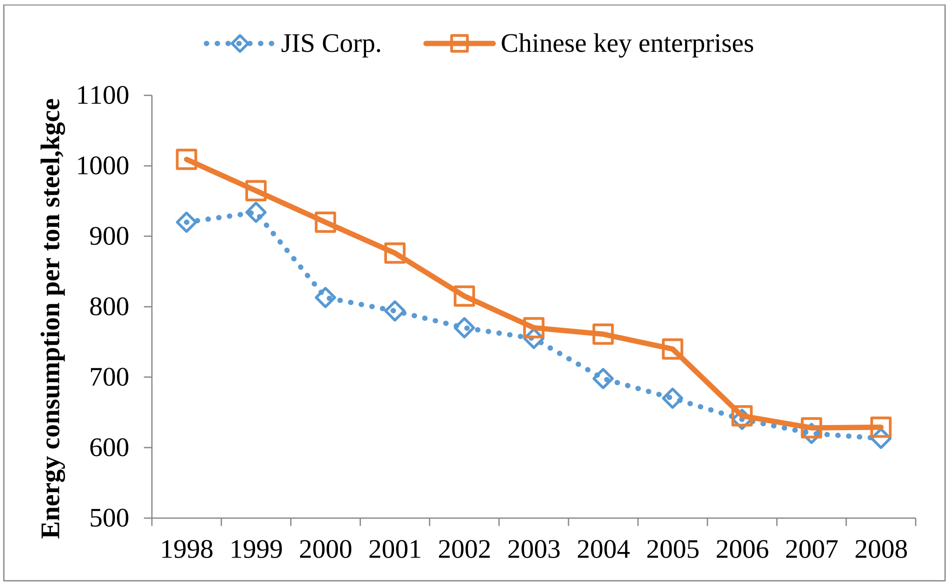

Figure 4-5 Energy consumption per ton steel of JIS

Since 2005, it had turned into the stage of developing circular economy. At this year, JIS became the national circular economy pilot enterprise. The main measures are constructing symbiosis network and spreading the production chain. Particularly, JIS engaged exchanging of materials, energy, water and byproducts with inner companies, neighbor industrial companies and the urban municipal system. The "three-level circular cycles mode" and "five technological integration chains" were established. The inner cycle focus on the inner iron/steel process, and the medium cycle focus on the energy and waste exchange between iron/steel process and other process, such as the linkage with chemical industry, cement industry, etc. JIS provided gas and steam for co-located enterprises including Jinan Chemical Corp., Cyener Corp., Lanxing Corp., etc. Total amount was 300 million m^3 gas and 300 thousand tons steam in the past five years. Furthermore, an outer cycle aiming to link iron/steel process with the urban community was proposed and being constructed, recent exchanged resource include energy, waste water, slag from other industries, and in the near future, municipal waste would also be included. A detail projects and technologies were summarized in *Table 4-1*. It was noted that compared with the case of LIS, more IS projects were included. The detail IS analysis was provided in the following part.

. ***Liuzhou iron/steel integrated corporation*** ***(simplified as LIS)*** locates in Liuzhou circular economy industrial park (Liuzhou CEIP). It is the largest iron/steel works. Its manufacturing process is typical long process of integrated iron/steel making (*Figure 4-6*). In 2009, its total production of crude steel was 8.18 million ton, associated with an energy consumption of 6.32 million tce, the comprehensive energy consumption was 624 kgce[9] per ton steel. In the industrial area, around the iron/steel plant, there are cement companies and chemical companies located.

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[9] It means kg coal equivalent. 1 kgce equals to 29.27MJ.

Table 4-1 Circular economy projects in JIS

CE project	**Key Technology**	**Reuse/recycle source**	**Benefits**
Energy recover, reuse and cascading utilization chain(CP)	Sinter waste heat recovery power generation, CDQ technology, CCPP technology, Combined heat and power plants(CHP), Top gas Recovery Turbine (TRT),	High calorific value and pressure waste heat	Energy consumption per ton steel reduced from 813 ton coal equivalent to 613 ton coal equivalent, total power generation install capacity was 620MW in 2008, satisfy 60% of the enterprise's electricity need, reduce coal consumption 587 thousand ton, equal to the CO_2 and SO_2 emissions reduction in 1.6 million ton and 15.1 thousand ton respectively.
	Coal moisture control technology, high efficiency hot air furnace technology; regenerative heating furnace technology.	Mediate and low calorific value and pressure waste heat	
	Dry dedusting technology, coal chemical production by use of heat conducing oil, energy management center.	Other	
Ferrous efficient utilization chain (CP)	High quality steel products manufacture; iron loss reduction technology as high temperature dynamic oxidation resistant coating technology applied to steel billet; process iron resource productivity enhancement technology.	Iron, iron dust, iron/steel scrap,	Iron consumption per ton steel reduced from 1120kg in 2000 to 1074 kg in 2008, Rolling yield rate of steel increased from 88.63% in 2000 to 95.55% in 2008, lime consumption per ton steel reduced by 69.7 kg from 2000 to 2008, equal to lime reduction in 600 thousand ton annually.
Emission reduction and waste utilization technological chain(CP+IS)	Waste water utilization technology as coking waste water utilization, salt pick up from desulpher waste water; slag and sludge utilization technology; process pollution control technology as sintering flue gas desulphurization and by-product utilization, tar distillation with minus pressure.	Waste water, blast furnace slag, steel slag, gypsum, sludge and dust.	Produce slag power 1.8 million ton/y, recycle steel slag 1.2 million ton/y, recycle coking slag 51.7 thousand ton/y, reduce SO_2 emission 4000 ton per year, utilize iron dust and coking dust 950 thousand ton in 2008, waste water emission per ton steel reduced from 14.9 m^3 in 2000 to 1.01 m^3 in 2008.
Water efficient use and recycle chain (CP+IS)	End-of-pipe technology as coking waste water hierarchical treatment technology, close looping of	Water, waste water	Water consumption per ton steel reduced from 9.63m^3 in 2000 to 3.18 m^3 in 2008, water reuse rate

	sewage and sludge; waster reuse and substitution technology; zero-water technology as non-steam ammonia technology; water and energy conservation integration technology; Close looping water technology as blast furnace soft-water close looping.		increased from 90.3% in 2000 to 97.3% in 2008. Reuse sludge 80 thousand ton per year.
Bulk social waste absorption chain (IS)	Waste water facilities with the capacity of 2.6 million ton per year; Environmental treatment for chromium slag; Extract ferrous in red mud from aluminum industry.	Red mud from aluminum industry, waste water from the community, waste slag from chemical industry, waste steel.	Recycle sludge and dust 798 thousand ton/y, recycle and reuse waste water 16 million ton/y, reuse chromium slag 120 thousand ton per year, extracted 450 thousand tons iron ore power annually from red mud.

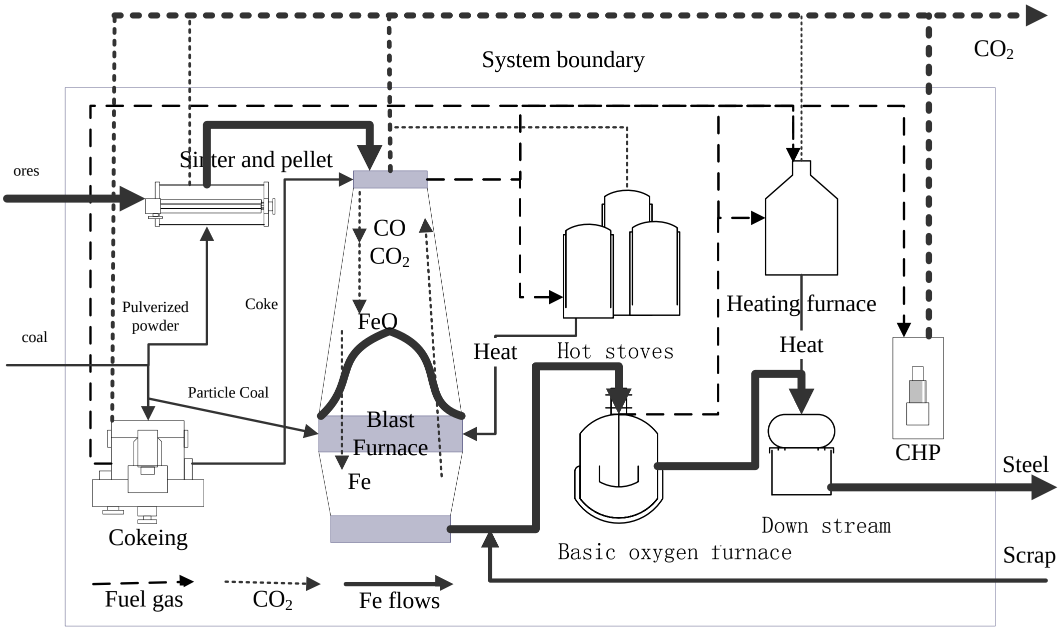

Figure 4-6 The sketch of an integrated iron/steel making factory

At this stage, LIS practiced the circular economy strategy mainly focus on the micro level inside the enterprises, a series of energy conservation and recycle, waste utilization technologies were launched (summarized in *Table 4-2*). Most projects were cleaner production.

Table 4-2 Key CE projects in LIS

CE Project	**Key Technology**	**Benefit**
Electricity production from second energy reuse and recovery (CP)	Top pressure recovery turbine (TRT) Coke dry quenching (CDQ) technology 2.5MW Sinter waste heat recovery power generation technology, and would expand to 5MW in the future 3 to 5 year.	BF gas recovery rate was 82.48% in 2009.58.2% of coke was dry quenching. Recovery sensitive heat of high pressure and temperature from hot coke equals to 220 to 330 kWh per ton coke.
Bulky solid waste utilization(IS)	Use BF slag to produce slag powder Steel slag recycled ferrous and the residue was utilized by cement and construction industry	Solid waste utilization rate increased to 91% in 2009.
Pollution prevention(CP)	Sintering flue gas desulfurization technology Coking Wastewater Utilization Technologies Dry dust removal technology	SO_2 emission, Waste water emission, COD emission and dust emission reduced to 2.09 kg/t, 1.42 m^3/t, 0.11 kg/t and 0.60 kg/t respectively in 2009.

4.2.3 Investigation on industrial symbiosis linkage and recycling technologies

Apart from the above cleaner production and circular economy technologies, Industrial symbiosis linkage and recycling technologies are also the key to construct local industrial symbiosis system.

To promote the industrial symbiosis, and regional recycling, China has launched the "National circular economy technologies inventory", of which, industrial symbiosis linkage and recycling technologies are key components. Based on this inventory and the projects the author used to attend[10], several key technologies fit to the case selection in this research the author reviewed and investigated.

The basic mechanism and application condition of the technologies would be reviewed. It is noted that for most of such technologies, they are still in the experiment stage, the large scale application would be in the 12th five planning (2011-2015) and 13th five planning (2016-2020) stage.

- **Steel Slag treatment and utilization technology**

Iron and steel industry is a key sector to form the industrial symbiosis (Li et al., 2010; Reh, 2013). And it is one of the most important industrial sectors when addressing environmental issues in China. As the main solid wastes generated from this industry, the steel slag treatment and utilization is important (Liu et al., 2014a; Ma et al., 2014; Yi et al., 2012).

Based on a national circular economy technology project in Jinan iron/steel corporation, one slag comprehensive utilization would be applied in this research (JIS, 2011). The general process is shown in *Figure 4-7*: in general, steel slag is preprocessed, and then utilized by multi-ways, including being provided to cement company to produce clinker, and for some chemical products production.

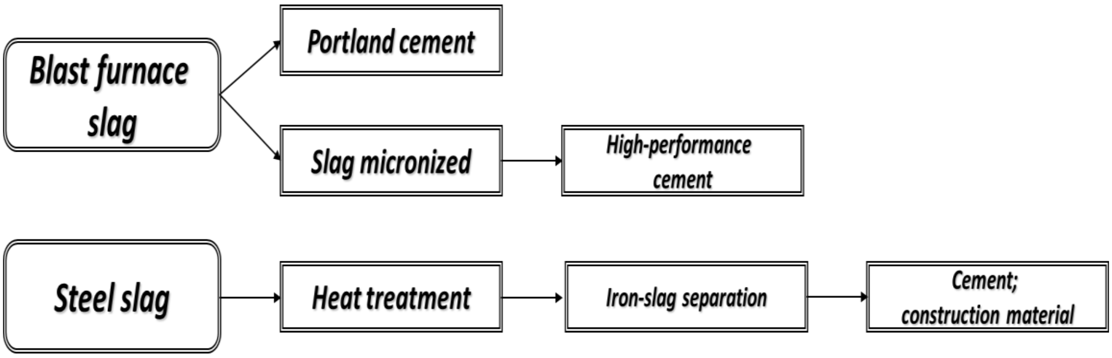

Figure 4-7 Process of slag utilization

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[10] The author attended the national science and technology supporting project in one large scale iron/steel centered industrial park in Jinan, Shandong province, from 2009-2012; The national science and technology supporting project "”National 12th five circular economy technology inventory", from 2009-2011, and The "12th five planning for Energy conservation " in Liuzhou, Guangxi province, from 2011-2012. Through such projects, the technologies information is collected.

- **Waste plastics recycling and utilization**

Waste plastics are key municipal waste, and with the enhancement of people’s living standard, it becomes more important. Most waste plastics from municipal sources include plastic containers and packages, including PET bottles and non-PET plastic containers and packaging (Al-Salem et al., 2009; Lazarevic et al., 2010; Subramanian, 2000). The author’s group had done some projects about waste plastics recycling in Japan (Chen et al., 2011; Van Berkel et al., 2009). Consider in China, the waste plastic recycling and utilization is not so mature, thus in this study, we consider a technology transformation to China enlightened from those projects when setting the scenarios, and fit to the local conditions accordingly.

We firstly introduce summarize the waste plastics recycling process based on the advanced experience in Japan. Consumers are requested to separate containers and packaging at source according to the collection service schedule offered by municipalities. Municipalities are in charge of collection, selection, clean, and storing separated waste containers and packaging. Recyclers take the sorted waste containers and packaging from municipalities and process them into recycled materials or products. One governmental association, named the Japan Container and Packaging Recycling Association (JCPRA) was established under the Law to promote the recycling process. To fulfill their obligations, municipalities can either contract recyclers to treat their waste containers and packaging directly, or pay a commission fee to the JCPRA, who operate an open bidding system for recyclers to bid for recycling waste plastics.

One innovative utilization of waste plastic proposed in this study to China is the recycling of municipal waste plastics to process industries to substitute the fossil fuels. In such process, waste plastics are recycled, and preprocessed, and then reused into the blast furnace of iron/steel industry and other process industry like the cement industry. The basic process is shown in *Figure 4-8*.

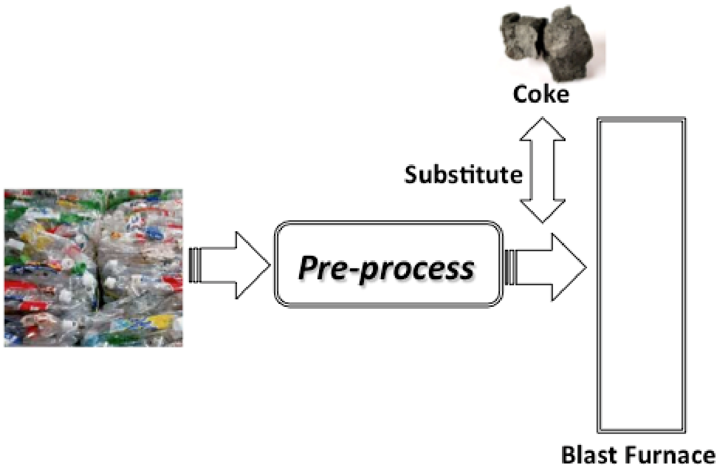


Figure 4-8 Process of waste plastics incineration in the blast furnace

In the cases of this research, such proposal is reflected in the local planning. In Jinan, with a 10 million scale iron and steel mill, there are large potential to utilize the waste plastics. A pilot program about incinerate waste plastics is being planned and would carried out in 2012, the designed amount was 200 thousand ton annually according to the survey, and the substitution rate of waste plastics is 4%, one ton waste plastics equals to 1.2 ton coal equivalent. As to Liuzhou case, it also locates with large scale iron/steel industry, but the recycling capacity is weaker than Jinan. The planned scale of waste plastics for incineration is 25000 ton/year annually in the 12th five planning.

- **Waste tires recycling and utilization**

This technology is also meaningful to China. It is known that China is in the progress of surging car ownership. As a result, the waste tires attract more and more attention (Lin et al., 2008; Shu and Huang; Wu and Zhou, 2009). It was reported that the production of reclaimed rubber in China had increased from 1.1 million ton to 2.5 million ton, from 2002 to 2009. This number accounted for 73% of total recycled rubber products and 81% of total reclaimed rubber worldwide (Liang and Zhang, 2012; Qu et al., 2013). Under this condition, China has promoted to recycle and reuse waste tires, and the production of reclaimed rubber plays a major role of utilization. What is more, one of our case city, Liuzhou city, is famous car production city in China. As a result, waste tires recycling and its utilization is important to our case study.

As a result, this study would propose the waste tires recycling and utilization follow the process of reclaimed rubber production. The main technical parameters are surveyed through the national "12th five science and technology supporting project" on "circular economy technologies inventory" (2009-2011) and "12th five energy conservation planning in Liuzhou city" (2011-2012), complemented with publications (Liang and Zhang, 2012; Molenaar, 2013; Qu et al., 2013) and reports on the pilot projects in China (CCID, 2011; JIS, 2011). Technical process is summarized in *Figure 4-9:*

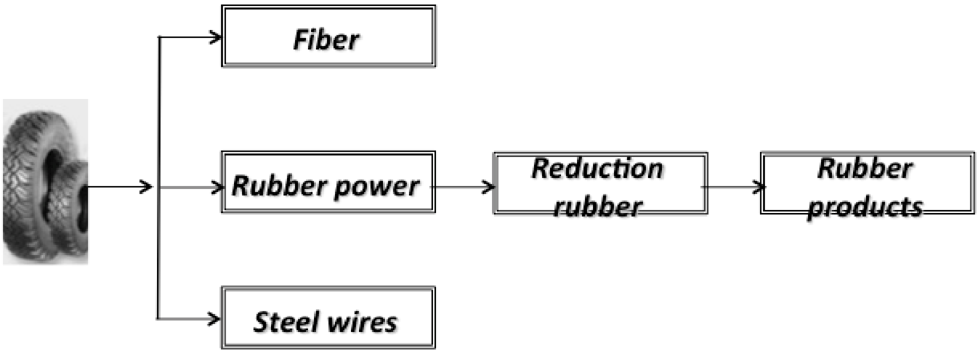


Figure 4-9 Process of waste tire utilization

■ Coal flying ash recycling and utilization

More than 80% of China's power generation is coal-fired, thus the coal flying ash is critical issue in China. Coal flying ash recycling and utilization is key technology in national planning. The usual way is to utilize them to produce different cement and construction materials (Li et al., 2010). The comprehensive utilization is summarized in *Table 4-3*.

In the case study of this research, the power plant and cement company is the key participants in the symbiosis network. As a result, the main utilization form for the coal flying ash in this study is to recycle it to cement company to produce cement (or clinker). In this way, it could reduce the raw material and fossil fuels for the clinker production. It is meaningful to resolve the serious problem of large scale flying ash stockpiling.

■ Waste heat recovery within factory and in energy network

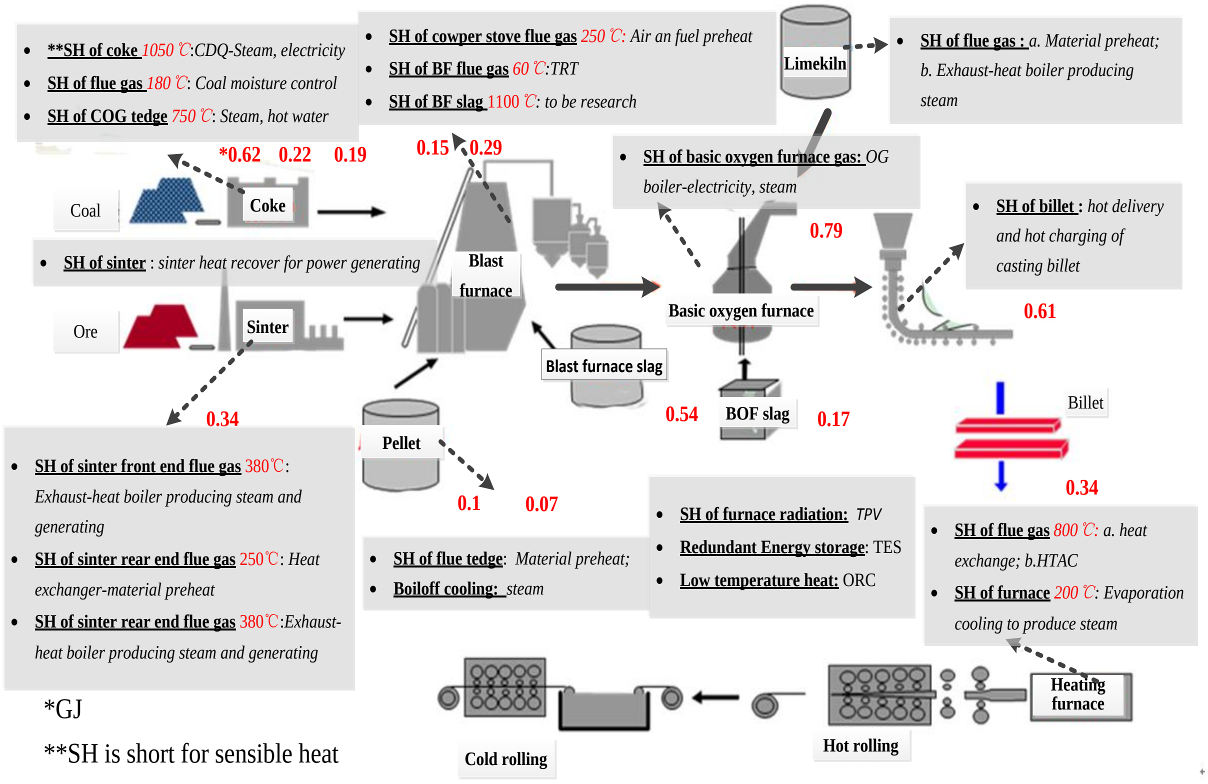
For process industries like the iron/steel industry, there is high potential for waste heat source. Under this condition, waste heat recovery and utilization is one key concern in this research. The waste heat recovery technology, as well as the waste heat potential inside the iron/steel company is summarized in *Figure 4-10*. The data of heat generation is through on-site monitor. It is noted that on the whole, the potential is rather considerable. The main utilization method is recovery inner the steel plant. The excess heat beyond recovery can be exchanged with nearby factories and urban area, e.g. steam and hot water provision to hotel.

Furthermore, for the scope of industrial cluster and its connection with commercial and residential areas, waste heat from boilers, turbines, combustion exhaust gas and excess steam can be exchanged between factories and between factories and residential/commercial area (*Figure 4-11*). Reported examples included energy exchange in chemical clusters(Park et al., 2008b; Zhou et al., 2012), iron/steel industrial parks(Dong et al., 2014; Zhang et al., 2013b), between power plant and industry/residential area(Chertow and Lombardi, 2005; Jacobsen, 2006) and so on. Such energy symbiosis is also very contributable to China's condition.

Table 4-3 Summary of comprehensive utilization of coal flying ash

Building materials	**Refining and grain refinement composite material**	**Functional materials**	**Agricultural application**
Sintered brick	Extracting unburned coal	Fly ash flocculants	Soil amendments
Cement compound material	Extraction of metallic iron	White carbon black	Multi-element compound fertilizer
Steam-cured fly ash brick	Extraction of Al_2O_3	Adsorption material basis of fly ash	
Substitution of clay with coal fly ash for cement production	Extraction of hollow glass bead		

Source: (Li, et al., 2010)



*GJ

**SH is short for sensible heat

Figure 4-10 Waste heat utilization potential for typical long-process iron/steel factory

Source: author's paper: (Zhang et al., 2013a).

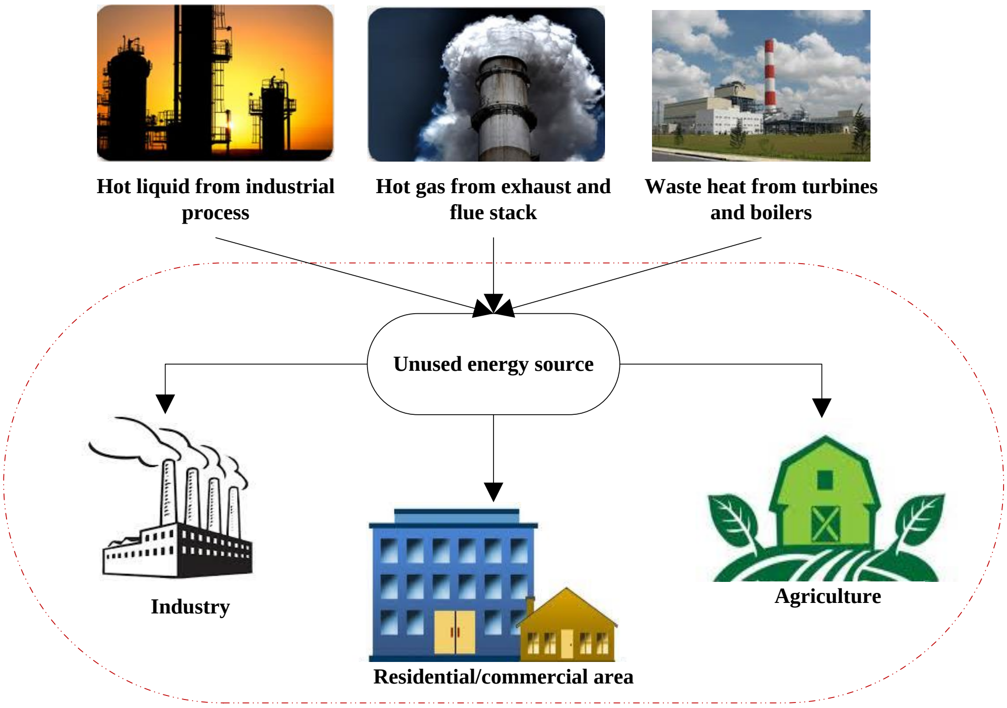


Figure 4-11 The idea of energy symbiosis

Source: author's paper: T. Togawa, L. Dong, et al., 2014.

4.3 Database construction

Finally, based the survey, local industrial symbiosis database is constructed. The very new and local data is collected compared with past works. The data sets in the database include:

- Key technologies' parameters, like the resource and energy consumption during the operation; cost to install and operate the technologies (initial cost; labor cost; operation cost and so on); second emissions from the operation of the technologies.
- Manufacturing process input-output data for certain companies. With these data, how the industrial symbiosis would affect the consumption and emission of the company is able to investigate.
- Carbon emission factors. Some carbon emission factors of certain material and energy is gained through on-site experiments, so as to be more accurate in Chinese condition.
- Basic information on the regional socio-economic condition.

4.4 Summary

This chapter presented a detail procedure on the case selection and survey for data collection. An innovative survey procedure was designed and presented. The participants included institution, central and local governments, as well as local companies. Hundreds of survey sheets were distributed, and on-site investigation was made. An integration of top-down and bottom-up process, as well as the collaboration among government, academic institute and local companies was conducted. The survey paved a foundation to the database construction. This chapter further reviewed the technologies that could be applied in the cases to construct the industrial and urban symbiosis, based on both local investigation and literatures' reviews. Finally, data acquisition and database construction procedure was illustrated. This section provided the necessary information for the case study section.

5.Material/Energy flows analysis and hybrid LCA model development

5.1 Research boundary and model integration

To evaluate the planning, an integrated model is developed to act the following functions:

- To analyze the quantified flows between synergies, which is the basis for evaluation;
- To assess the direct and indirect environmental impacts of the industrial symbiosis, in a life cycle perspective;
- To forecast the future changes of the planned industrial symbiosis activity, so as to support the local socio-economic planning;
- To make a better output of the model, several indicators would be designed.

To serve these functions, an integration model is developed. The boundary and sub-model integration of the model is illustrated in *Figure 5-1*. The core part is the integration of material/energy flow analysis, process based LCA and hybrid IO model. IO model could provide up-stream and down-stream flows information. In this way, a life cycle consumption and emission with and without industrial symbiosis implication could be evaluated. In addition, IO model could reflect the economic and technical change in the future, so as to support scenario analysis. As to the boundary, this research mainly focuses on industries and its linkage with residential and commercial areas, and the material/energy flows among them.

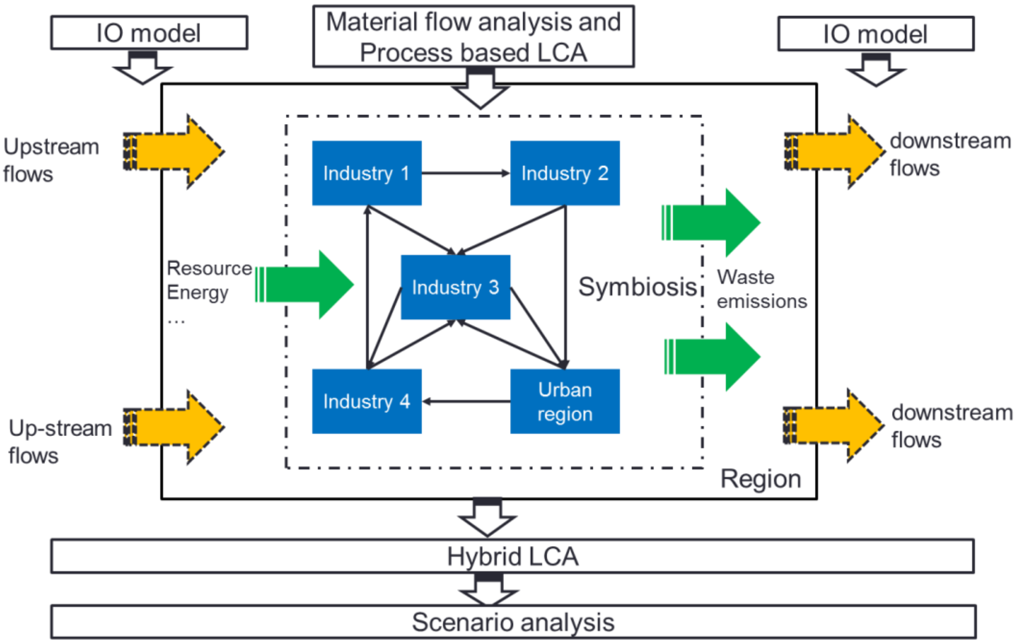


Figure 5-1 Illustration of model integration and boundary

5.2 Model description

This section would describe the sub-models one by one.

5.2.1 Material/Energy Flows Analysis (MEFA)

Quantifying the flows in the symbiosis network is the basis for evaluation. We calculate the difference of principal material and energy flows such as virgin materials, energy, by-product or waste in scenarios with and without the symbiosis, applying the material (Energy) flow analysis (MEFA). A two-step model procedure is conducted as shown in *Figure 5-2*.

The basic material/energy analysis model is a typical process balance model, shown in upper side of *Figure 5-2*. In this case, one company could be seen as one process, if its manufacturing process is single or simple. The flows include material and energy flows, and the material flow is the basis. The input flows include: the flows from environment A_M; from adjacent upstream process F_{M-1}, the recycle flows from other process Q_M. The output flows include: F_M which denotes the flow output from process M. The products flow P_M. Recycle flow R_{M-i} is reclaimed from the process M to feed the upstream process M_{-i}. J_{M+j}, the flow reclaimed from the process M to the downstream process M_{+j}. $D_{M,}$ the dissipative flows discharge to the environment.

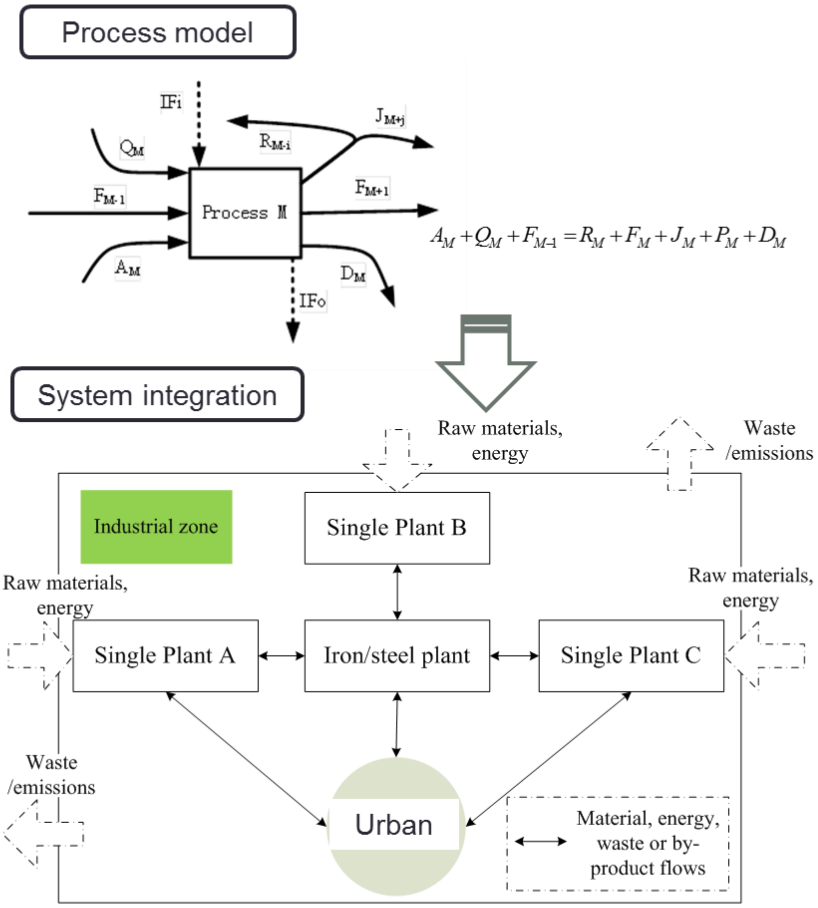


Figure 5-2 Framework of MEFA

The material flows include general raw material such as iron ore, coal, slag, and also include the substance, components and chemical elements such as Fe, C, and S. The material/energy balance equation is:

$$A_M + Q_M + F_{M-1} = R_M + F_M + J_M + P_M + D_M \qquad (1)$$

Based on the process analysis, system integration could be made. In this way, the material flow (Energy) flows between companies or sectors could be quantified and the substitute effects of industrial symbiosis could be calculated. It is also the basis for process inventory analysis. For the company or sector *i*:

$$\boldsymbol{EnvG_{ij}}=\boldsymbol{R_{ij}} \text{ or } \boldsymbol{W_{ij}} \qquad (2)$$

$$\boldsymbol{R_{ij}}=\boldsymbol{S_j}\times\boldsymbol{M_{ij}} \qquad (3)$$

Where, $\boldsymbol{EnvG_i}$ is the avoided consumption or emission for the company *i*. $\boldsymbol{R_{ij}}$ is the avoided resource consumption and $\boldsymbol{W_{ij}}$ is the avoided waste emission due to the symbiotic activity. *j* is the type of resource or waste. When come to the avoided resource, $\boldsymbol{R_{ij}}$ is the multiplication of the resource substitution rate ($\boldsymbol{S_{ij}}$) and the quantity of reused/recycled materials ($\boldsymbol{M_{ij}}$). For the avoided waste emissions, the $\boldsymbol{W_{ij}}$ is the quantity of the recycled waste *j*. It is noted that there is some limitations of the calculation, including exclusion of resource consumption and waste emission that occurs as tradeoff of the symbiosis, incomplete data availability from company, thus it is only the first-proxy quantifications of resource conservation and emissions reduction from the symbiosis.

After quantifying the flows and gaining the avoided consumption or emission, we could calculate the CO_2 emission reduction through the CO_2 emission coefficient of the resources or waste. $\boldsymbol{CR_{ij}}$ is the CO_2 emission reduction from the avoided resource or waste *j* in company *i*, $\boldsymbol{Cof_j}$ is the CO_2 emission coefficient of the resources or waste *j*. The $\boldsymbol{Cof_j}$ could be gained from published reports and literatures. The detailed carbon emission factors are listed in *Table 5-1* (Zhang et al., 2013b).

$$\boldsymbol{CR_{ij}}=\boldsymbol{Cof_j}\times\boldsymbol{EnvG_{ij}} \qquad (4)$$

Table 5-1 The main carbon emission factors in this study

Item	Value	Item	Value	Item	Value
Washed coal $kgCO_2/kg$	2.46	Diesel $kgCO_2/kg$	2.72	Waste steel $kgCO_2/kg$	0.422
Hard coal $kgCO_2/kg$	2.53	Natural Gas $kgCO_2/m^3$	2.09	Dolomite $kgCO_2/kg$	0.477
Coke $kgCO_2/kg$	2.69	BFG $kgCO_2/m^3$	0.836	Limestone $kgCO_2/kg$	0.440
Electricity $kgCO_2/kWh$	0.8494	COG $kgCO_2/m^3$	0.853	Clinker $kgCO_2/kg$	1.05
Plastics $kgCO_2/kg$	1.64	LDG $kgCO_2/m^3$	1.06	Tar $kgCO_2/kg$	3.39

Finally, through the flows analysis, economic benefit ($\boldsymbol{EcoG_i}$), which is defined as the revenue streams or avoid costs through the reduction of virgin materials consumption, waste generation or by-product/waste reuse and recycle in this study, could be quantified. The calculation is according to the material exchange in the symbiosis network:

$$\boldsymbol{EcoG_i}=\boldsymbol{P_{ij}}\times\boldsymbol{R_{ij}}\,(\text{or } \boldsymbol{W_{ij}}) \quad (5)$$

$\boldsymbol{EcoG_i}$ is the economic benefits. $\boldsymbol{P_{ij}}$ is the price for the resource or waste j (particular, for waste, the price is the disposal fee or the price in the trade market). It is noted that we don't discuss invest cost for facilities due to two reasons: (1) we aims to show an intuitive or direct benefit of symbiotic activities, it could be seen as direct benefit. (2) as to most projects, the investment data is neither not available or confidential. Price data could refer to our former research (Dong et al., 2013b).

5.2.2 Hybrid physical input and monetary output model

To help to quantify some upstream and downstream flows of industrial and urban symbiosis, and support scenario analysis, a hybrid input-output model is constructed.

On the basis of previous works about using input-output model in environmental study fields (Giljum S. and Hubacek, 2009; Liang et al., 2010; Xu, 2010; Xu et al., 2008), here we construct an improved hybrid physical input and monetary output model (HPIMO) to assess how industrial symbiosis and waste recycling could contribute to energy saving and pollutants mitigations.

The basic principle is: Material and energy inventory for each sector is gained, and the monetary IO table would provide the consumption coefficient matrix between the sectors each other. In the way, we could convert monetary flows into physical flows.

Table 5-2 shows the structure of Liuzhou HPIMO model. The $n \times n$ matrix M indicates monetary interactions among sectors. The $m \times n$ matrix $\boldsymbol{E}$ indicates physical energy interactions among sectors. The $n \times 1$ column vectors of $\boldsymbol{Y}$ and $\boldsymbol{X}$ indicate final demand and total output of each sector in monetary forms. The $n \times k$ matrix $\boldsymbol{P}$ indicates the pollutants emissions in each sector.

Table 5-2. The structure of hybrid physical input monetary output model

Monetary Input		**Intermediate Monetary Output Sector**	**Final demand**	**Total output**	**Pollutants emissions**
		1 …. n	$\boldsymbol{Y}$	$\boldsymbol{X}$	$\boldsymbol{P}$
Intermediate monetary input	1	$\boldsymbol{A}$	Y_1	X_1	P_{11}
	…		…	…	. .
	n		Y_n	X_n	. . P_{kn}
Added value	**V**				
Total monetary output	**X**				
Physical energy input		**Physical input distribution**			
Energy resource	1 … m	$\boldsymbol{E}$			

The definitions of direct monetary consumption matrix $\boldsymbol{A}$, Leontief inverse matrix $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ and the row balances are keep consistence with previous studies (Giljum S. and Hubacek, 2009; Holub and Schnabl, 1985; Leontief, 1936). The row balances equations are shown as:

$$\boldsymbol{AX}+\boldsymbol{Y}=\boldsymbol{X} \quad (6)$$

$$\boldsymbol{X}=(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{Y} \quad (7)$$

The $m \times n$ matrix $\boldsymbol{E}$ denotes the energy intensity among sectors. The $n \times k$ matrix $\boldsymbol{P}$ denotes the pollutants emissions intensity among sectors. Relationships between total energy consumption and final demand as well as pollutants emission and final demand are shown in equations (8) and (9), respectively:

$$\boldsymbol{D}=\boldsymbol{EX}=\boldsymbol{E}(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{Y} \quad (8)$$

$$\boldsymbol{W}=\boldsymbol{PX}=\boldsymbol{P}(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{Y} \quad (9)$$

$\boldsymbol{D}$ denotes the total or cumulative energy consumption. $\boldsymbol{W}$ denotes the total or cumulative pollutants emissions.

For the inputs, the energy resources were presented in standardized energetic units, the output was presented in monetary units, and air pollutants were presented in mass units. The model could quantitatively represent the correlations between economic sectors by monetary input output table (MIOTs), shaping the connections between the environmental system and the economic system(Liang and Zhang, 2013). The details about the HPIMO table are listed in "Appendix". $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ and $\boldsymbol{D}$ are showed in *Table 5-3* and *5-4*.

Table 5-3 $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ matrix

	Agriculture	Coal mining and washing	Ming of petroleum and natural gas	Ming and processing of non-metal ores	Food products and tabacoo	Texile and leather	Saw mills and furniture	Paper and pulp	Petroleum processing and coking	Chemicals	Non-metal making
1	1.2850	0.1916	0.0000	0.1510	0.5436	0.4664	0.3533	0.2584	0.0793	0.2069	0.1907
2	0.0465	1.1602	0.0000	0.0964	0.0623	0.0553	0.0763	0.1279	0.0386	0.1038	0.2505
3	0.0267	0.0638	1.0000	0.0730	0.0292	0.0250	0.0318	0.0385	0.3657	0.0481	0.0743
4	0.0089	0.0209	0.0000	1.0226	0.0103	0.0092	0.0108	0.0146	0.0037	0.0336	0.1456
5	0.1343	0.0721	0.0000	0.0496	1.1743	0.0888	0.0579	0.0596	0.0168	0.0775	0.0689
6	0.0193	0.0565	0.0000	0.0340	0.0228	1.3133	0.0229	0.0406	0.0082	0.0304	0.0485
7	0.0726	0.2067	0.0000	0.2389	0.0893	0.0761	1.0998	0.1226	0.2146	0.1500	0.2419
8	0.0382	0.0988	0.0000	0.0708	0.0694	0.0436	0.0652	1.3580	0.0206	0.0821	0.1346
9	0.0871	0.2089	0.0000	0.2406	0.0954	0.0813	0.1038	0.1256	1.2155	0.1523	0.2440
10	0.3574	0.6840	0.0000	0.4704	0.3430	0.3832	0.4277	0.5313	0.1369	1.7648	0.6514
11	0.0184	0.0566	0.0000	0.0334	0.0297	0.0176	0.0220	0.0326	0.0085	0.0299	1.1771
12	0.4029	1.4090	0.0000	0.8329	0.5055	0.3930	0.5486	0.6894	0.2011	0.5668	1.2109
13	0.0646	0.2185	0.0000	0.1277	0.0833	0.0652	0.1006	0.1145	0.0343	0.0928	0.1842
14	0.4481	1.5330	0.0000	0.9334	0.5700	0.4382	0.5975	0.7965	0.2212	0.6243	1.3448
15	1.0885	3.6642	0.0000	2.2294	1.3445	1.0427	1.4331	1.7876	0.5309	1.4788	3.1518
16	0.1756	0.6936	0.0000	0.3758	0.2248	0.2125	0.2997	0.3787	0.1070	0.3320	0.6769
17	0.0688	0.2538	0.0000	0.1433	0.0873	0.0684	0.0943	0.1197	0.0352	0.0984	0.2083
18	0.0348	0.1164	0.0000	0.0718	0.0449	0.0355	0.0471	0.0604	0.0177	0.0505	0.1031
19	0.0223	0.0728	0.0000	0.0437	0.0376	0.0216	0.0295	0.0752	0.0107	0.0319	0.0804
20	0.0048	0.0153	0.0000	0.0106	0.0066	0.0050	0.0064	0.0085	0.0027	0.0077	0.0141
21	0.1227	0.3782	0.0000	0.3230	0.1648	0.1251	0.1657	0.2078	0.0616	0.1942	0.3825
22	0.4219	1.2955	0.0000	0.8349	0.5708	0.4516	0.5591	0.7360	0.2210	0.6413	1.2196
23	0.0614	0.1921	0.0000	0.1700	0.0800	0.0615	0.0805	0.1051	0.0335	0.0949	0.1765

$(\boldsymbol{I}-\boldsymbol{A})^{-1}$ matrix (continued)

Iron and steel	Non-ferrous metal	Machinery	Transportation equipment	Electricity, steam and hot water supply	Electric equipment and machinery	Telecommunication products	Environmental production industry	Construction	Transportation	Commercial and service	Other Public service
0.1166	0.1063	0.2581	10.9416	0.1004	0.1016	0.1823	0.1697	0.2035	0.5523	0.1569	0.1557
0.1210	0.0948	0.1909	8.1807	0.3294	0.0825	0.1348	0.1207	0.1659	0.3498	0.0901	0.1083
0.0457	0.0395	0.0875	3.7920	0.0350	0.0365	0.0615	0.0649	0.0759	0.2198	0.0442	0.0551
0.0144	0.0124	0.0293	1.2585	0.0104	0.0119	0.0230	0.0182	0.0567	0.0534	0.0131	0.0171
0.0451	0.0415	0.1054	4.3443	0.0395	0.0402	0.0725	0.0655	0.0784	0.1937	0.0817	0.0603
0.0293	0.0267	0.0654	2.9168	0.0281	0.0246	0.0465	0.0411	0.0501	0.1257	0.0383	0.0399
0.1486	0.1284	0.2836	12.2927	0.1138	0.1184	0.1990	0.2113	0.2467	0.7166	0.1432	0.1788
0.0600	0.0607	0.1434	5.9142	0.0537	0.0601	0.1095	0.0891	0.1108	0.2568	0.0914	0.1144
0.1499	0.1296	0.2865	12.4167	0.1150	0.1196	0.2011	0.2132	0.2490	0.7228	0.1450	0.1805
0.4011	0.3719	0.9472	41.4437	0.3374	0.3831	0.7331	0.5863	0.7054	1.7570	0.4270	0.5602
0.0387	0.0343	0.0728	3.2594	0.0283	0.0310	0.0688	0.0464	0.2705	0.1367	0.0348	0.0451
2.1461	1.2982	2.1652	90.3736	0.6896	1.0971	1.4293	1.3101	1.5729	3.7072	0.8764	1.0842
0.1244	1.1621	0.3315	13.2284	0.1114	0.1197	0.2783	0.2016	0.2375	0.5508	0.1359	0.1681
0.9128	0.8602	3.2905	100.7913	0.7648	0.7174	1.4552	1.8970	1.4830	4.1300	0.9705	1.2359
2.0056	1.8377	4.8591	250.2164	1.8031	1.6148	3.3766	3.0409	3.5303	10.1894	2.3746	2.9055
0.4504	0.3591	0.7484	32.0833	1.9135	0.3160	0.5219	0.4698	0.5865	1.3728	0.3640	0.4269
0.1359	0.1303	0.3490	15.2381	0.1234	1.2222	0.3034	0.2142	0.2731	0.6311	0.1566	0.1912
0.0684	0.0667	0.1837	7.4323	0.0609	0.1300	1.7292	0.1111	0.1174	0.3110	0.0952	0.1031
0.0970	0.0622	0.1125	4.6813	0.0359	0.0525	0.0736	1.5693	0.0827	0.1925	0.0467	0.0576
0.0107	0.0093	0.0221	0.9136	0.0089	0.0086	0.0148	0.0138	1.0201	0.0441	0.0169	0.0166
0.1980	0.2044	0.4845	21.5672	0.2061	0.1843	0.3433	0.3383	0.4122	1.9796	0.2548	0.2969
0.8479	0.7805	2.0159	80.1170	0.7528	0.7425	1.2892	1.2255	1.3651	3.4264	1.9407	1.1064
0.1117	0.1101	0.2575	11.4608	0.1130	0.0931	0.1825	0.1655	0.2014	0.4933	0.1437	1.1968

Table 5-4 $\boldsymbol{D}$ matrix

Ene type	Agriculture	Coal mining and washing	Ming of petroleum and natural gas	Ming and processing of non-metal ores	Food products and tabacoo	Texile and leather	Saw mills and furniture	Paper and pulp	Petroleum processing and coking	Chemicals	Non-metal making
1	107.4794	290.3028	0.0000	233.8174	125.2449	120.0338	146.7439	392.8882	49.8542	364.3244	574.8665
2	55.1370	187.2567	0.0000	140.8647	68.1759	54.1218	74.5025	93.5831	27.1178	89.8998	165.8677
3	0.6036	1.6714	0.0000	1.0460	0.6904	0.6182	0.7979	1.0009	0.2741	1.7577	1.4901
4	0.2939	0.8280	0.0000	0.5160	0.3584	0.2986	0.3787	0.4878	0.1327	0.8133	0.8141
5	0.0034	0.0105	0.0000	0.0065	0.0041	0.0034	0.0044	0.0057	0.0016	0.0071	0.0093
6	0.4610	1.3992	0.0000	0.8582	0.6563	0.4599	0.6044	1.4447	0.2163	0.9606	3.6572
7	0.0473	0.1130	0.0000	0.0745	0.0533	0.0496	0.0608	0.2439	0.0203	0.1728	0.1088
8	0.0010	0.0033	0.0000	0.0020	0.0012	0.0009	0.0013	0.0016	0.0005	0.0013	0.0028
9	0.0045	0.0154	0.0000	0.0094	0.0057	0.0044	0.0060	0.0079	0.0022	0.0063	0.0135
10	0.2822	1.1143	0.0000	0.6038	0.3611	0.3413	0.4815	0.6084	0.1719	0.5334	1.0898
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12	301.4265	634.9133	0.0000	420.2181	298.3523	327.0665	375.2078	467.1243	121.9208	1401.2680	607.2854
13	19.4371	52.6176	0.0000	32.5909	23.9214	26.1684	24.8644	46.5242	8.6422	50.8155	71.1730
14	0.0085	0.0337	0.0000	0.0182	0.0109	0.0103	0.0146	0.0184	0.0052	0.0161	0.0329

Continued

Iron and steel	Non-ferrous metal	Machinery	Transportation equipment	Electricity, steam and hot water supply	Electric equipment and machinery	Telecommunication products	Environmental production industry	Construction	Transportation	Commercial and service	Other Public service
229.3746	197.2524	382.5033	16398.8863	354.6081	165.5229	281.6699	236.7385	344.7805	692.4326	176.5891	221.0343
278.4435	171.1700	286.6807	11984.1025	91.6858	144.2093	190.4480	173.6023	209.5709	492.1866	116.4867	144.4354
0.9850	2.9761	2.9106	105.1855	0.8355	0.8634	1.7861	1.9260	1.7012	4.3690	1.0495	1.3374
0.4794	0.5409	1.2238	52.8542	0.5349	0.4919	0.8054	0.7483	0.8266	2.1850	0.5220	0.6533
0.0061	0.0080	0.0191	0.6901	0.0052	0.0050	0.0102	0.0113	0.0103	0.0284	0.0067	0.0085
1.0240	0.9400	2.1338	88.9734	0.8706	0.7826	1.3838	1.3001	1.8555	3.6753	0.8956	1.1174
0.0648	0.0640	0.1548	7.1671	0.0563	0.0587	0.1152	0.0963	0.1148	0.2997	0.0754	0.0958
0.0018	0.0017	0.0044	0.2262	0.0016	0.0015	0.0031	0.0027	0.0032	0.0092	0.0021	0.0026
0.0090	0.0085	0.0307	1.0220	0.0077	0.0071	0.0146	0.0179	0.0149	0.0418	0.0098	0.0124
0.7237	0.5769	1.2024	51.5474	3.0740	0.5078	0.8385	0.7549	0.9428	2.2057	0.5848	0.6859
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
379.4104	342.2661	844.7612	36853.6923	568.5826	343.8368	644.4542	523.9379	633.8482	1564.4383	385.1376	497.0834
46.2267	52.3966	75.0583	3159.9339	44.4304	32.7845	54.2714	46.5973	60.0716	133.3265	35.1825	43.2188
0.0219	0.0174	0.0363	1.5576	0.0929	0.0153	0.0253	0.0228	0.0285	0.0667	0.0177	0.0207

Note: energy types and input could be seen in *Table S-2* in the appendix

5.2.3 Hybrid LCA model

- Establishment of Hybrid LCA model

LCA is popular tool to assess the industrial symbiosis. In some developed countries, process LCA is popular and useful to quantify the industrial symbiosis. But in China, Some life cycle inventory data like the upstream material supply, transport are usually not available, thus process based LCA could not fully support this study (Laura, 2011). On the other hand, in order to overcome the truncation error of process-based LCA, and resolve the lack of process inventory data, input-output analysis has been integrated with life cycle assessment (Suh and Huppes, 2002). In this so called “input-output life cycle assessment (IO-LCA)”, an environmentally extended input-output table is usually applied without using any process-based life cycle inventory data (Suh and Huppes 2005). However, such “IO-LCA” could not reflect the IS process specificity.

To resolve the problems, process-based LCA and data from the established hybrid input-output model are combined. Several key process data of certain symbiosis is gained from survey and literature review, and IO table would complement the data like the upstream and substitution flows. Even though there is some uncertainty on the hybrid LCA model, it could complement the LCA for IS in China’s data scarcity condition.

Detail description on the hybrid LCA model would be presented below. Traditional “process based LCA” and “input-output LCA” are described first.

- Process based LCA analytical framework

Process based LCA includes four key phases (Laura, 2011):

(1) Goal and scope definition. In this study, the goal is to evaluate the environmental impacts of the industrial symbiosis, in different life cycle phases: raw material extraction; transportation; production; consumption and waste disposal. The scope is industrial symbiosis system and its related supply-demand chain. The unit function is 1 t product related to the symbiosis system.

(2) Life cycle inventory analysis (LCI): in the process of LCI, the input and output data related

to the products in the symbiosis are collected and complied.

(3) Impact analysis: with the inventory data, the environmental impacts could be calculated. The impact category in this study especially focus on CO_2 emissions and resource/fossil fuel saving.

(4) Interpretation: make further analysis and improvement proposal based on the inventory analysis and impacts analysis.

The advantage of process based LCA is it could specify the symbiosis process. The avoided consumption and emission within the symbiosis process could be specifically analyzed. However, when application, the detail inventory data is usually not integrated. In addition, some cut-offs flows outside the IS process could not be reflected.

- Input-output LCA

There are some problems of truncation error, e.g. the neglect of the trade-off flows, in the traditional process based LCA. In order to improve such problems, input-output analysis is usually integrated with LCA (Suh and Huppes, 2002). In the input-output LCA (IO-LCA), economic input-output or environmental input-output data could be used for LCA. The advantage of IO-LCA is, the production of goods and services can be completely traced through the supply chain.

In the IO analysis, Leontief inverse matrix $(\boldsymbol{I}\text{-}\boldsymbol{A})^{-1}$ could provide the total consumption coefficients for each sector (or products). In the way, the cumulative resource consumption and emission in a lifecycle way could be calculated.

Based on the process LCA and IO-LCA, then the hybrid LCA model is presented in detail:

- System boundary of hybrid LCA for IS system

System boundary is shown in *Figure 5-3*. Process based method could specifically analyze the industrial symbiosis process, while input-output model could supply the data of upstream flows, transportation, and some avoided consumptions and emissions.

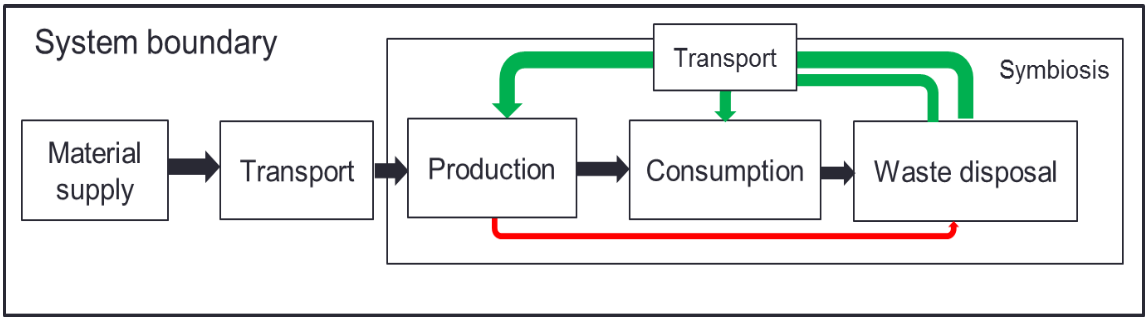


Figure 5-3 System boundary of LCA for IS

■ Calculation approach

Process inventory data (showed as *Table 5-5*) of certain symbiosis is gained to calculate the increased/avoided consumption, emission in the IS process and each related sector. This is the first round calculation for the IS.

Based on process inventory data, increased or avoided consumption and emission in the IS could be calculated based on equation (10). Emissions could be further calculated based on the consumption and waste change, times the emission factors, which is described in equation (4).

$$\boldsymbol{R_{ij}=S_j \times M_{ij}} \qquad \boldsymbol{W_{ij}=r_j \times TW_{ij}} \quad (10)$$

IO table would complement the data like the upstream and downstream flows. The upstream material related emissions could be calculated by equation (11), and waste disposal related emissions could be calculated by equation (12). ***E*** denotes the energy intensity among sectors. ***P*** denotes the pollutants emissions intensity among sectors. As the matrix E denotes the energy intensity among sectors, thus emission related to certain sectors (like transportation) could also be calculated. *i* means certain sector related to the emissions of each life cycle phases, showed as equation (13). IS related material and energy consumption and intensity could be calculated based on the process based LCA.

$$\boldsymbol{E_{mat}=\sum Cof_j \times V_{mat,k} \times E(I-A)^{-1}Y} \quad (11)$$

$$\boldsymbol{E_{wat}=\sum Cof_j \times V_{wat,l} \times P(I-A)^{-1}Y} \quad (12)$$

$$\boldsymbol{SE_i=Cof_j \times E_i(I-A)^{-1}Y_i} \quad (13)$$

$\boldsymbol{V_{mat,k}}$-Resource/energy ***k*** intensity related to IS;

$\boldsymbol{V_{wat,k}}$-Waste ***l*** intensity related to IS;

$\boldsymbol{SE_i}$-Total (commulative) emissions for certain sector

$\boldsymbol{Cof_j}$-emission factor.

■ Life cycle phases focused in this study

In the analysis, this study focus on “raw material supply”, “energy consume in production”, “transport” and waste disposal (*Figure 5-4*). Cut-off flows of service (consumption side) are not considered, according to the theme of this study and data availability.

Table 5-5 Example of process inventory data

Items	Products	Consumption
1 ton scrap tires	0.6500 ton rubber powder	0.0369 tce electric power
1 ton coal flying ash	1 ton cement	0.0007 tce electric power and 5.8900 ton of water

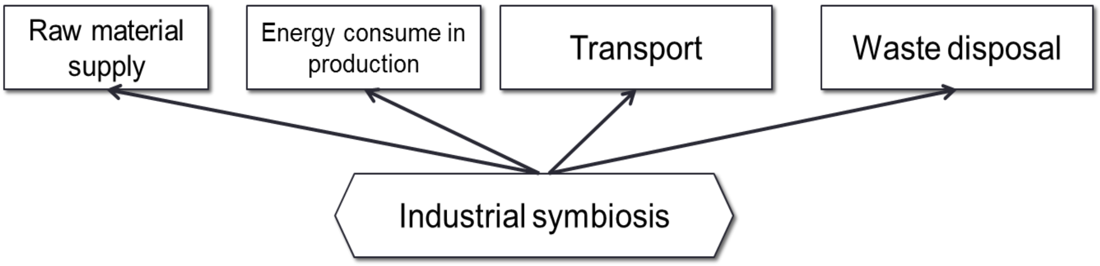


Figure 5-4 Life cycle phases of IS focused in this study

5.2.4 Scenario analysis

Scenario analysis is important to support policy making. Input-output modeling approach provides useful tool to simulate the effects of certain measure on the future scenarios, as it could model how the final demand and technical change could affect different sectors and the whole system.

Based on the established model, simulation algorithm is designed for scenario analysis (*Figure 5-5*). Key steps including:

- Scenarios are set depending on designed measures. In this study, the socio-economic economic setting is based on local 12th five year planning. The technical scenarios are mainly our industrial and urban symbiosis planning.
- Detail variables and constants are chosen based on the scenarios. Parameters are set accordingly. Detail parameters setting would be in the "Case study section".
- Within the scenarios, economic structure and material intensity coefficient is indicated by the model, according to material and energy efficiency matrix and material and energy distribution.
- The model calculates the total resource required and waste generated by the economic-ecological system represented by corresponding scenarios.
- Results are calculated and could be further interpreted, e.g., use some indicators.

As to the scenario year, it is well known that China (both in central government and local government level) has launched the five year planning to issue the future five years' socio-economic development, technology advancement and so on. It is one of the most important guideline for future development in China. To match this policy, our scenario year setting would follow the 12th five-year planning (2011-2015). All the scenarios' year is set up to 2015 (2015 is the final target year for China's 12th Five-Year Planning, FYP). Related economic growth, demand change, technologies change in each economic sector is set based on local governmental documents.

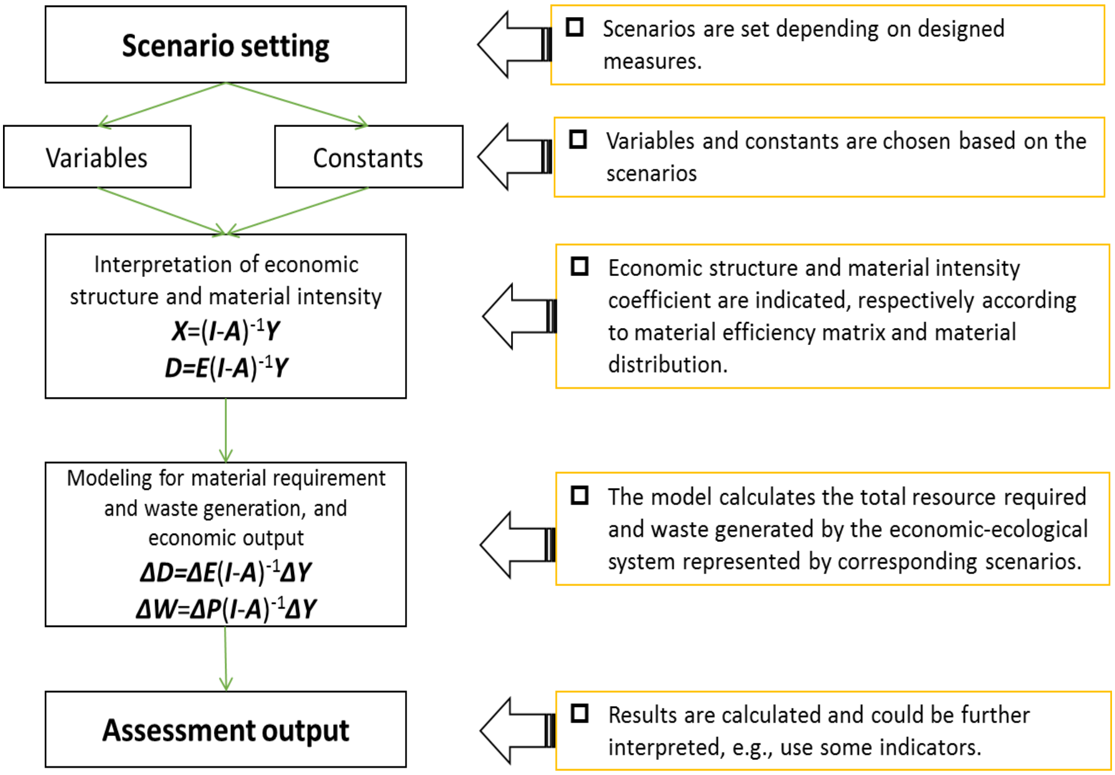


Figure 5-5 Simulation algorithm for scenario analysis

5.3 Summary

This chapter presented the integrated model development. Research boundary, methodology of material/energy flow analysis, establishment of city-level hybrid input-output model, integration of IO-LCA and process based LCA, construction of hybrid LCA, as well as algorithm of scenario analysis was presented. To help to make quantitative assessment on the following industrial symbiosis planning, and to resolve the problems of lacking inventory data, process based LCA and data from the established hybrid input-output model was combined. Several key process data of certain symbiosis was gained from survey and literature review, and IO table complemented the data like the upstream and substitution flows. Through the model development, life cycle impact of planned IS was able to be evaluated in China’s data availability condition.

6. Case study-Assessment on a national pilot project in Jinan city

This section would make an investigation and evaluation on the national industrial symbiosis pilot project in Jinan city. The results could serve to the IS planning in other city.

6.1. Importance of the iron/steel industry to industrial symbiosis in China

As one of the national pillar industries, Chinese iron/steel industry is in large scale and rapid growth (*Figure 6-1*). The total production of crude steel in China had grown from 95.36 million tons in 1995 to 567.84 million tons in 2009, overtook Japan as the world's largest producer in 1996. The share of the world steel production had leaped from 12.68% in 1995 to 46.39% in 2009[11]. Meanwhile, as an energy intensive industry (EII), the booming energy consumption and environmental pollution emissions are serious problems for this industry. In China, it accounts to about 0.6 to 0.8 ton coal, 1.6 ton iron ore, 3 to 8 ton water to produce 1 ton crude steel, with a discharges of 2 ton atmospheric pollutant and 0.5 to 0.8 ton solid waste. Take CO_2 emission as example (*Figure 6-2*), in 2009, the CO_2 emission from Chinese iron/steel sector amounts to 1.17 billion tons[12], share 16.29% of Chinese total CO_2 emission(Zeng et al., 2009), nearly equal to total Japanese CO_2 emission(1.22 billion tons in 2009[13])and 50% of the world's steel industry CO_2 emission(Liu and Gallagher, 2010). Therefore, promoting energy efficiency measures and waste reduction strategy in iron/steel industry is significant for Chinese sustainable development.

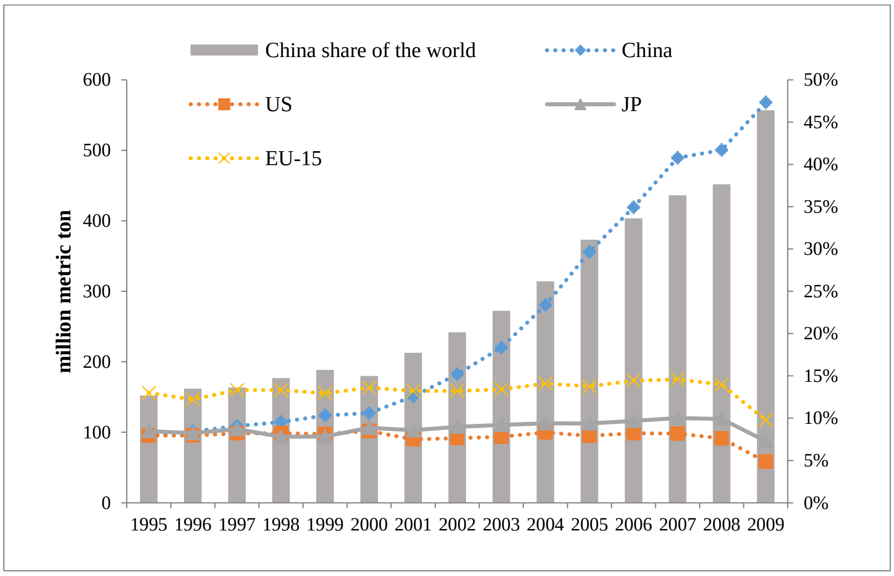


Figure 6-1 Rapid growth of Chinese total production of crude steel
Source: World steel association, Steel Statistical Yearbook

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[11] World steel association, Steel Statistical Yearbook

[12] Data source: CO_2 emission from Chinese iron/steel sector is calculated from the consumed energy type.

[13] Data source: BP statistics, 2010.

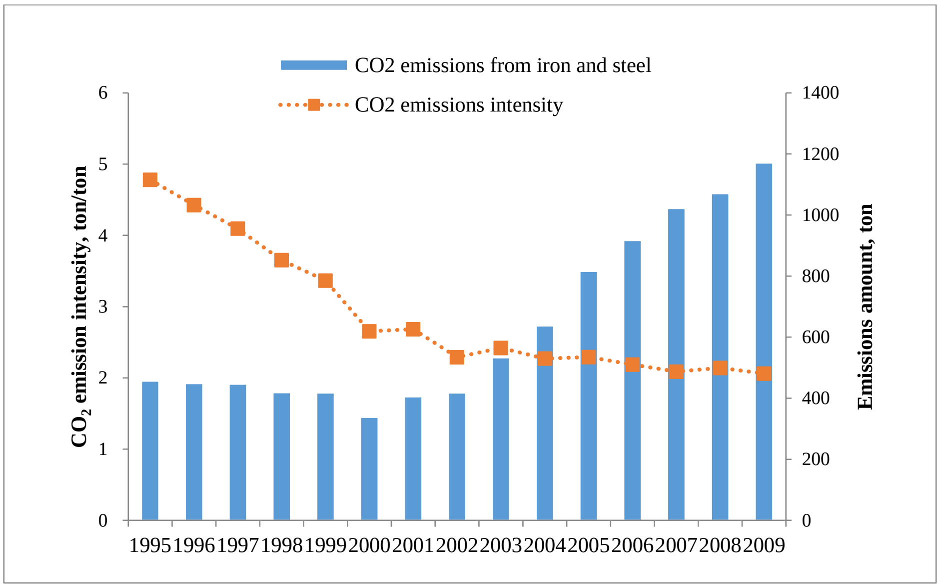


Figure 6-2 CO_2 emission amount and intensity of Chinese iron/steel industry

In developed countries, iron/steel industry already played an important role in IS. Several case studies were conducted. Case in Kwinana, Australia showed the iron plant play an important role in the IS in terms of importing water from the water reclamation plant and providing steam to other company. However, there was no quantified assessments(van Beers et al., 2007). (Johansson and Söderström, 2011) qualitatively presented that IS would provide options of energy efficiency and CO_2 emission reduction for iron/steel plants, including waste from other sectors as reducing agents or fuel and integration with the district heating system. In the symbiosis projects in Mipo and Onsan industrial complexes in Ulsan, South Korea, 21 steel plants participated, gain synergic effect from the steam production/sale and the metal recovery (Park et al., 2008b). In Japan, iron/steel played a core role in the urban symbiosis to utilize the refuse from the society as alternative fuels and resources (AFR)(Van Berkel et al., 2009). Above studies emphasized the cooperation between iron/steel and the other industries not only brought the economic revenue for the company, but also reduced the environmental impacts. However, on the whole, current studies had few real projects' identification and quantitative analysis.

Compared with developed countries, most Chinese iron/steel industry is still in the statement of cleaner production and waste utilization inside the company(Guo and Fu, 2010; Li et al., 2010), which is an early stage of IS (Harris and Pritchard, 2004). There is need to utilize iron/steel industry in a better way to make coordination of economic, environment and social functions. There are new international attention paid to understanding the evolution of IS over time(Chertow and Ehrenfeld, 2012; Ehrenfeld and Gertler, 1997; Paquin and Howard-Grenville, 2012), and there are some advanced iron/steel enterprises in China such as Baoshan iron/steel (in Shanghai)and Jinan iron/steel (in Jinan), have already begun to participate in more linkage with other industries and social function.

However, few studies present their effort and projects, and the accordingly environmental and economic benefit. Especially, very few studies compared with Chinese cases with the other developed countries, which is important for the generalization of IS.

6.2 Industrial symbiosis and circular economy in Chinese iron/steel industry

In China, industrial symbiosis (IS) was an important part of circular economy (CE). CE was inherent with industrial ecology in implying a closed-loop of materials, energy and waste flows(Geng and Doberstein, 2008). It was first proposed in China in 1998 and formally accepted by the central government in 2002. It presented a new concept of more sustainable urban economic and industrial development (Geng and Doberstein, 2008; Zhu et al., 2010). Under the CE strategy, IS was promoted in forms of energy saving and emission reduction, material/energy and or waste exchange and recycling, and eco-industrial Parks (EIP).

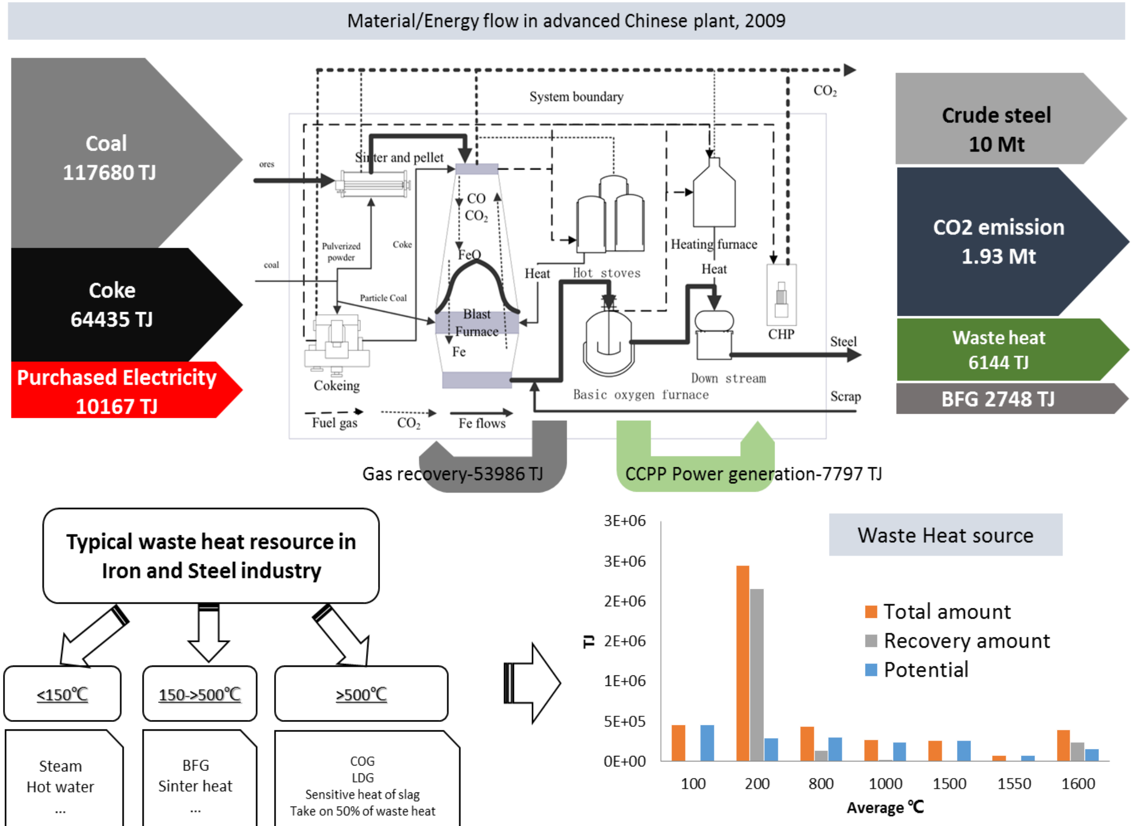
China took circular economy as a basic state policy and enacted the "Circular Economy Promotion Law of the People's Republic of China" in January 1st, 2009. Furthermore, during the national 11th five-year plan (2006-2010), China issued two batches of circular economy pilots in 2005 and 2007 to promote circular economy philosophy into action, including key industries, key areas, key enterprises and urban demonstrations (Geng and Doberstein, 2008; Shi et al., 2010).

As typical process industry, iron/steel industry has specific advantages to take part in industrial symbiosis and circular economy practice. In the two batches of the national pilots, 10 iron/steel companies were included. The advantages mainly include:

Iron/steel manufacturing is an open synthesis process with intensive material and energy, as well as serious pollutions. The process is fit to be a dynamic system with cross-linked material and energy flows. Hence, applied with industrial symbiosis and circular economy strategy could effectively enhance the resource and energy efficiency and reduce pollution emissions.

There is considerable waste heat source from the steel industry, which can be utilized by other factories (*Figure 6-3*). Meanwhile, steel plant can import, for example, fuel and reducing agents, which make iron/steel industry is feasible to be the core of an eco-industrial network and links with other industries in terms of the exchange of energy, water, and by-products or waste in a large scale. From the technology and facilities perspective, the steelmaking core facilities such as the metallurgy furnaces are compatible for nearly all the physical material due to its operating features of large scale and high temperature. As a result, iron/steel manufacturing process provides an ideal place for the co-processing of materials, energy and waste. These are of importance for symbiotic network construction.

Large iron/steel enterprise has the potential to coordinate industry and environment to constitute an integrating eco-industrial system. Its social functions such as waste material treatment and energy transition can link it with urban communities. Examples include the absorption of bulk municipal waste and provision of excess metallurgy energy for residential heating.



Note: BFG-blast furnace gas; COG-coke oven gas; LDG-converter oven gas

Data Source: Survey in 2007 by Cai, et al., in 20 main companies.
The steel production is 489 million ton, in 2007.

Figure 6-3 material and energy flows analysis in the case plant

6.3 Case study on the national iron/steel centered industrial cluster

We would introduce and analyze an advanced iron and steel centered low-carbon IS system in Jinan, which belong to the national circular economy pilot project. It could be seen as the China's advanced level promotion on IS.

Jinan city is located with large scale iron/steel company and clustered with other heavy industries as the chemicals, cement, and so on, the Jinan government promotes an iron/steel centered low-carbon industrial symbiosis system. Since 2005, this project becomes a national circular economy pilot project (Dong et al., 2013b; Li et al., 2010). It could be seen as an advanced practice in China.

6.3.1 Industrial symbiosis network analysis

IS network in Jinan is analyzed first. *Figure 6-4* shows the current low-carbon IS system. Large iron/steel enterprise could act to coordinate economic, environmental and resources to constitute an integrating eco-industrial system. Its social functions such as waste material treatment and energy transition can link it with urban communities. Examples include the absorption of bulk municipal waste and provision of excess metallurgy energy for residential heating.

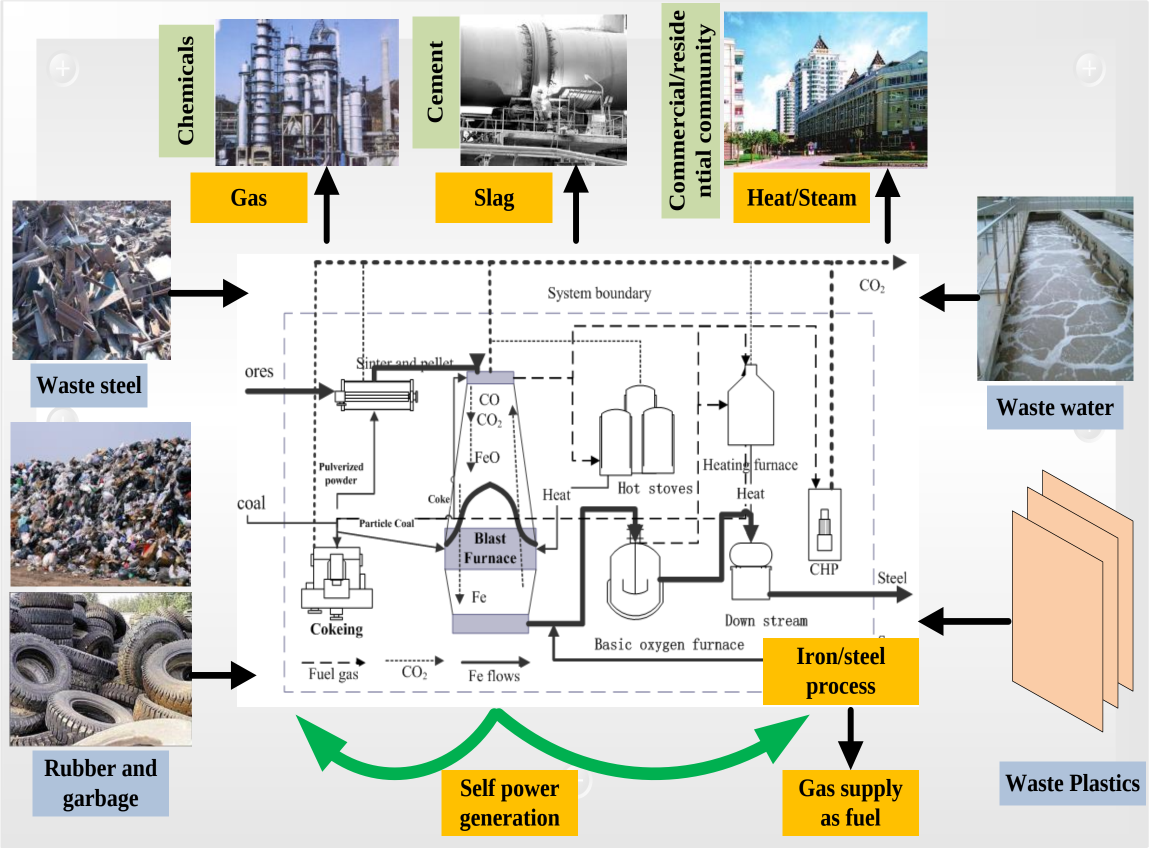


Figure 6-4 Schematic graph of Iron/steel centered low-carbon IS system in Jinan

Figure 6-5 shows the detail synergies and flows in the network. 12 IS activities are established and one is being constructed. Among the 13 linkages, 9 symbiotic links are between industries, and 4 links urban community with iron/steel plants. 9 symbiotic links are material symbiosis (reuse and recycling of materials) and 4 are energy symbiosis (second energy or waste heat utilization).

In material and energy flow perspective, there is over 10 million materials and 20 thousands tce energy exchanged in the whole symbiosis network, not only including traditional exchanged materials as waste steel, BF slag, waste water, but also new materials through the technology innovation such as gas and steam provided for nearby industries and community, red mud and chromium slag from heavy chemical industry, by-product utilized by cement and construction industry, etc. A pilot program about incinerate waste plastics is being planned and would carried out in 2012, the designed amount was 200 thousand ton annually according to the survey, the potential CO_2 emission reduction would be 592.8 thousand tons[14]. The detail numbers are summarized in *Table 6-1*.

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[14] According to the survey, the substitution rate of waste plastics is 4%, one ton waste plastics equals to 1.2 ton coal equivalent.

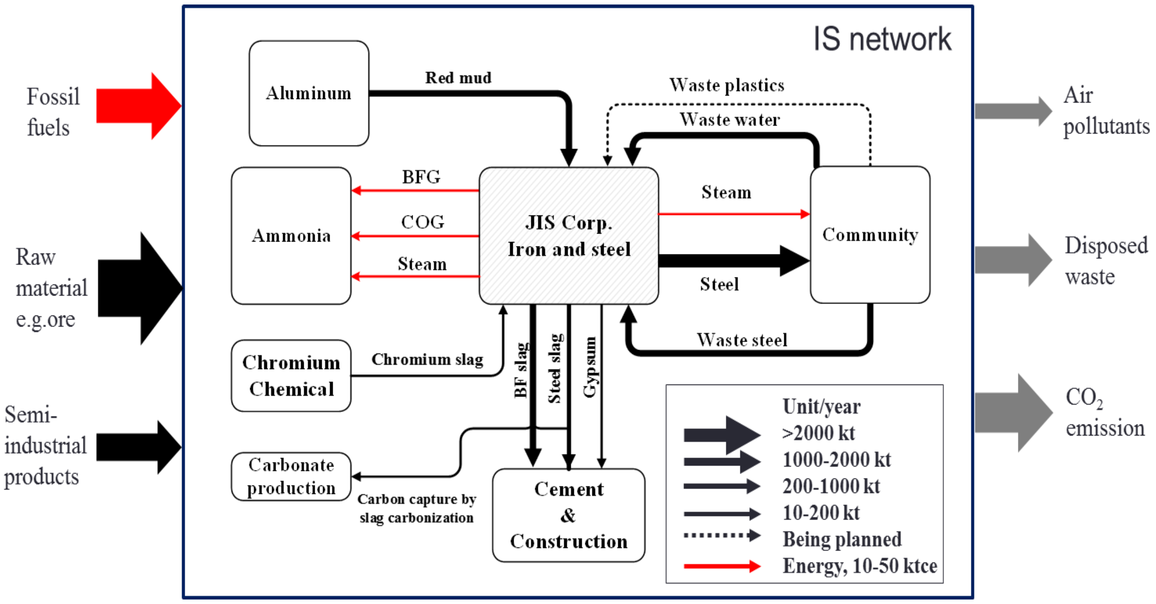

Figure 6-5 Quantified material/energy flows in the IS system in Jinan city

Note: tce-ton coal equivalent. 1 tce =29.27 GJ; BFG-blast furnace gas; COG-coke oven gas.

Table 6-1 Material/energy exchanges in the IS network in Jinan

#	**Symbiosis**	**Resource/waste exchange**	**Participants**	**Volume**
1	Production of powder from slag	BF slag	Iron/steel-> cement	1.2 Mt/year
2	Recycling of steel slag	Steel slag	Iron/steel -> cement/construction	1.2 Mt/year
3	Red mud reuse to refine ferrous element	Red mud	Aluminum->Iron/steel	1.6 Mt/year
4	Alternative fuels for ammonia production	Steam	Iron/steel->chemical	60kt/year
5	Alternative hydrogen production	COG	Iron/steel-> chemical	47.16 Mm^3/year[a]
6	Recycling of desulfurization byproduct	Gypsum	Iron/steel-> cement	10 kt/year
7	Recycling of chromium slag as sinter ore	chromium slag	Chromium chemical->Iron/steel	120 kt/year
8	Industrial water reuse	Urban waste water	community-> iron/steel	2 Mt/year
9	Waste steel recycling	Waste steel	Community(recycling company)->Iron/steel	1.82 Mt/year
10	Steam provision for community	Steam	Iron/steel-> community	10.9 ktce/year
11	BFG supply as fuel	BFG	Iron/steel->chemicals	222.81 Mm^3/year (10.9 ktce/year)
12	CO_2 capture by slag and carbonate production	CO_2, slag	Iron/steel->chemicals	8000t/year
13	Waste plastics recycling	Waste plastics	Community(recycling company)->Iron/steel	200 kt/year

[a] It is not confirmed whether the chemical company use the COG as fuel or raw material, here we consider it as raw material to produce hydrogen.

6.3.2 Evaluation on environmental gains

(1) Material/energy saving and waste reduction effect

Based on the IS network analysis, the related environmental benefit is quantified. Detail information is shown in *Table 6-2*. There is large material/energy saving and waste reduction is achieved through the IS project. In total, more than 4 million ton raw material and 1.5 million tce energy is saved, and more than 4 million ton waste is reduced.

(2) CO_2 reduction

Based on the materials/energy saving and waste reduction effects, we calculate the CO_2 reduction potential. It is noted that based on the data availability, not all the CO_2 reduction could be accounted. Thus the reduction potential could be seen as the lowest one.

Results highlight that in total, 3944.05 ktCO_2/year emissions is reduced. What is more, if we investigate from the perspective of material symbiosis and energy symbiosis, in current condition, the CO_2 reduction is much more in the material symbiosis than energy symbiosis, due to the scale difference. Results show that material and energy symbiosis could reduce CO_2 emissions by 3792.42 and 151.62 ktCO_2/year (Results are summarized in *Figure 6-6*).

Table 6-2 Material/energy saving and waste reduction through IS in Jinan

#	**Symbiosis**	**Main environmental benefit**
1	Production of powder from slag	Save raw material of cement. Reduce slag stock-pilling 1.2 Mt/year.
2	Recycling of steel slag	Reduce material for clinker 1.2Mt/year.
3	Red mud reuse to refine ferrous element	Extracted iron ore power 450 kt/year Reduce red mud stock-pilling 1.6 Mt/year
4	Alternative fuels for ammonia production	Save energy 7546tce/year
5	Alternative hydrogen production	Save energy 28970tce/year.
6	Recycling of desulfurization byproduct	Save raw material of construction industry
7	Recycling of chromium slag as sinter ore	Save sinter ore 120kt/year.
8	Industrial water reuse	Save fresh water 2Mt/year
9	Waste steel recycling	Save raw material 2.5t and energy 12.25GJ/t steel
10	Steam provision for community	Save energy 10900tce/year.
11	BFG supply as fuel	Save energy 10900tce/year.
12	CO_2 capture by slag and carbonate production	Reduce 8000t CO_2/year. Reduce 25200t/year slag
13	Waste plastics recycling	Save energy 240000tce/year

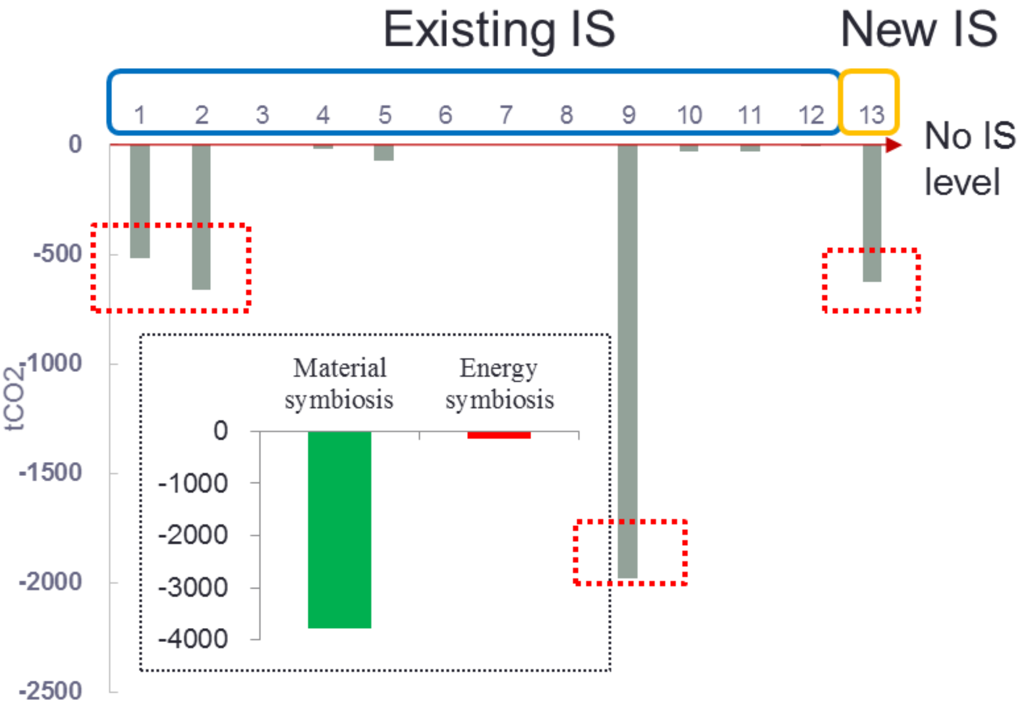

Figure 6-6 CO_2 reduction through the IS in Jinan

Note: The number is in accordance with Table 6-2.

6.4 Discussion of results

In this section, based on the first hand data of CE and IS projects in China, a quantified assessment on the environmental and economic gains of IS in one national pilot project in Jinan city was conducted.

This case stands for the advanced pilot. However, for most of the cases, the industrial symbiosis is still in the stage of bulky solid waste exchange. The system stability, the lack of the standard technology and products, the immature waste management system and the lack of supporting policy are critical factors for IS promotion.

To help to resolve the issues, several policy implications are needed to address:

In order to improve the problems of system stability and the lack of standard technology/products, it is required the promotion of circular economy technology and industrial linkage technology. Circular economy technology and product standard, as well as quality standards for the input material as guidance for waste generators should be established so as to guarantee the stable product and waste flows. In addition, there is need to develop a comprehensive decision tool which based on material flow analysis and life cycle analysis, to direct waste materials between industries and external waste generators in an optimized manner.

To improve the immaturity of waste management system and regulation system, on the one hand, in order to establish a stable and innovative municipal solid waste management system needed to establish, public or commercial collectors needed to be encouraged to participate in the waste collection and recycling. On the other hand, the third party should be made to coordinate the stakeholders of the symbiosis. For sharing information between the industries or companies, the establishment of information platform was important. For the regulation system improvement, waste management legislation considering extended responsibility of the companies should be launched and implemented widely.

6.5 Summary

In this chapter, investigation and assessment on the symbiosis network in the national pilot project in Jinan city was made. Results highlighted extinguish environmental benefit through the IS implementation: in total, more than 4 million ton raw material and 1.5 million tce energy was saved, and more than 4 million ton waste was reduced. Considerable CO_2 reduction was achieved through the implementation of industrial symbiosis. 3944.05 ktCO_2/year emission was reduced and material and energy symbiosis reduced CO_2 emissions by 3792.42 and 151.62 ktCO_2/year respectively. In addition, as an advanced national pilot project, Jinan’s experience could be transformed into local case.

7. Case study-Planning and assessment on local industrial symbiosis in Liuzhou city

Based on the analysis on the national pilot project in Jinan, this section would plan and evaluate a local industrial symbiosis in Liuzhou city. Advanced experiences of Jinan is transformed into Liuzhou and verified with evaluation.

7.1 Planning local industrial symbiosis

Learned from the experience from the national project in Jinan, we apply a comprehensive planning for industrial and urban implementation in Liuzhou city. At the first step of analysis of the region, a database is constructed based on local statistics and so as to provide basic data like natural resource, land use, industry, infrastructure, solid waste and socio-economic information, etc. Such information further incorporated into geographical information system (GIS) for decision making support. This information will be utilized for standardization of local condition analysis and to integrate multi-sphere environmental information on spatial boundaries. After the database construction and local condition analysis, demand-supply analysis is made focused on the material/energy flow and process synergy. Based on above, symbiotic network is planned and related supporting policy is proposed to realize the design. Finally, an evaluation on the cost-benefit of planning would help to make feedback and improve the planning.

As planning procedures, a supply and demand match analysis based on regional industrial features and resource quality is important to make the synergy between processes and sectors. As shown in *Figure 7-1* , in Liuzhou city, based on a match analysis, there are seven types of solid waste and waste heat are identified with high utilization potential: (1) Blast furnace (BF) and Steel slag from iron/steel industry could be reused by cement industry for clinker production; (2) metallurgical gas from iron/steel industry could be reused for ammonia manufacturing; (3) by-products of desulfurization process could be reused to produce ammonium sulfate and further used for fertilizer production; (4) Waste steel from society could be recycled into iron/steel company for reproducing steel. In such way, the life-cycle environmental impacts per unit ton steel would be reduce considerable; (5) municipal waste plastics and scrap tires could be recycled into the furnace of iron/steel and cement industry, so as to substitute fossil fuels; (6) coal fly ash could be reused through extracting valuable element (like aluminum) and producing high value added cement products; (7) excess waste heat generated from power plants could provide to nearby factories.

It is found that there is high potential to implement the industrial symbiosis. Based on the material and energy features of supply side and demand side, symbiosis network is analyzed and planned.

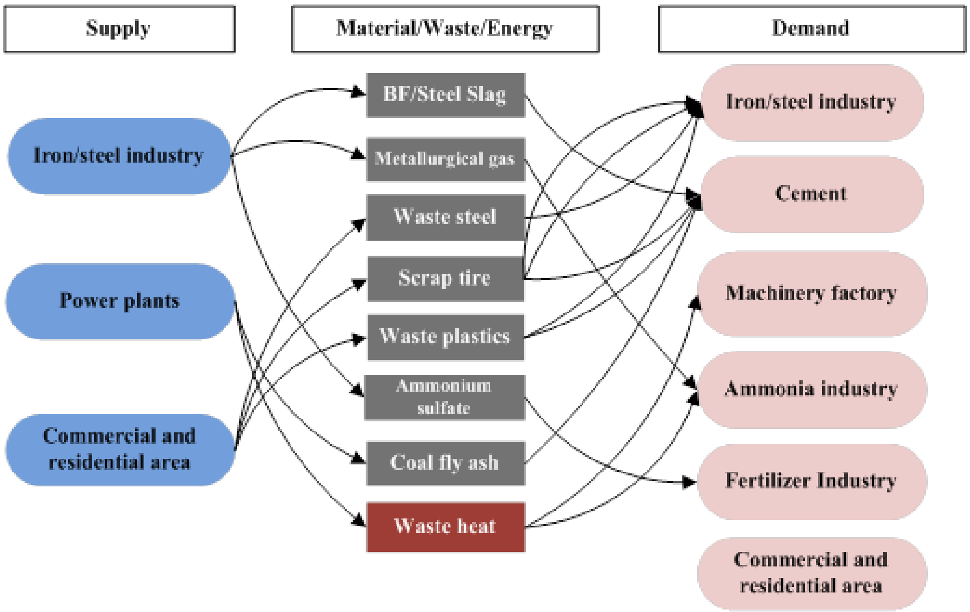

Figure 7-1 Supply and demand match analysis for the symbiosis design in Liuzhou city

Currently, there is limited IS formed in Liuzhou, shown as *Figure 7-2*, the solid lines. The existing symbiotic activities include BF slag being reused to produce powder (1.2 million ton/year), steel slag being utilized by cement and construction industry (1.2 million ton/year), by-product from the desulfurization process being utilized to produce fertilizer (8100 ton/year). The current IS is rather single, some waste and/or byproducts are underused.

Based on the supply and demand match analysis, we design new IS for Liuzhou (*Figure 7-2*, dotted lines).

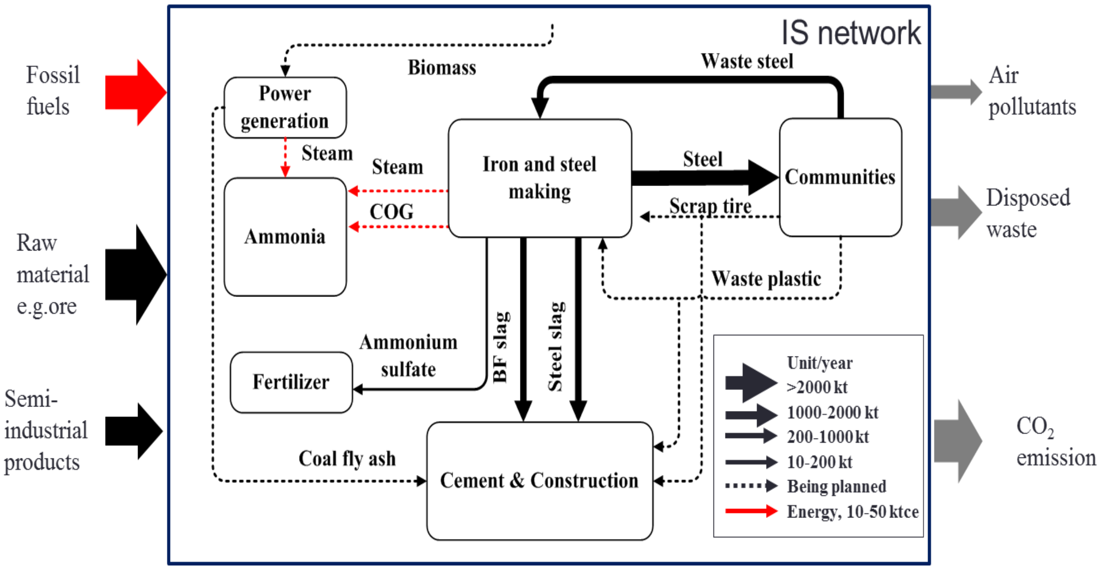

Figure 7-2 Quantified material flows of industrial and urban symbiosis in Liuzhou city
Note: The solid line indicated the current situation. The dotted line indicated planned.

The emerging IS options including: (1) waste plastics can be recycled by iron and steel industry and cement industry; (2) scrap tires (auto mobile is the largest industry in this city) can be burned by the furnace of iron and steel industry and cement industry; (3) flying ash from coal burning can be reused by cement industry/construction sector as raw materials; (4) Energy exchange between industries, like steam, and gas from iron/steel industry; (5) some waste heat utilization opportunities.

With planning, in total, 11 IS are identified and of which, 7 is newly planned based on the local conditions. Among the 11 linkages, 8 symbiotic links are between industries, and 3 linked urban community with iron/steel plants. 7 symbiotic links are material symbiosis (reuse and recycling of materials) and 4 are energy symbiosis (second energy or waste heat utilization). After planning, more than 2.5 million ton material and 45 thousand tce energy is exchanged in the whole network.

7.2 Evaluation on environmental benefit[15]

Based on the established model, environmental benefits are evaluated for the planning.

7.2.1 Evaluation on resource saving and waste mitigation for key synergies

First of all, effects of resource saving and waste mitigation on key synergies are evaluated. After planning, there is considerable environmental benefits are achieved. In total, more than 2.4 million ton raw material and 903.3 thousand tce energy is saved, and more than 2 million ton waste is reduced. Detail number is shown in *Table 7-1*. It is noted that some symbiotic linkage presents particular high environmental benefits, like the waste steel recycling, recycling and reuse of slag.

On the whole, the existing IS contributes to most of the CO_2 reduction, especially for the material symbiosis. The reason is that the existing IS is mainly bulky industrial solid waste recycling, its scale is large. However, planning IS contributes to all the energy symbiosis and increase the diversity of the IS. A lot of underused material/waste could be recycled and reused under the planning IS, like the waste plastics recycling and heat exchange. In addition, it is noted that the planning IS requires more for the waste management system, that is also the reason why currently such IS difficult to realize in Liuzhou. The detail policy implication to resolve this bottleneck would be discussed in the policy implication section.

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[15] Mainly comes from the author's paper: Dong, L., et al., 2013. Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan. Journal of Cleaner Production 59, 226-238.

Dong, L., et al., 2014. Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China. Energy Policy 65, 388-397.

Table 7-1 Material/energy saving and waste reduction through IS in Liuzhou

#	***Symbiosis***	***Main environmental benefit***
1	Production of slag powder	Save raw material of cement. Reduce slag stock-pilling 1.2 Mt/year. Save energy 200000tce/year.
2	Substitute cement material with BF and steel slag	Save material of clinker 1.2 Mt/year and reduce the process CO_2 emission by 660000t/year.
3	Production of fertilizer from desulfurization byproduct	Reduce SO_2 4 kt/year Reduce solid waste stock-pilling
4	Alternative fuels for ammonia production	Save energy 25153tce/year.
5	Waste steel recycling	Save raw material 2.5t and energy 12.25GJ/t steel
6	Alternative hydrogen production	Save energy 47915.4tce/year.
7	Heat exchange (200t/y)	Save energy 12576tce/year.
8	Waste plastics recycling (25kt/y)	Save energy 78000tce/year.
9	Scrap tires recycling (30 kt/y)	Save 19500t rubber
10	Coal flying ash recycling (240 kt/y)	Reduce solid waste. Save raw material of cement and reduce the process CO_2 emission by 240kt/y.
11	Biomass utilization	Results would be shown in scenario analysis.

7.2.2 Evaluation on CO_2 mitigation potential

We further calculate the total CO_2 reduction potential based on the established methodology and the material/energy saving and waste reduction effects. Results highlight that in total, 2347.88 ktCO$_2$/year CO_2 is reduced. Of which, industrial and urban symbiosis contribute to 1493.07 and 854.81 ktCO$_2$/year respectively (*Figure 7-3*).

A lot of underused material/waste could be recycled and reused under the planning IS, like the waste plastics recycling and heat exchange. In addition, it is noted that the planning IS requires more for the waste management system, that is also the reason why currently such IS difficult to realize in Liuzhou. The detail policy implication to resolve this bottleneck would be discussed in the policy implication section.

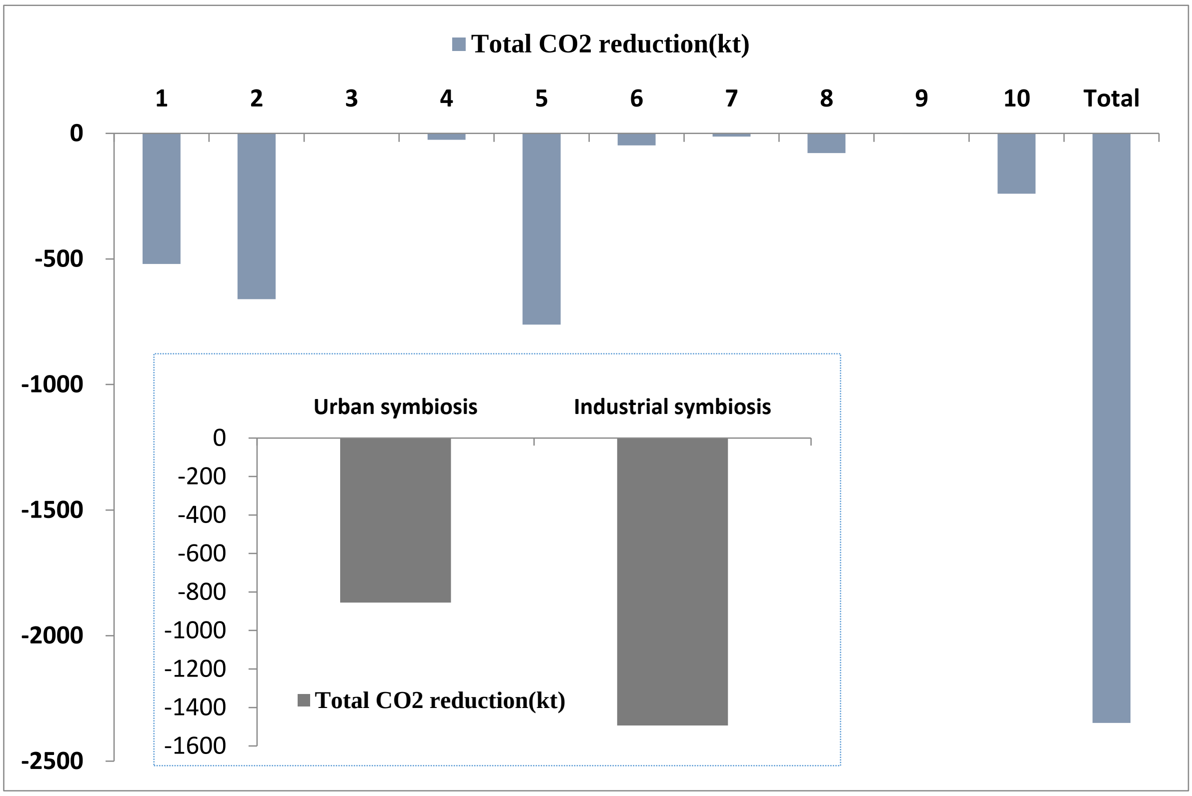

Figure 7-3 CO_2 reduction through the IS in Liuzhou city

Note: The number is in accordance with Table 7-1. Results of biomass utilization is not included.

7.2.3 Evaluation on resource efficiency in supply-demand chain

Finally, effects of industrial symbiosis on resource efficiency is investigated. The results are shown in *Figure 7-4*. It is noted that, with the industrial symbiosis planning, in the resource input side, fossil fuel (mainly coal) import would decrease from 12.37 million ton to 11.10 million ton. Ore which mainly used by process industries like iron/steel, and cement industries, would decrease from 219.07 million ton to 204.75 million ton. In the consumption, mainly trace the energy consumption, which decreases from 10.74 million tce to 9.83 million tce. As to the output side, the solid waste would decrease from 29.86 million ton to 22.96 million ton, while the CO2 emission would decrease from 26.33 million ton to 23.98 million ton.

This result emphasizes that the implementation of IS can enhance the total resource efficiency in the whole supply-demand chain. Through properly improve the flows in the supply and demand chain, the system efficiency is able to enhance.

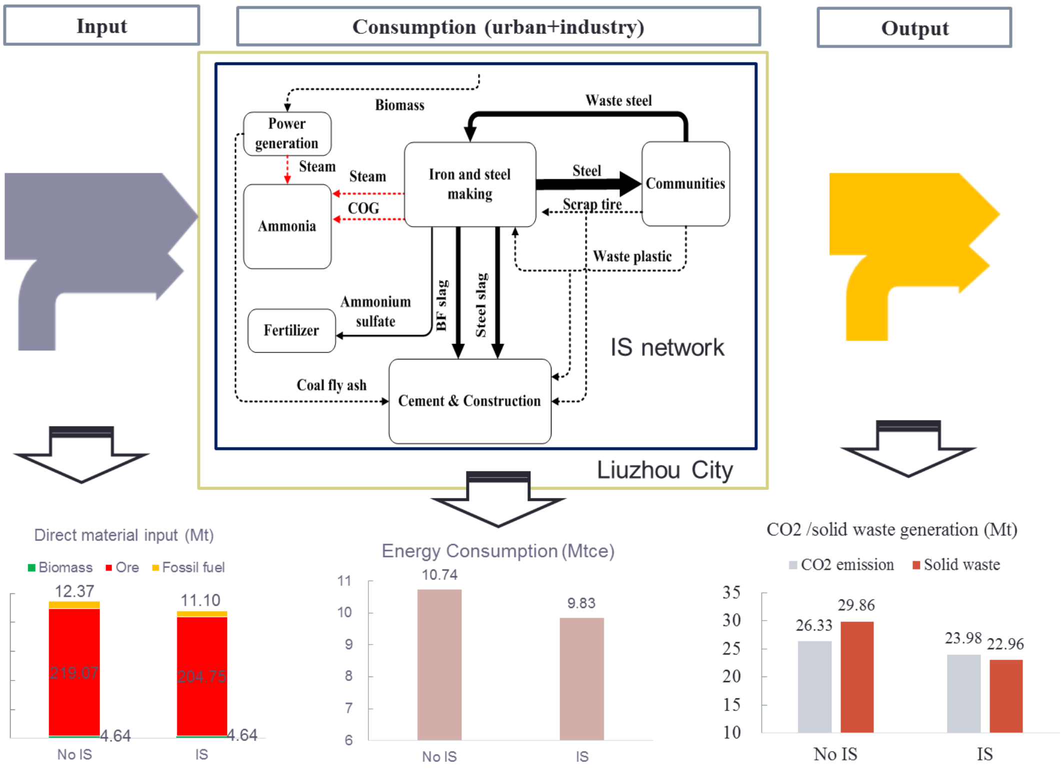

Figure 7-4 Effects of IS on resource efficiency

7.3 Hybrid LCA analysis on key symbiosis[16]

Based on the planning, four synergies is selected to be evaluated with the established hybrid LCA model, according to data availability. Six scenarios are established, shown as *Table 7-2* (Dong et al., 2013a; Dong et al., 2014). This section particularly focuses on the carbon mitigation effects.

Table 7-2 Scenarios description

Scenarios	***Definition***	***Description***
BAU	Business as usual	There no linkages between companies
IS1	Waste plastics recycling	Waste plastics recycled from society to furnace of iron/steel company and cement company, 25kt/y.
IS2	Scrap tires recycling	Scrap tires recycled from society to produce raw rubber, 30 kt/y.
IS3	Coal flying ash recycling	Coal flying ash generated from power plants are recycled to produce cement and construction materials, 240kt/y.
IS4	Biomass utilization	Use biomass for power generation, 503kt/y.

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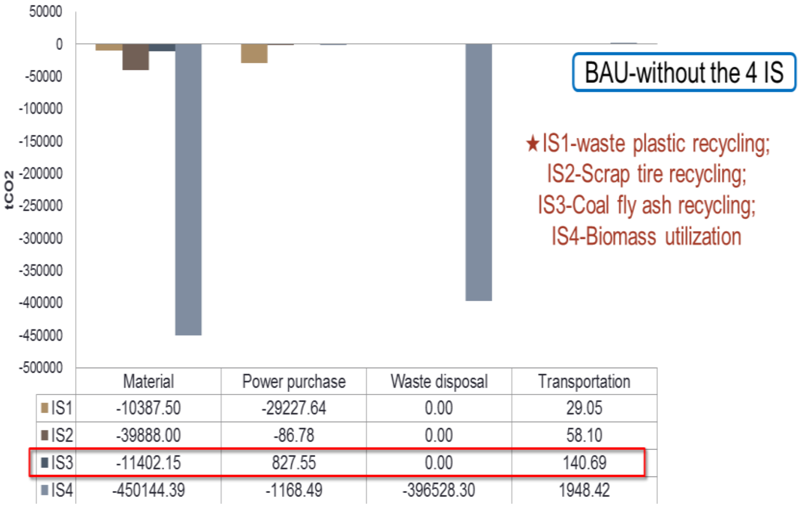
[16] Mainly comes from the author's paper: Dong L., Fujita T., 2014. Life cycle assessment on an industrial and urban symbiosis in China. Chinese Journal of Urban and Environmental Studies. (Under review)

Based on the established evaluation model and system planning, life cycle carbon emissions/reductions in terms of material consumption, power purchase, waste disposal and cross boundary transportation stages, and under different scenarios are evaluated.

Results are shown in *Figure 7-5*, in total, compared with BAU, planned industrial and urban symbiosis could contribute to the CO_2 reduction by 1104.96 $ktCO_2/y$. IS1 (waste plastics recycling), IS2 (waste tire recycling) and IS4 (biomass utilization) present great CO_2 mitigation in the lifecycles. They could reduce 39.59, 39.92 and 845.89 $ktCO_2/y$ respectively, without adding emissions from power purchase (as they smartly utilize the furnace in the industries and waste). IS3 (coal flying ash recycling) could reduce 11.40$ktCO_2/y$, but would increase 827.55 tCO_2/y as second energy consumption.

As a cost of establishing industrial and urban symbiosis, emissions from cross-boundary transportation would increase by 2246.61 tCO_2/y (*Figure 7-6*). In detail, from IS1 to IS4, cross-boundary transportation CO_2 emissions would increase by 29.05, 58.1, 140.69, and 1948.42 tCO_2/y, respectively.



	Material	Power purchase	Waste disposal	Transportation
■ IS1	-10387.50	-29227.64	0.00	29.05
■ IS2	-39888.00	-86.78	0.00	58.10
■ IS3	-11402.15	827.55	0.00	140.69
■ IS4	-450144.39	-1168.49	-396528.30	1948.42

Figure 7-5 Life cycle carbon mitigations

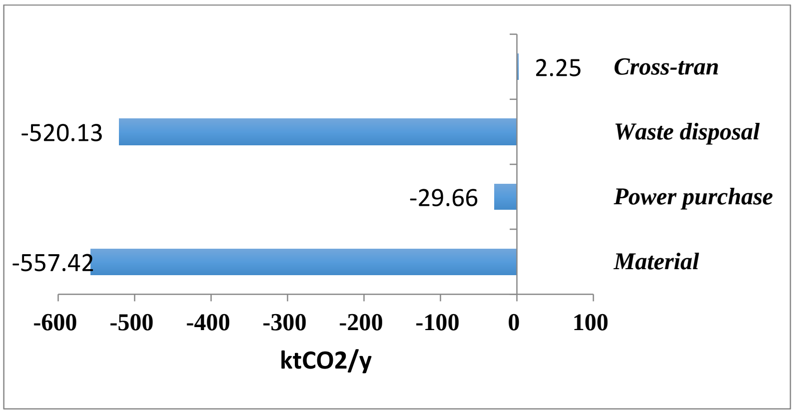


Figure 7-6 Emission of different life cycles for the assembled planned scenarios

7.4 Scenario analysis on key industrial symbiosis planning in Liuzhou[17]

To further investigate our planning's benefit to future policy scenarios, scenarios up to 12th five period (2011-2015) is conducted.

7.4.1 Scenarios and parameters setting

(1) Current condition

To set further scenario parameters, current condition is analyzed. Liuzhou's sector energy consumption and industrial added values have shown in *Figure 7-7*, sector air pollutions have shown in *Figure 7-8*. Sectors are listed in *Table 7-3*. Several sectors are critical for implementing energy conservation and low-carbon strategy due to their high level of energy consumption, such as iron and steel, cement, power generation and chemical industry.

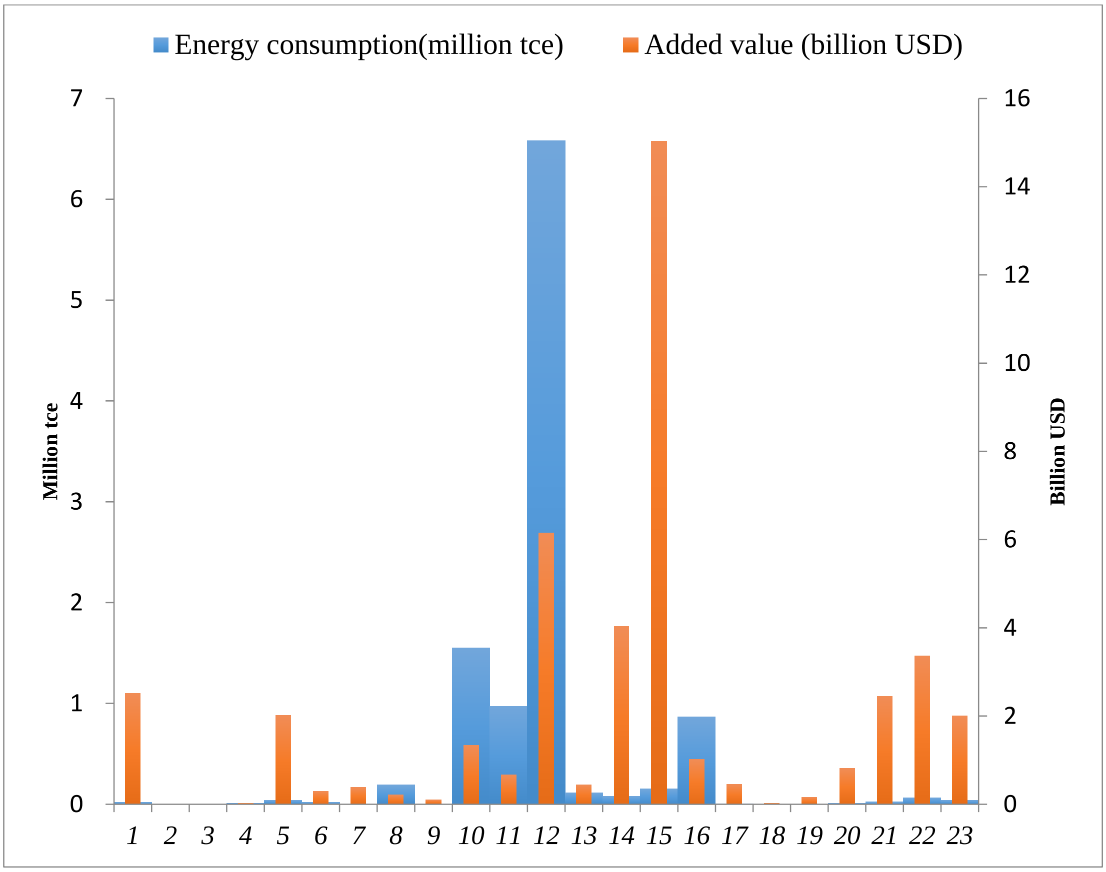


Figure 7-7 Energy consumption and added value of each sector in Liuzhou city in 2009

Note: tce-ton standard coal equivalent, 1 tce = 29.27 GJ.

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[17] This content mainly coms from the author's paper: Dong, L., et al., 2013. Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model. Energy Policy 61, 864-873.

Table 7-3 List of sectors

No.	***Sector***	***No.***	***Sector***
1	Agriculture	13	Non-ferrous metal
2	Coal mining and washing	14	Machinery
3	Ming of petroleum and natural gas	15	Transportation equipment
4	Ming and processing of non-metal ores	16	Electricity, steam and hot water supply
5	Food products and tobacco	17	Electric equipment and machinery
6	Textile and leather	18	Telecommunication
7	Saw mills and furniture	19	Environmental production industry
8	Paper and pulp	20	Construction
9	Petroleum processing and coking	21	Transportation
10	Chemicals	22	Commercial and service
11	Non-metal making	23	Other Public service
12	Iron and steel		

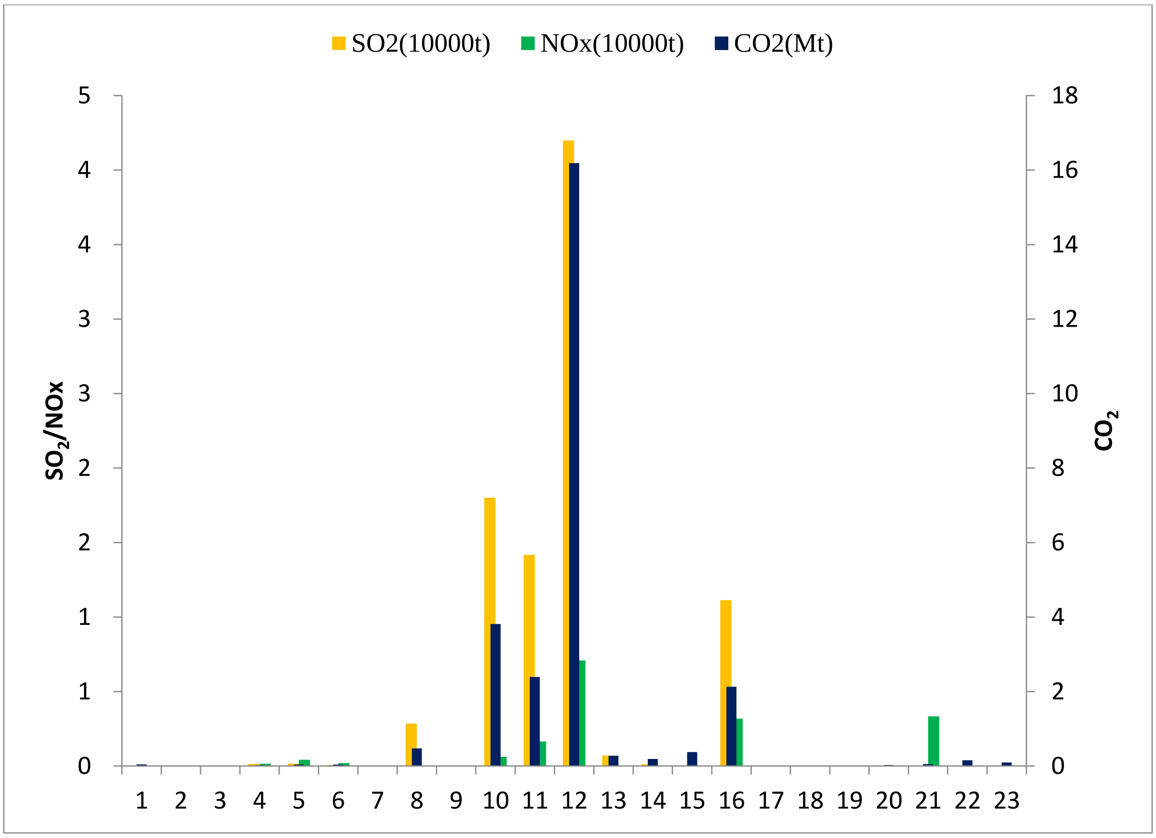


Figure 7-8 Air pollutants emissions of each sector in Liuzhou city in 2009

Note: the meaning of the numbers of each sector was the same as above description

(2) Scenarios

Scenarios design would follow the local 12th five year planning, from 2011 to 2015.

- **Business as usual scenario (BAU) in 2015**: BAU scenario reflects the on track economic growth and technology advancement if no innovative IS efforts are made. The economic growth and the industrial structure adjustment are reflected by the growth of final demand. The technology development is reflected by energy efficiency improvement. The parameters' values are according to the Liuzhou's 12th FYP, energy conservation planning and environmental production planning.
- **Industrial symbiosis scenarios**: Four IS scenarios are designed on the basis of potential IS options which mentioned above, in all the four IS scenarios we assume that 100% of the above mentioned wastes could be recycled due 2015 (*Figure 7-9*).

Several IS prospects due to 2015 can be initiated on the basis of potential reusable resources (*Table 7-4*), key potential IS options including: (1) waste plastics can be recycled by iron and steel industry and cement industry; (2) scrap tires can be burned by the furnace of iron and steel industry and cement industry; (3) flying ash from coal burning can be reused by cement industry/construction sector as raw materials; (4) food waste/straw can be incinerated for power generation. The IS scenarios will be developed based on these four potential IS options.

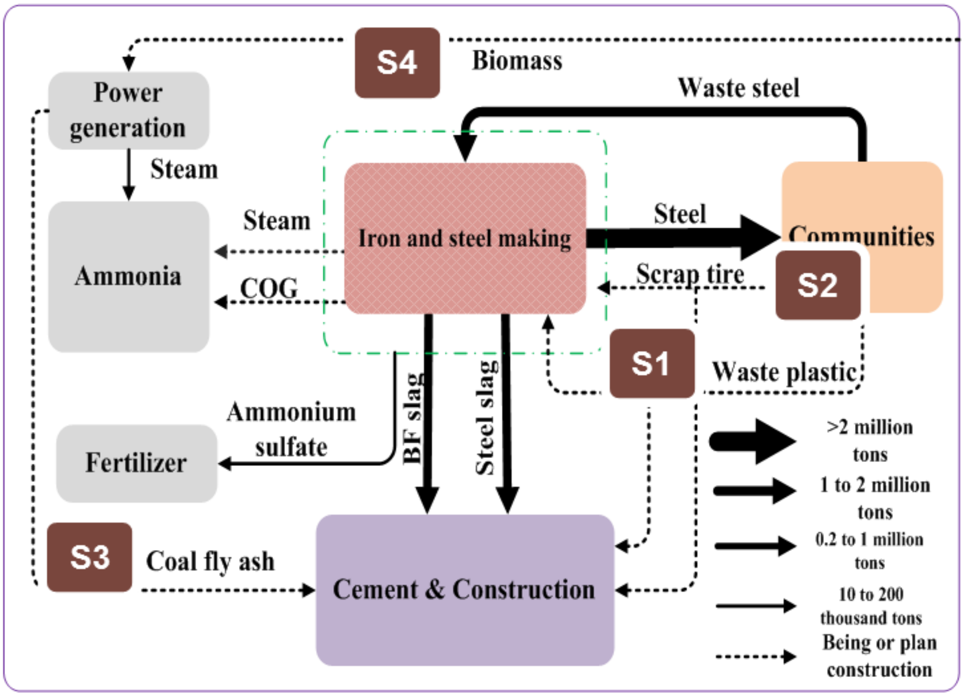


Figure 7-9 Existing and potential industrial symbiosis linkages in Liuzhou city
Note: The solid lines indicate the current industrial linkages. The dotted lines indicate the potential industrial symbiosis options.

Table 7-4. Potential reused or recyclable resources in Liuzhou city

Waste types	***Technological capacity***	***Available amounts***	***Data sources***
Waste plastics	More than 200000 ton[a]	2.50×10^4 ton	Liuzhou Twelfth-five Energy conservation planning (unpublished)
Waste tires	-	3.00×10^4 ton	Liuzhou Twelfth-five Energy conservation planning (unpublished)
flying ash	4416598 ton[b]	24.21×10^4 ton	Cleaner production report in Liuzhou power generation company
Straw	-	50.30×10^4 ton	Calculated according to the agricultural products and the coefficient of turning into straw

Note: [a] The substitution rate of waste plastics in the furnace is about 4%.

[b]Refer to the production of cement products.

(3) Socio-economic parameters

BAU parameters have shown in *Table 7-5*. The final demand change and technical advancement for each sector is reflected. Related economic growth, demand change, technologies change in each economic sector is set based on local governmental documents.

(4) Technical parameters setting

Technical parameters for each scenarios are summarized in *Table 7-6*. As industrial symbiosis is closely related to the transportation, thus this study would also simulate transportation related emissions. Parameters for transportation are summarized in *Table 7-7*.

Table 7-5. The economic structure change and technology development of each sector in Liuzhou for BAU scenario, up to 2015

Sectors	***Growth rate of final demand***	***Energy consumption per unit of economic output***
Agriculture	107.19%	-5%
Coal mining and washing	0%	0%
Ming of petroleum and natural gas	0%	0%
Ming and processing of non-metal ores	80.00%	-20%
Food products and tobacco	200.00%	-25%
Textile and leather	150.00%	-25%
Saw mills and furniture	158.00%	-25%
Paper and pulp	258.70%	-25%
Petroleum processing and coking	100%	0%
Chemicals	62.93%	-15%

Non-metal making	80.00%	-20%
Iron and steel	80.00%	-20%
Non-ferrous metal	500.00%	-25%
Machinery	460.00%	-30%
Transportation equipment	500.00%	-30%
Electricity, steam and hot water supply	153.33%	-25%
electric equipment and machinery	222.00%	-30%
Telecommunication products	220.00%	-20%
Environmental production industry	222.00%	-20%
Construction	150.00%	-20%
Transportation	180.00%	-10%
Commercial and service	182.32%	-10%
Other public service	182.32%	-10%

Table 7-6. Detail parameter settings of different scenarios

Scenarios		***Description***	***parameters***	***Source***
BAU	Business as usual in 2015	Technology development and industrial structure change. Waste plastics is landfilled, no scrap tires and flying ash recycling, no biomass utilization.	Shown in *Table 7-7*	Liuzhou Twelfth-five planning and Liuzhou Twelfth-five Energy conservation planning (unpublished)
S_1	Waste plastics recycling in 2015	BAU+Waste plastics recycle to iron and steel industry as primary energy.	1 ton waste plastics could substitute 1 ton coke in iron and steel industry	Survey in the Liuzhou Iron and steel company/Iron/steel association
S_2	Scrap tires recycling in 2015	BAU+Scrap tires recycle to iron and steel industry and cement industry as primary energy.	1 ton scrap tire could produce 0.65 tons rubber powder, consume 0.04 tce electricity.	Survey
S_3	Flying ash recycling in 2015	BAU+ flying ash recycle to cement industry as raw materials.	1 ton coal flying ash substitute 1 ton cement, and consume 0.0007 tce electricity.	Survey in Liuzhou Power generation company/ cleaner production audit report
S_4	Biomass utilization in 2015	BAU+Use straw to make power generation.	Recycled into power generation sector.	Liuzhou Twelfth-five Energy conservation planning (unpublished)

Table 7-7 Parameters of transportation for wastes

Waste	***Energy consumption of transportation[a]***	***Average distance***	***Source***
Waste plastics	7.82L diesel/100 ton.km	6km	(CCID, 2011)
Scrap tires	7.82L diesel /100 ton.km	10km	(CCID, 2011)
Coal fly ash	7.82L diesel /100 ton.km	10km	(CCID, 2011)
Straw	7.82L diesel /100 ton.km	30km	(CCID, 2011)

7.4.2 Results of scenarios

- Results of BAU scenario

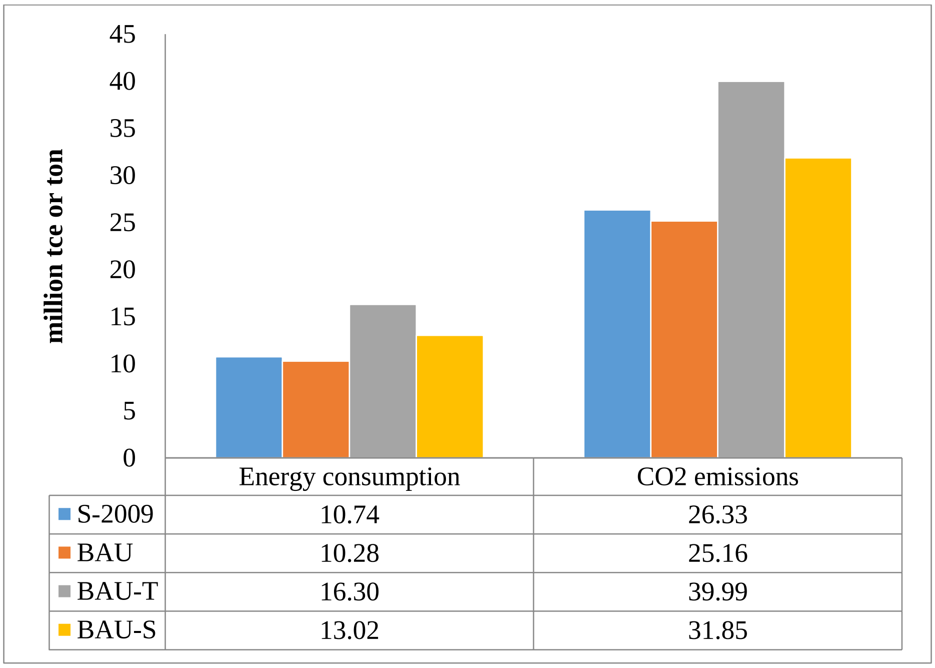
To reflect the effects of industrial structure change and technical advancement, we separated BAU scenario into 3 scenarios: (1) BAU-T: technological developed, but the economy keep consistence of economy growth rate in 2006-2009; (2) BAU-S: structural changed, but the energy efficiency is constant with level in 2009; and (3) BAU: both technological development and structural changed. Results show that solely relies on technology development or structural change cannot control the amount of energy consumption and CO_2 emissions (*Figure 7-10*).

Compared with the year of 2009, although the energy efficiency would increase due to the industrial structure change and technology development, total energy consumption and CO_2 emissions would still increase in most industries. Energy saving and emission control requires improvement from both industrial structure adjustment and technology advancement.

- Results of four IS scenarios

Four IS scenarios in comparison of BAU scenario were shown in *Table 7-8.*

. According to an input-output relationship among sectors, reducing or increasing the energy consumption could cause the correlative change of related sectors. The total consumption matrix could reflect this cumulative effect. Recycling waste plastics could directly substitute the coke consumption, then reduce the energy input from other sectors as a result. Meanwhile, the energy consumption of transportation sector, and relative energy input from other sectors to transportation sector would increase.



	Energy consumption	CO2 emissions
🟦 S-2009	10.74	26.33
🟧 BAU	10.28	25.16
⬜ BAU-T	16.30	39.99
🟨 BAU-S	13.02	31.85

Figure 7-10. The energy consumption and CO_2 emission in 2009 for different BAU scenarios

Note: S-2009 means the condition of 2009.

Table 7-8 Cumulative energy savings for different IS scenarios, unit: tce.

Sectors	BAU	S1	S2	S3	S4
Agriculture	0.00	-2907.42	-24.47	128.04	798.12
Coal mining and washing	0.00	-3020.03	-10.19	81.10	440.66
Ming of petroleum and natural gas	0.00	-1140.25	-3.06	50.96	317.67
Ming and processing of non-metal ores	0.00	-359.12	-5.01	12.38	60.43
Food products and tobacco	0.00	-1125.72	-9.55	44.91	275.15
Textile and leather	0.00	-731.42	-2.32	29.13	-5.70
Saw mills and furniture	0.00	-3705.33	-8.66	166.14	-372.85
Paper and pulp	0.00	-1495.12	-8.62	59.54	-1119.49
Petroleum processing and coking	0.00	-3738.28	-8.93	167.59	-363.81
Chemicals	0.00	-10001.94	-293.66	407.35	-8084.73
Non-metal making	0.00	-966.43	-1.91	31.68	-401.07
Iron and steel	0.00	-53598.09	-4.02	859.51	-70729.92
Non-ferrous metal	0.00	-3101.08	-2.27	127.69	-3386.78
Machinery	0.00	-22760.31	-3.09	957.53	2594.98
Transportation equipment	0.00	-49993.29	4.37	2362.41	14642.82
Electricity, steam and hot water supply	0.00	-11241.40	-25.30	318.29	-449.42
electric equipment and machinery	0.00	-3389.67	-1.06	146.33	-24138.46
Telecommunication products	0.00	-1704.40	-0.91	72.11	-9907.14
Environmental production industry	0.00	-2422.04	-0.68	44.64	278.24
Construction	0.00	-266.20	-0.23	10.22	20.93
Transportation	0.00	-4922.13	19.00	458.98	-1690.43
Commercial and service	0.00	-21147.76	-26.61	794.41	-17771.95
Other Public service	0.00	-2784.25	-4.32	114.37	-154.07
Total	0.00	-206521.67	-421.52	7445.32	-119146.82

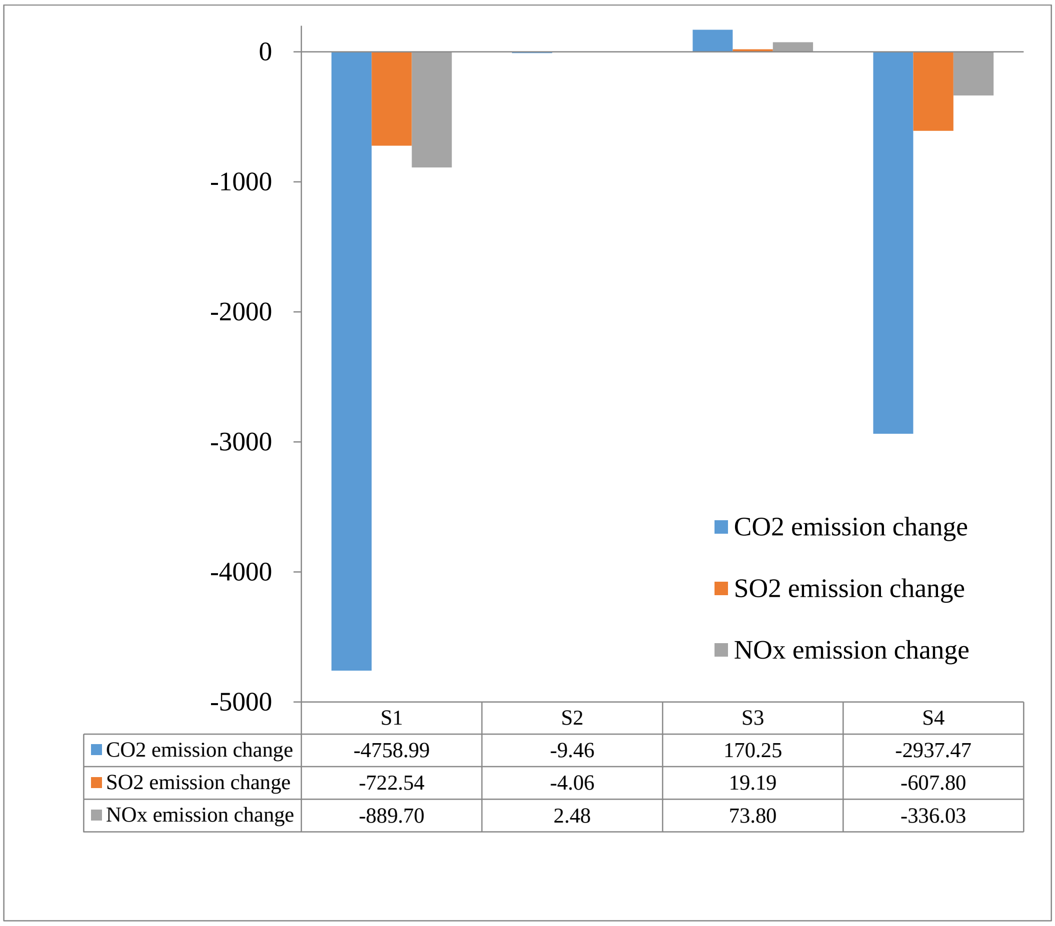
Note: the results were net cumulative values.

Scenarios of S1,S2,S3 and S4 represented the IS options of recycling waste plastic, recycling scrap, reusing flying and biomass utilization, respectively. Results show that the net cumulative energy saving could be 20.65×10^4 tce by recycling waste plastic (S1). Recycling scrap tires (S2) would reduce the energy consumption of chemical industry, but increase the energy consumption of service and transportation sectors, thus the net cumulative energy saving could be 4.21×10^2 tce. Reusing flying ash (S3) from coal burning to produce cement would increase the energy consumption by 74.45×10^2 tce. It has benefit for the reduction of solid waste, but not for energy saving and air pollutants reduction. Biomass utilization (S4) would reduce the final demand of electricity sector, but would increase the energy consumption in agriculture, transportation, etc. The net cumulative energy saving would be 11.91×10^4 tce.

Energy saving in different sectors would further result in different air pollutants reduction (*Figure 7-11*), in which waste plastic recycling (S1) and biomass utilization (S4) could lead to CO_2, SO_2 and NOx reduction. For scrap tire recycling (S2), NOx would increase, while for flying ash reuse (S3), all the CO_2, SO_2 and NOx would increase. This means that flying ash reuse could only reduce solid waste.

With regard to CO_2 emissions reduction per unit of waste reduction (tCO_2/t), waste plastics recycling (S1), scrap tires recycling (S2) could reduce 19.03 ton and 0.03 ton CO_2 per unit of waste reduction respectively, flying ash reuse (S3) would increase 0.07 ton CO_2 per unit of waste reduction, and biomass utilization (S4) could reduce 0.58 ton CO_2 per unit of waste reduction.

With regard to SO_2 reduction and NO_x reduction per unit of solid waste reduction, waste plastics recycling (S1) could reduce 0.029 ton SO_2 and 0.035 ton NO_x per ton solid waste reduction. Scrap tires recycling (S2) could reduce 0.0001 ton SO_2 per ton solid waste, while increasing 0.0001 ton NO_x per ton solid waste reduction, flying ash reuse (S3) would increase the SO_2 and NO_x emission by 0.079kg and 0.30kg per ton solid waste reduction, respectively. Biomass utilization (S4) would reduce 1.21kg SO_2 and 0.67kg NO_x per ton solid waste reduction, respectively.



	S1	S2	S3	S4
■ CO2 emission change	-4758.99	-9.46	170.25	-2937.47
■ SO2 emission change	-722.54	-4.06	19.19	-607.80
■ NOx emission change	-889.70	2.48	73.80	-336.03

Figure 7-11 Air pollutants and CO_2 emission changes in different scenarios

Note: BAU as zero. The unit of CO_2 was 100 tons, and the unit of SO_2 and NOx was ton.

Finally, economic revenue could be gained through energy saving and pollutants reduction. Waste plastics recycling (S1) would gain 255.46 million CNY annually, scrap tire recycling (S2) would gain 1.05 million CNY annually. Flying ash reuse (S3) would gain 4.84 million CNY from solid waste reduction, but lose 8.51 million CNY annually due to the increase of energy consumption and air pollutants emission. Biomass utilization (S3) would gain 122.69 million CNY annually. Prices of related material and waste are listed in *Table S4* in the "Appendix".

Rapid urbanization and industrialization has resulted in more challenges to China's sustainable development. This requires innovative efforts from local governments and industries thus low-carbon cities can be developed. Industrial symbiosis is one effective and efficient approach to respond such challenges since it can reduce both virgin material consumption and waste emissions. Particularly, the extraction and refining processes for virgin materials are usually energy intensive, therefore, active promotion of IS could not only contribute to solid waste reduction, but also to the CO_2 reduction and SO_2, NO_X reduction. In this study, a quantitative evaluation in one Chinese city was conducted by using HPIMO model. The results reflect that waste plastics recycling and biomass utilization could generate more co-benefits, while flying ash reuse could reduce the solid waste but increase energy consumption and related air pollutants. Scrap tires recycling is another effective way to achieve co-benefits. In general, industrial symbiosis could contribute to co-benefits of energy saving, material recycling as well as air-pollution mitigations, thus more policy attentions need be addressed.

Scenario analysis show that IS could contribute to waste reduction and further generate co-benefits of energy saving, CO_2 mitigation and air pollutants reduction. Especially, solely rely on technological development or structural change is difficult to reduce the energy consumption and CO_2 emissions. Thus, a systematic innovation such as IS is crucial for low-carbon development in Chinese urban areas.

Results also indicate that different IS efforts may bring different benefits. While waste plastics recycling and biomass utilization could generate more co-benefits, flying ash reuse could only reduce the total amount of solid wastes, but increase energy consumption and related air pollutants. Hence, smart design on IS patterns by considering the local realities is critical.

7.5 Summary

This chapter conducted the planning and quantitative assessment in Liuzhou city. The outcomes included: based on the analysis in the pilot project and the advanced experience from international projects, and combined with local condition, a local industrial symbiosis was planned in Liuzhou city. Furthermore, several key symbiotic linkages were evaluated with hybrid LCA method. Then, to support its '12th five-year planning', scenarios were set and simulated. Co-benefit and co-cost was presented. To enhance the co-benefit and reduce the co-cost, future research and policy implications on increasing the eco-efficiency of IS network and reducing second emissions were emphasized.

8. Policy implications and conclusions

8.1 Policy implications

8.1.1 Discussion on the results

In the previous sections, IS network analysis, life cycle assessment and scenario analysis was conducted in national pilot as well as local area. Our findings highlighted a cost and benefit of promoting industrial symbiosis in China.

From the perspective of environmental benefit of IS, IS provides systematical innovation to achieve co-benefit of resource efficiency enhancement and pollutants reduction. Embodied carbon emissions are reduced significantly through proper IS design. The benefit is particular important for China, which owns large scale and integral industries.

However, a trade-off thinking is also needed. IS would also increase the CO_2 emissions in terms of transportation, thus an optimization for the recycling network would be important. Therefore, the best available design for the IS network would provide further second resource saving and pollution reduction (the scale of recycling, location of facilities and so on).

What is more, our planning on the industrial symbiosis could support sustainable urban development in China. Apart from utilizing the industrial symbiosis to “green” the industries, it would be also beneficial to improve the industrial layout policies in China. The symbiosis idea could contribute to a sustainable urban planning from the perspective of network design. With symbiosis, material, energy and waste flow could be optimized. As key node, emerging industries like recycling company and environmental protection industry, as well as infrastructure facilitating such flow exchange is necessary. What is more, turn to a regional industrial layout planning, with considering industrial and regional symbiosis, better location could be determined.

Finally, planning would be always planning, if there is no policy implication for generalizing IS. The barriers to promote IS in China should be paid intensive attention. Even though our planning and calculation results seems positive, IS is only at the beginning stage in China, facing multi barriers. From the industry side, stable waste supply chain and compatible technology is needed. It is also important to standardize the recycling products system. Finally, National technology inventory and standard, special subsidies on IS is required. Such barriers and challenges require proper supporting policy package.

8.1.2 Extension and generalization of IS

Our evaluation results verify the positive effects of IS application in China. Based on the quantitative evaluation and international experience, several policy implications are highlighted:

- **Generalization and extension of industrial symbiosis: new comprehensive industrial and urban energy symbiosis in the case city.**

Our focusing cases in this study are heavy industries centered industrial clusters and the urban that located with such heavy industries. Based on the international advanced experiences, some new planning ideas could be gained: shown as *Figure 8-1*: with more concerns on energy, a comprehensive energy symbiosis could be proposed. This figure shows an emerging planning for our Jinan and Liuzhou case, where has iron/steel industries and other process industries like chemical industry. In the symbiosis, the waste heat could be utilized through three ways: (1) most of the high calorific value waste heat could recovered through advanced energy recovery technology and reused inside the steel plant. (2) as to the left waste heat, one utilization way is to recovered and export to nearby factories. They could be utilized in both energy and material way. Particularly, apart from the provision as fuels to other company, some metallurgical gas like BFG and COG, they could be utilized to produce some chemical semi-product with high added value, e.g. hydrogen. (3) the waste heat or steam could be also supplied to nearby urban areas, like the hotel and office. In this way, a low carbon district could be supported.

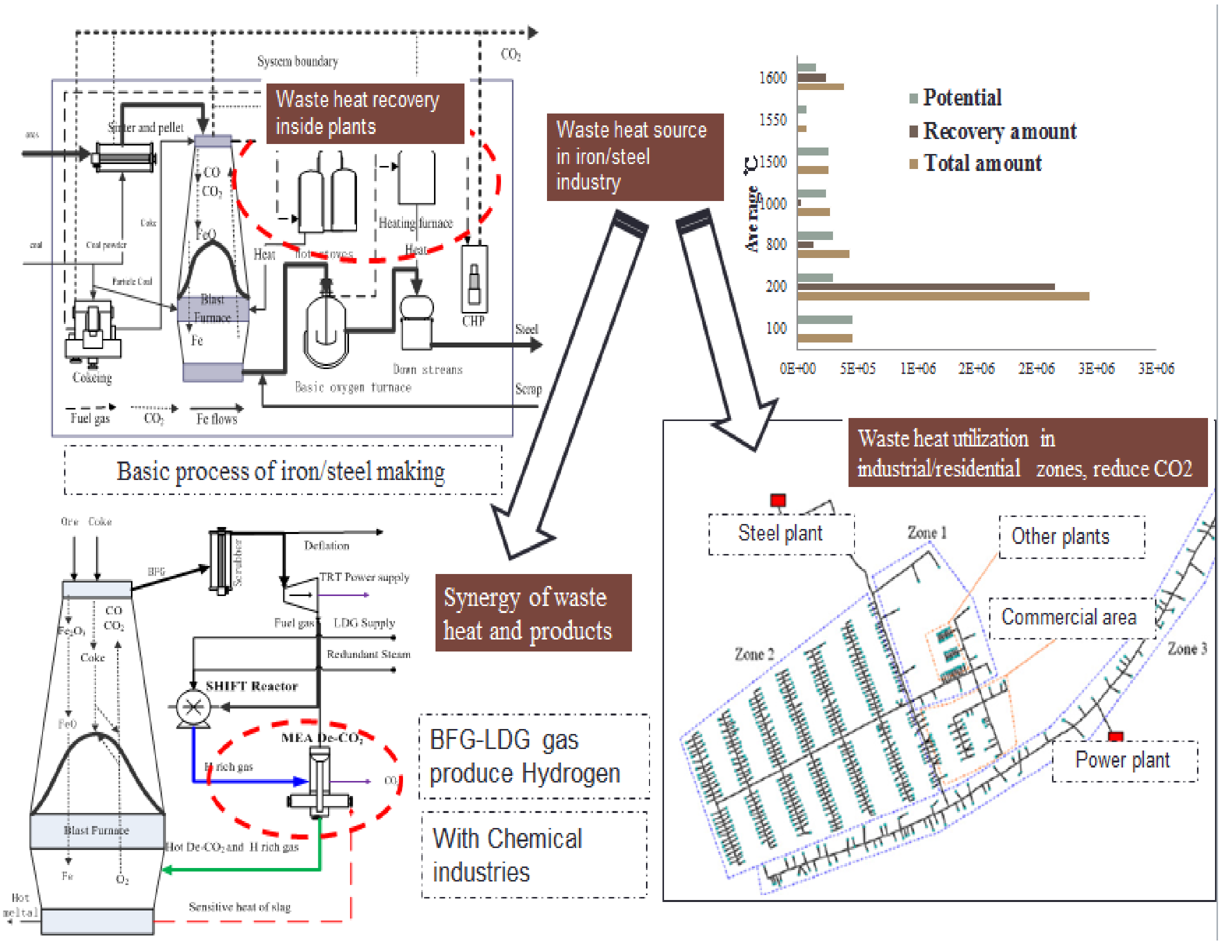


Figure 8-1 Image of proposed comprehensive industrial and urban energy symbiosis

- **Utilize IS to support transit oriented development for China's industry.**

Our results emphasize a potential second emission generated by the implementation of IS. Thus it is important to consider the optimization on transportation route and patterns for IS, so as to support the transit oriented development for China's industry. Two issues are important: (1) optimize the location of industry and transportation network. Through change the location pattern of industries and urban, could improve their interaction in terms of material and energy flows, to save resource and reduce emissions; (2) Meanwhile, second emissions are generated from IS, through transportation and increased activities related to IS. As a result, to optimize the transportation network and locations of industry, as well as make technology shift, enhance the technical efficiency, like transportation pattern change (e.g. trucks changed into more energy efficient railway) is important to further reduce second emissions. Such policy implications should be considered by the policy makers.

8.1.3 Supporting policy implications

Based on the results discussion, policy package to support the generalization of industrial and urban symbiosis in China is proposed:

- **In technological perspective**, it requires the promotion of circular economy technology and industrial linkage technology to resolve the challenge in technology perspective. Circular economy technology and product standard, as well as quality standards for the input material as guidance for waste generators should be established so as to guarantee the stable product and waste flows. In addition, there is need to develop a comprehensive decision tool which based on material flow analysis and life cycle analysis, to direct waste materials between industries/urban area and external waste generators in an optimized manner.
- **Supply-demand chain monitor for the IS network and support network optimization.** One key issue to promote and improve the industrial symbiosis is the monitor on the flows in the system and to optimize the flows route. In this point, a monitor system construction is important. In our international comparison part, it is highlighted that to improve the problems of system stability is important to keep the IS network stable and efficient. With the development of information and communication technology (ICT), a monitor system on the material, waste and energy flows become available. A DCS system (Distributed Control System) is the basis for such monitor system. The monitor on the flows and its integration could provide useful information to the companies and researchers to improve the symbiosis activity, and verify the effect of IS. In addition, it also provides a basis to develop a comprehensive decision tool based on material flow analysis and life cycle analysis, to direct waste materials between industries and external waste generators in an

optimized manner.

- Then, **in environmental management aspect**, this study proposes to improve the immaturity of waste management system and regulation system. In order to establish a stable and innovative municipal solid waste management system needed to establish, public or commercial collectors needed to be encouraged to participate in the waste collection and recycling. What is more, the third party should be made to coordinate the stakeholders of the symbiosis and information platform is necessary to be constructed for information share.
- **Finally, in the public idea aspect**, this study proposes some planners and policy makers to make mind change and accept the idea of industrial and urban symbiosis properly. In developing country like China, a number of local policy makers prefer remove heavy industry out of the cities under energy saving and pollution control pressure (some political mission for them). This in return would have negative impacts on local economy and employment. Based on our analysis, it is proved that utilize the industry smartly is a win-win strategy for economy and environment. We urge the academic field and policy makers should get out of the traditional sense and apply effort to make system innovation, and promote supporting policy on such innovation.

8.2 Conclusions

8.2.1 Main findings

This study made a planning and quantitative evaluation study on industrial and urban symbiosis in China. Based on the research background discussion in **Chapter 1** and literatures review in **Chapter 2**, the main outcomes and findings included:

In **Chapter 3**, international comparison between China and Japan was made. It was found that even though both the two countries had promoted “sound material-cycle society” related strategy, the development stage was different. In Japan, industrial and urban symbiosis was promoted like Kawasaki eco-town, and regional symbiosis was implemented. While to China, development stage was still focus on cleaner production and EIP, to promote industrial and urban symbiosis and regional symbiosis would be the focus in the next development stage. Based on the review on Japanese case, advanced industrial symbiosis was learned and transformed to this case study.

In **Chapter 4**, local industrial symbiosis projects’ data in Jinan and Liuzhou city was collected, local industrial symbiosis database was constructed including technical data, company input-output data, economic data, emission factors and general regional socio-economic data. Main findings in this chapter were that the industrial symbiosis development condition in Jinan and Liuzhou could present two levels: national advanced level with more synergies and primary urban symbiosis, and local level with focusing on cleaner production and bulky waste recycling. Even though Liuzhou had the similar industrial system as Jinan, a lot of industrial symbiosis opportunities were not uncovered.

In **chapter 5**, material and energy flow analysis, process based LCA and hybrid input-output model was integrated to assess the planning of industrial symbiosis. To help to make quantitative assessment on the industrial symbiosis planning, and to resolve the problems of lacking inventory data, process based LCA and data from the established hybrid input-output model was combined. The main findings and contributions were through the model integration, it resolved the bottleneck of process based LCA and IO-LCA application in IS evaluation and lack of scenario analysis in China.

In **chapter 6**, investigation and assessment on the symbiosis network in the national pilot project in Jinan city was made. There were extinguish resource saving and waste mitigation effects. In total, more than 4 million ton raw material and 1.5 million tce energy was saved, and more than 4 million ton waste was reduced. Considerable CO_2 reduction was achieved through the implementation of industrial symbiosis. 3944.05 ktCO_2/year was reduced and material and energy symbiosis reduced CO_2 emissions by 3792.42 and 151.62 ktCO_2/year respectively. In addition, as an advanced national pilot project, Jinan's experience could be transformed into local case.

In **chapter 7**, based on the experience in Jinan, planning and quantitative assessment for IS in Liuzhou was presented. There were two critical findings:

(1) Considerable environmental benefits were achieved: compared with BAU, planned industrial and urban symbiosis could contribute to the CO_2 reduction by 1104.96 ktCO_2/y. Waste plastics recycling, waste tire recycling and biomass utilization presented great CO_2 mitigation in the lifecycles. They reduced 39.59, 39.92 and 845.89 ktCO_2/y respectively, without adding emissions from power purchase (as they smartly utilize the furnace in the industries and waste). Scenario by 2015 highlighted that industrial symbiosis could help the local city through realizing co-benefit, reduce CO_2 emissions, and air pollutants together. IS provided an extra measure beyond traditional technological development or structural change measures.

(2) Trade-off thinking was needed: coal flying ash recycling could reduce 11.40ktCO_2/y, but would increase 827.55 tCO_2/y as second energy consumption. As a cost of establishing industrial and urban symbiosis, emissions from transportation would increase by 2246.61 tCO_2/y. In detail, from waste plastic recycling, waste tire recycling, coal flying ash recycling to biomass utilization, transportation CO_2 emissions increased by 29.05, 58.10, 140.69, and 1948.42 tCO_2/y, respectively. This finding highlighted a future research need to optimize the symbiosis and transportation network, and make technology shift to reduce second emissions.

Finally, **in chapter 8**, discussions about generalization of findings and policies implications were elaborated, and conclusion of this work and future concerns were drawn. Generalization and extension of industrial symbiosis was discussed with focus on new comprehensive industrial and urban energy symbiosis in the case cities. Utilizing IS to support transit oriented development for China’s industry was proposed and discussed. A series of supporting policies for IS promotion were elaborated.

The main findings of this research would be critical for China’s future industrial planning and regional planning policy. They would also enlighten the industrial policies and low carbon policies in other developing countries.

8.2.2 Future concerns

This research would be a complement to China’s research statement on the industrial symbiosis. However, there is no doubt that this research is only one small step in this field, there are several future concerns need to consider.

Two main contributions of this study are “planning on new industrial symbiosis in local area” and “integrated evaluation model development with database construction”, so as to support decision making. As a result, we propose the future research concerns to resolve the limitation in this research from these aspects.

- For future planning of industrial symbiosis in China and developing countries: negotiate the industry and urban would be long term and key issue for China’s and developing countries’ sustainable development. While this study makes an innovative industrial symbiosis planning based on international experience and local condition, the main part we consider is still material exchange and some traditional way of energy exchange. With more concerns on climate change and sustainable urban development, two aspects need to be emphasized in future planning: (1) smart energy system, or energy symbiosis, makes full use of waste heat and renewable energy. (2) Design more linkage with urban area. This study only considers some municipal waste used by industries and in turn, the industries provide living necessity to urban regions. In the future, more complex system integration is needed, like heat network between factories and living/commercial area. To support such new-generation industrial symbiosis planning, hardware technologies are also important. Examples as smart grid, efficient energy transformation facilities and waste treatment facilities, and pipelines construction.
- For integrating decision support model development: As emphasized in the international comparison part, as to the decision support tool, in developed countries like Japan, GIS based life cycle assessment is becoming popular. With the help of such tools, the optimal location of factories, waste treatment facilities, waste recycling route could be gained, and the best planning way to realize the highest eco-efficiency could be presented. With the data limitation, the spatial optimization part is not considered in this study, thus in the future, such direction would be very meaningful to IS research in China. In addition, to facilitate the optimization, a tool to tracing and monitor the flows would be also important. China has already planned to launch the project on the monitor system in its eco-industrial parks,

focusing on material and solid waste flows, in its 12th five-year planning period (2011 to 2015). In the future, the monitor on the energy flows, and the corresponding Carbon flows, with the help of advanced information and communication technologies (ICT) would be very meaningful to the research field.

- Model extension and application in other developing countries: This research developed a general hybrid LCA approach fit to the condition that detail and integrated inventory data for IS was not available. Such situation usually happened in developing countries, in which, statistical system is not perfect and local data is very difficult to gain. In this condition, the LCA model established in this research could be applied in other developing countries, with modification on key parameters to make it fit to case by case condition. The results could strongly support their policy making on IS promotion.

Appendix

This material would provide some detail information about the hybrid physical input and monetary output table, as well as the survey sample.

Table S1 showed the sectors.

Table S1 Sectors

Sector	Number
Agriculture	1
Coal mining and washing	2
Ming of petroleum and natural gas	3
Ming and processing of non-metal ores	4
Food products and tobacco	5
Textile and leather	6
Saw mills and furniture	7
Paper and pulp	8
Petroleum processing and coking	9
Chemicals	10
Non-metal making	11
Iron and steel	12
Non-ferrous metal	13
Machinery	14
Transportation equipment	15
Electricity, steam and hot water supply	16
electric equipment and machinery	17
Telecommunication products	18
Environmental production industry	19
Construction	20
Transportation	21
Commercial and service	22
Other Public service	23

Table S2 showed the energy input in each sector. Data is gained from energy balance table of Liuzhou city. Some unavailable data for certain industry is further acquired through survey.

Table S2 Energy inputs in sectors

Energy source		1	2	3	4	5	6	7	8	9	10	11	12
Raw coal	ton	0.00	0.00	0.00	7642.00	12644.56	5273.40	0.00	237675.35	0.00	1415300.60	1177789.33	1637398.00
Washing coal and other	ton	0.00	0.00	0.00	4140.00	0.00	0.00	0.00	0.00	0.00	85025.87	2548.00	5361035.00
Coke	ton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6589.47	0.00	0.00
Gasoline	ton	0.00	0.00	0.00	0.00	315.78	0.00	0.00	13.30	0.00	2905.81	298.82	122.72
Kerosine	ton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.16	0.00	0.00
Diesel oil	ton	0.00	0.00	0.00	0.00	1060.41	0.00	0.00	766.64	0.00	2140.72	9752.01	6398.94
Fuel oil	ton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	192.20	0.00	748.58	0.00	0.00
LNG	ton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LPG	10^4 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COG	10^4 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.01	0.00
BOG	10^4 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat	Million kJ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6992343.00	0.00	0.00
Electricity	10^4 kWh	14360.79	0.00	0.00	0.00	24683.92	10396.40	0.00	17640.19	0.00	170280.08	93100.46	468749.00
Renewables	tce	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S2 Energy inputs in sectors (continued)

Energy source		13	14	15	16	17	18	19	20	21	22	23
Raw coal	ton	54727.61	9840.67	3857.26	928090.42	432.09	0.00	0.00	0.00	0.00	0.00	0.00
Washing coal and other	ton	3920.76	0.00	51.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coke	ton	5924.03	12723.23	885.50	0.00	0.00	0.00	141.00	0.00	0.00	0.00	0.00
Gasoline	ton	298.19	2641.17	9960.48	554.21	252.59	0.00	0.70	0.00	0.00	0.00	0.00
Kerosine	ton	6.46	108.85	76.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diesel oil	ton	296.94	5163.26	12629.33	775.78	111.96	0.00	2.00	0.00	0.00	0.00	0.00
Fuel oil	ton	10.02	0.00	1213.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LNG	ton	0.00	0.00	92.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LPG	10^4 m^3	0.00	224.65	82.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COG	10^4 m^3	0.00	0.00	0.00	11122.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BOG	10^4 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat	Million kJ	0.00	0.00	0.00	1125329.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity	10^4 kWh	51432.76	37280.64	91768.20	79605.82	3655.73	141.43	414.93	8882.13	17741.49	51008.97	31597.25
Renewables	tce	0.00	0.00	0.00	336.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S3 showed the emissions of each sector. SO_2 and NOx data is gained from local EPB. CO_2 data is calculated based on the energy consumption.

Table S3 Pollutants emissions of each sector, ton

Sector	CO_2	SO_2	NOx
Agriculture	43417.55	0.00	0.00
Coal mining and washing	0.00	0.00	0.00
Ming of petroleum and natural gas	0.00	0.00	0.00
Ming and processing of non-metal ores	22594.31	141.38	154.00
Food products and tabacoo	38811.10	151.73	425.59
Texile and leather	40698.15	63.28	198.52
Saw mills and furniture	0.00	0.00	0.00
Paper and pulp	474441.78	2852.10	13.20
Petroleum processing and coking	0.00	0.00	0.00
Chemicals	3813531.35	18003.92	616.26
Non-metal making	2392865.13	14164.05	1652.09
Iron and steel	16187099.82	41990.60	7080.18
Non-ferrous metal	276704.07	703.78	0.00
Machinery	189816.86	118.09	19.09
Transportation equipment	375700.31	46.90	0.00
Electricity, steam and hot water supply	2127085.42	11137.09	3188.64
electric equipment and machinery	13127.38	5.19	0.00
Telecommunication products	427.59	0.00	0.00
Environmental production industry	1601.12	0.00	0.00
Construction	26853.70	0.00	0.00
Transportation	53638.56	0.00	3336.89
Commercial and service	154217.46	0.00	0.00
Other Public service	95529.23	0.00	0.00

Table S4 showed the prices of related material and waste.

Table S4 The prices of material, energy and by-product or waste in China

Items	**Value**	**Unit**	**Source**
Raw coal	800	CNY/t	http://www.coalcn.com/
Electricity	0.64	CNY/kWh	China Price Statistical Year book, 2010.
COG	500	CNY/t	China Price Statistical Year book, 2010.
Coke	2000	CNY/t	(Zhang, 2007; Zhou et al., 2012)
Steam	220	CNY/t	(Zhang, 2007; Zhou et al., 2012)
Waste plastics	400	CNY/t	China reuse resource online, http://baojia.feijiu.net
Straw	150	CNY/t	Survey

Scrap tires	1500	CNY/t	China reuse rubber web, http://www.51zsj.com/
CO_2	70	CNY/t	(Zhang, 2007)
SO_2	1260	CNY/t	(Zhang, 2007)
NOx	18000	CNY/t	http://wbnews.sxrb.com/news/sx/1470055.html
Waste disposal cost	20	CNY/t	(Zhang, 2007)

Finally, the following tables show the survey questionnaire with iron/steel industry as example. It is noted that the survey is conducted for the "Liuzhou twelfth-five energy conservation planning", not all the data is used in this study.

Table S5 Interview table

<table>
<tr><td>Name</td><td colspan="2"></td><td>Contact info</td><td colspan="2"></td></tr>
<tr><td>Company/Department</td><td colspan="2"></td><td>Position</td><td colspan="2"></td></tr>
<tr><td>Number</td><td colspan="4">Content</td><td>Note</td></tr>
<tr><td>1</td><td colspan="4">Main condition of energy conservation and pollutants reduction</td><td></td></tr>
<tr><td></td><td colspan="4">The target of energy conservation and pollutants reduction in the past 5 years (2005 to 2010):
Energy consumption and pollutants emission condition for each process:
Please introduce the technology implementation for energy consumption and pollutants reduction:</td><td></td></tr>
<tr><td>2</td><td colspan="4">Future concerns</td><td></td></tr>
<tr><td></td><td colspan="4">The target of energy conservation and pollutants reduction in the future 5 years (2011 to 2015):
The main measures of energy conservation and pollutants reduction in the future 5 years (2011 to 2015):
The main measures to enhance the economic output:
Please introduce the future measures for reuse and recycling:</td><td></td></tr>
</table>

Table S6 Survey table for process inventory data (No.1 to No.9)

General info for the company			
Indicator		**Unit**	**Value**
Number of workers			
Industrial output		10000 CNY	
Production output (crude steel)		10000 ton	
Number of sintering machine	Volume/number	M^3/number	
	Production scale	t/year	
BF	Volume/number	M^3/number	
	Production scale	t/year	
COF	Volume/number	M^3/number	
	Production scale	t/year	
EF	Volume/number	M^3/number	
	Production scale	t/year	

Raw material/energy consumption		
Indicator	**Unit**	**Value**
Iron ore	t/year	
Sintering ore	t/year	
Pellet ore	t/year	
Lime stone	t/year	
Coke	t/year	

Coal	t/year	
Electricity	Gwh/year	
Plastics	t/year	
Others	t/year	

Process data: Sintering		
Indicator	**Unit**	**Value**
Production per unit of time/number	t/h.number	
Coal consumption	kg	
Back to mine rate for the sintering ore	%	
Production of sintering ore	t	
Consumption of gas	M3	
Consumption of electricity	Kwh	
Consumption of raw material	Kg	
Other consumption	t	

Process data: Pellet		
Indicator	**Unit**	**Value**
Production per unit of time/number	t/h.number	
Consumption of Powdered Iron	ton	
Consumption of Binder	ton	
Consumption of gas	M^3	

Consumption of electricity	Kwh	
Production of pellet ore	t	
Other consumption	t	

Process data: Coking		
Indicator	**Unit**	**Value**
Consumption of coking coal	t	
Consumption of washing coal	t	
Consumption of gas	M3	
Consumption of electricity	Kwh	
Production of coke	t	
Blending ratio for coking coal	%	
Blending ratio for gas	%	
Gas generation	M^3	
Coke ratio	%	
Generation of COG	M^3	
Recovery of COG	M^3	
Generation of steam/waste heat	t	
Recovery of steam/waste heat	t	

Process data: Iron making		
Indicator	**Unit**	**Value**

Furnace volume	M3	
Grade of the iron core into furnace	%	
BF utilization co-efficient	$t/m^3.d$	
Ratio of coke	kg/t	
Ratio of coal	kg/t	
Consumption of electricity	kWh	
Production of iron	t	
Pass rate of iron	%	
Other consumption		
Generation of BFG	M^3	
Recovery of BFG	M^3	
Generation of steam/waste heat	t	
Recovery of steam/waste heat	t	

Process data: Ferroalloy furnace/electric furnace		
Indicator	**Unit**	**Value**
Coke ratio into the furnace	%	
Consumption of electricity	Kwh	
Consumption of Solvent	kg	
Consumption of Manganese	t	
Silica	t	
Steel scrap	t	

Production of Ferroalloy	t	
Other consumption		
Generation of steam/waste heat	t	
Recovery of steam/waste heat	t	
Process data: Steel making BOF/EF		
Indicator	**Unit**	**Value**
Volume of the furnace	t	
Consumption of iron/steel	t	
Consumption of Refractory	t	
Consumption of Oxygen	M^3	
Consumption of Molten iron	t	
Consumption of Alloy	t	
Consumption of electricity	kWh	
Consumption of Ferrosilicon	t	
Consumption of Ferromanganese	t	
Consumption of lime stone	t	
Production of steel	t	
Other consumption		
Generation of gas	M^3	
Recovery of gas	M^3	
Generation of steam/waste heat	t	
Recovery of steam/waste heat	t	

Emissions

Process	Waste water pollutants/(t·a^{-1})				Air pollutants/(t·a^{-1})			Solid waste/slag (10^4 t·a^{-1})
	COD	SS	Petroleum hydrocarbons	Ammonia	SO_2	NO_x	Dust	
Coking								
Sintering								
Iron making								
Steel making								
Rolling								

Table S7 Survey table for technology

Name of the technology					
Inventing company/institution		Contact person		Tel	
		Address			
		Email			
Type	☐ Reduce ☐ Reuse ☐ Recycling ☐ Industrial symbiosis/linkage ☐ Software technology ☐ Other____________				
	☐ Developed by-self ☐ Imported				
Stage of the technology	☐ R&D ☐ Demonstration ☐ Market industrialization				
Introduction of the technology	**Application field/industry** **Technology scale** **Main parameters** **Technology principle and process scheme** **Environmental benefit/economic benefit** **Advantage of the technology and its contribution to circular economy?**				

Application case	Please write one application case of this technology： **Application company** **Scale, running time, etc** **The economic and environmental benefit of the technology application**							
Technology parameters	Item	Parameter		Unit	Data			
	Economic	Investment cost		CNY/t steel 、CNY/a				
		Running cost		CNY/t steel 、CNY/a				
		Benefit 、 Avoided benefit	Benefit	CNY/t steel			Note：The avoided befit refers to the benefit from the by-products utilization, reduced waste generation and manufacturing cost, etc.	
			Avoided benefit	CNY/t steel				
			Other benefit	CNY/t steel				
	Material/energy saving	Item	Name	Unit	Consumption before technology application	Consumption after technology application	Change	Average consumption in this industry
		Raw material	ore	kg/t steel				
			Metal	kg/steel				
			Other	kg/steel				
		Energy	Coal	t/t steel				
			Electricity	kWh/t steel				
			Other	/t steel				
		Fresh water		M3/t steel				

	Waste reduction	Pollutants		Unit	Emission before technology application	Emission after technology application	Change	Average in this industry
		Item	Name					
		Waste water pollutants	Waste water	M3/t steel				
			CODcr	kg/t steel				
			Petroleum hydrocarbons	kg/t steel				
			PAHs	kg/t steel				
			Other	kg/t steel				
		Air pollutants	SO_2	kg/t steel				
			Dust	kg/t steel				
			Ash	kg/t steel				
			NOx	kg/t steel				
			Other					
		Solid waste	Slag	kg/t steel				
			Other	kg/t steel				
		Hazardous pollutants		kg/t steel				
				kg/t steel				
		Other		kg/t steel				
				kg/t steel				

	Reuse/ recycling	Indicator		Unit	Before technology application	After technology application	Change	Average in this industry
		Water reuse rate		%				
		Iron sludge recycling		%				
		Slag utilization rate		%				
		Waste heat recovery		%				
		Solid waste utilization		%				
				%				
				%				
		Absorb solid waste		kg/t steel				
				kg/t steel				
				kg/t steel				
		Other resource reuse/recycling		kg/t steel				
				kg/t steel				
				kg/t steel				

Table S8 Survey table for technology inventory data

Technology Input-output data		
Input data	Unit	Data
Electricity	kWh	
Heavy oil	kg	
Coal	kg or J	
Heat	J	
Natural gas	m^3 or J	
Other fossil energy	J	
Other		
Output data	Unit	
CO_2	kg	
SO_2	kg	
NOx	kg	
Ash	kg	
Solid waste	kg	
Other		

Publications

Journal papers

1. **Dong, L.**, Fujita, T., Zhang, H., Dai, M., Fujii, M., Ohnishi, S., Geng, Y., Liu, Z., 2013. Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model. Energy Policy 61, 864-873. (SCI, IF=2.743)
2. **Dong, L.**, Zhang, H., Fujita, T., Ohnishi, S., Li, H., Fujii, M., Dong, H., 2013. Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan. Journal of Cleaner Production 59, 226-238. (SCI, IF=3.398)
3. **Dong, L.**, Gu, F., Fujita, T., Hayashi, Y., Gao, J., 2014. Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China. Energy Policy 65, 388-397. (SCI, IF=2.743)
4. **Dong, L.**, Liang, H., 2014. Spatial analysis on China's regional air pollutants and CO2 emissions: emission pattern and regional disparity. Atmospheric Environment, 92: 280-291. (SCI, IF=3.110)
5. **Dong, L.**, Dong H., Fujita T., Geng Y. and Fujii M., 2014. Cost-benefit analysis for SO2 control strategy in China's regional level: regional disparity, inequity and future challenges. Journal of Cleaner Production. Minor revision. (SCI, IF=3.398)
6. **Dong L.**, Dai M., Liang H., Fujita T. and Wang Y., 2014. Achieving sustainable industry and urban development: planning and assessment with case study in China, 2014. Cities. Submitted. (SCI, IF=1.127)
7. **Dong L.**, Fujita T., 2014. Life cycle assessment on an industrial and urban symbiosis in China. Chinese Journal of Urban and Environmental Studies. (Under review)
8. Kanada, M., **Dong, L.**, Fujita, T., Fujii, M., Inoue, T., Hirano, Y., Togawa, T., Geng, Y., 2013. Regional disparity and cost-effective SO2 pollution control in China: A case study in 5 mega-cities. Energy Policy 61, 1322-1331. (SCI, IF=2.743)
9. Zhang, H., **Dong, L.**, Li, H.-q., Chen, B., Tang, Q., Fujita, T., 2013. Investigation of the residual heat recovery and carbon emission mitigation potential in a Chinese steelmaking plant: A hybrid material/energy flow analysis case study. Sustainable Energy Technologies and Assessments 2, 67-80.
10. Zhang H., **Dong L.**, Li H., Fujita T., Ohnishi S., Tang Q., 2013. Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park: A case study with carbon flow analysis. Energy Policy 61, 1400-1411. (SCI, IF=2.743)
11. Li H., **Dong L.**, Wang D., 2013. Economic and environmental gains of China's fossil energy subsidies reform: A rebound effect case study with EIMO model. Energy Policy 54, 335-342. (SCI, IF=2.743)
12. Dong, H., Ohnishi, S., Fujita, T., Geng, Y., Fujii, M., **Dong, L.**, 2014. Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. Energy 64, 277-286. (SCI, IF=3.651)
13. Li H., Liang H., **Dong L.**, 2014. Towards resilient cities: a review on China's resource dependent cities project and solutions with industrial and regional symbiosis. Landscape and Urban Planning. Under review. (SCI, IF=2.314)
14. Fujita T., Ohnishi S., **Dong L.**, Fujii M., 2014. Eco-industrial development as a circularization policy framework toward sustainable industrial cities. Lesson and suggestions from the eco town program in Japan. BDC, 13(1): 35-52.
15. Togawa T., Fujita T., **Dong L.**, Fujii M., Ooba M., 2014. Feasibility assessment of power plant source waste heat to plant factory considering spatial configuration, 2014. Journal of Cleaner Production 81, 60-69 (SCI, IF=3.398)

16. Liang H., Tanikawa H., Matsuno Y., **Dong L.**, 2014. Modeling in-use steel stock in China’s buildings and civil engineering infrastructure using time-series of DMSP/OLS nighttime lights. Remote Sensing, 6(6): 4780-4800. (SCI, IF=2.10)
17. Dong H., Dai H., **Dong L.**, Fujita T., Inoue T., Bunya S., Geng Y., Fujii M., Masui T., 2014. Pursuing air pollutant co-benefits of CO2 mitigation in China: a provincial leveled analysis. Applied Energy. Submitted. (SCI, IF=4.781)
18. Dong H., Geng Y., Fujita T., Fujii M., Yu X., Hao H., Liu Z., **Dong L.**, Ohnishi S., 2014. Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows. Water Research, Submitted. (SCI, IF=4.655)
19. 大西悟, 藤田壮, 藤井実, **Dong Liang**, 戸川卓哉. 産業都市での地区内熱供給による環境改善効果の評価システム. 土木学会論文集 G（環境）, 第 69 巻, 第 6 号, pp. Ⅱ_227- Ⅱ_237. 2013 年 6 月.
20. 大西悟，藤田壮，藤井実，戸川卓哉，**Dong Liang**. 地域循環による各主体の GHG アカウンティングへの影響分析. 日本 LCA 学会誌, 第 10 巻、第 3 号, pp.2-9. 2014 年 7 月.
21. 大西悟，藤田壮，**Dong Liang**，藤井実. 産業共生と都市共生に向けた研究のこれまでの流れと今後の展開. 環境共生, 掲載予定, 12 枚, 2014 年 7 月頃.

Book chapters

1. Dong L., Fujita T., Promotion of low-carbon city through industrial and urban system innovation: Japanese experience and China’s practice, 2014. *Actions on Climate Change by Asian Countries, world scientific press*. Accepted.

Conference proceedings and presentations (as first author only)

1. ***Dong Liang***, Fujita Tsuyoshi, Dai Ming. Urban energy conservation planning and CO2 mitigation: a case study in Chinese heavy industrial city using hybrid energy input-output model. ISIE-MFA 2012 “Socio-Economic Metabolism”, Darmstadt University of Technology, Germany. September, 2012. (Oral)
2. ***Dong Liang***, Fujita Tsuyoshi, Ohnishi Satoshi. Co-benefit Opportunity of Industrial Symbiosis in Iron and Steel Industry: Kawasaki's Experience and China's Practice. The Third ISIE Asia-Pacific Meeting, Tsinghua University, Beijing, China, October, 2012.(Poster)
3. ***董亮***, 张辉，藤田壮，藤井実，戸川卓哉，大西悟，董会娟, 2013. Life Cycle Thinking for Industrial Symbiosis Case Study in China’s Iron/Steel Industrial Park Using Value Chain Analysis. 第 8 回日本 LCA 学会研究発表会，立命館大学. (Oral)
4. ***Dong Liang***, Fujita Tsuyoshi, Fujii Minoru, Togawa Takuya, Ohnishi Satoshi, Dong Hujuan. How Industrial Symbiosis Contributes to Low-carbon Strategy from the Perspective of Scope 2 and 3? A Case Study in China. “Industrial Ecology: Strategy for Green Economy”, ISIE2013, 7th International Conference of the International Society for Industrial Ecology, University of Ulsan, Ulsan, South Korea, June 25-28, 2013. (Poster)
5. ***Dong Liang***, Fujita Tsuyoshi, Fujii Minoru, Togawa Takuya, Ohnishi Satoshi, Dong Hujuan. Accounting for the low-carbon benefit of industrial symbiosis from the perspective of Scope 3: a case study in China. The Third Symposium on Industrial Ecology for Young Professionals, University of Ulsan, Ulsan, South Korea, June 29, 2013. (Poster).
6. ***董亮***, 藤田壮，大西悟，藤井実，戸川卓哉，董会娟：Promoting low-carbon city through industrial symbiosis: case study and policy implication in China，日本環境共生学会第 16 回地域シンポジウムポスターセッション，P-5，2013.5.

7. ***Dong L***.,Fujita T.,Fujii M.,Ohnishi S. , Bring brightness of low-carbon district in China through industrial symbiosis. International Symposium on Regional Sustainable Development, 26th – 27th November, 2013, Shenyang, China. (Oral)

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References

Abiola, A., Fraga, E.S., Lettieri, P., 2010. Multi-Objective Design for the Consequential Life Cycle Assessment of Corn Ethanol Production, in: Pierucci, S., Ferraris, G.B. (Eds.), Computer Aided Chemical Engineering. Elsevier, pp. 1309-1314.

Al-Salem, S.M., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Management 29, 2625-2643.

Allenby, B.R., 1992. Design for Environment: Implementing Industrial Ecology. University of Michigan, Ann Arbor, MI.

Andrews, R., Pearce, J.M., 2011. Environmental and economic assessment of a greenhouse waste heat exchange. Journal of Cleaner Production 19, 1446-1454.

Aurangzeb, Q., Al-Qadi, I.L., Ozer, H., Yang, R., 2014. Hybrid life cycle assessment for asphalt mixtures with high RAP content. Resources, Conservation and Recycling 83, 77-86.

Ayres, R.U., 1989. Industrial metabolism. National Academy Press, Washington, DC.

Bai, L., Qiao, Q., Yao, Y., Guo, J., Xie, M., 2014. Insights on the development progress of National Demonstration eco-industrial parks in China. Journal of Cleaner Production 70, 4-14.

Bai, X., Imura, H., 2000. A comparative study of urban environment in East Asia: Stage model of urban environmental evolution. International Review for Global Environmental Strategies 1, 135-158.

Barles, S., 2009. Urban Metabolism of Paris and Its Region. Journal of Industrial Ecology 13, 898-913.

Behera, S.K., Kim, J.-H., Lee, S.-Y., Suh, S., Park, H.-S., 2012. Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. Journal of Cleaner Production 29–30, 103-112.

Berkel, R.V., Fujita, T., Hashimoto, S., Fujii, M., 2009. Quantitative Assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. Environmental Science & Technology 43, 1271-1281.

Blengini, G.A., Busto, M., Fantoni, M., Fino, D., 2012. Eco-efficient waste glass recycling: Integrated waste management and green product development through LCA. Waste Management 32, 1000-1008.

Broberg, S., Backlund, S., Karlsson, M., Thollander, P., 2012. Industrial excess heat deliveries to Swedish district heating networks: Drop it like it's hot. Energy Policy 51, 332-339.

Broto, V.C., Allen, A., Rapoport, E., 2012. Interdisciplinary Perspectives on Urban Metabolism. Journal of Industrial Ecology 16, 851-861.

Brunner, P., Daxbeck, H., Baccini, P., 1994. Industrial metabolism at the regional and local level: A case-study on a Swiss region. United Nations University Press, Tokyo.

Brunner, P., Rechberger, H., 2004. Practical handbook of material flow analysis. Int J LCA 9, 337-338.

Côté, R.P., Cohen-Rosenthal, E., 1998. Designing eco-industrial parks: a synthesis of some experiences. Journal of Cleaner Production 6, 181-188.

CCID, 2011. 12th Five Energy Conservation Planning for Liuzhou city, 2011-2015 (In Chinese). CCID consulting company, Beijing China;

Liuzhou Development and Reform Commission.

Cellura, M., Ardente, F., Longo, S., 2012. From the LCA of food products to the environmental assessment of protected crops districts: A case-study in the south of Italy. Journal of Environmental Management 93, 194-208.

Chen, C., Wan, Y., Chen, H., Wang, J., 2009. Environmental and Economic benefit of Circular Economy Project in Iron and Steel Industry, China Iron and Steel Annual Meeting, Beijing, pp. 50-55.

Chen, M., Liu, W., Tao, X., 2013. Evolution and assessment on China's urbanization 1960–2010: Under-urbanization or over-urbanization? Habitat International 38, 25-33.

Chen, X., Xi, F., Geng, Y., Fujita, T., 2011. The potential environmental gains from recycling waste plastics: Simulation of transferring recycling and recovery technologies to Shenyang, China. Waste Management 31, 168-179.

Chertow, M., Ehrenfeld, J., 2012. Organizing Self-Organizing Systems. Journal of Industrial Ecology 16, 13-27.

Chertow, M.R., 1998. The Eco-industrial Park Model Reconsidered. Journal of Industrial Ecology 2, 8-10.

Chertow, M.R., 2000. Industrial symbiosis: literature and taxonomy. Annual Review of Energy and the Environment 25, 313-337

Chertow, M.R., Lombardi, D.R., 2005. Quantifying Economic and Environmental Benefits of Co-Located Firms. Environmental Science & Technology 39, 6535-6541.

Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. Energy 34, 2116-2123.

Cleveland, C.J., Ruth, M., 1998. Indicators of Dematerialization and the Materials Intensity of Use. Journal of Industrial Ecology 2, 15-50.

Costa, I., Massard, G., Agarwal, A., 2010. Waste management policies for industrial symbiosis development: case studies in European countries. Journal of Cleaner Production 18, 815-822.

Cronholm, L.Å., Grönkvist, S., Saxe, M., 2009. Excess heat from industrial firms and heat recovery from premises) Report 2009:12. Svensk Fjärrvärme AB, Stockholm (in Swedish).

Diwekar, U., Small, M.J., 1998. Industrial Ecology and Process Optimization. Journal of Industrial Ecology 2, 11-13.

Domenech, T., Davies, M., 2011. Structure and morphology of industrial symbiosis networks: The case of Kalundborg. Procedia - Social and Behavioral Sciences 10, 79-89.

Dong, L., 2011. A Study on the Comprehensive Assessment Methodology for Circular Economy Technology. Institution of Process Engineering, Chinese Academy of Sciences, CAS, Beijing.

Dong, L., Fujita, T., Zhang, H., Dai, M., Fujii, M., Ohnishi, S., Geng, Y., Liu, Z., 2013a. Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model. Energy Policy 61, 864-873.

Dong, L., Gu, F., Fujita, T., Hayashi, Y., Gao, J., 2014. Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China. Energy Policy 65, 388-397.

Dong, L., Zhang, H., Fujita, T., Ohnishi, S., Li, H., Fujii, M., Dong, H., 2013b. Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan. Journal of Cleaner Production 59, 226-238.

Eckelman, M.J., Chertow, M.R., 2009. Quantifying Life Cycle Environmental Benefits from the Reuse of Industrial Materials in Pennsylvania. Environmental Science & Technology 43, 2550-2556.

Ehrenfeld, J., Gertler, N., 1997. Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg. Journal of Industrial Ecology 1, 67-79.

Eurostat, 2001. Economy-wide material flow accounts and derived indicators: A methodological guide.

Eurostat, 2007. Economy-wide material flow accounting: A Compilation Guide European Statistical Office: Luxembourg.

Eurostat, 2009. Economy-wide material flow accounts: Compilation guidelines for reporting to the 2009 Eurostat questionnaire (Version 01,June 2009). European Statistical Office: Luxembourg.

Feng, Y.Y., Zhang, L.X., 2012. Scenario analysis of urban energy saving and carbon abatement policies: A case study of Beijing city, China. Procedia Environmental Sciences 13, 632-644.

Finney, K.N., Sharifi, V.N., Swithenbank, J., Nolan, A., White, S., Ogden, S., 2012. Developments to an existing city-wide district energy network – Part I: Identification of potential expansions using heat mapping. Energy Conversion and Management 62, 165-175.

Frosch, R.A., Gallopoulos, N.E., 1989. Strategies for manufacturing. Scientific American 261, 94-102.

GEC, 2005. Eco-Towns in Japan-Implications and Lessons for Developing Countries and Cities.Global Environment Centre Foundation.

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

Geng, Y., Tsuyoshi, F., Chen, X., 2010. Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. Journal of Cleaner Production 18, 993-1000.

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

Gibbs, D., Deutz, P., 2005. Implementing industrial ecology? Planning for eco-industrial parks in the USA. Geoforum 36, 452-464.

Giljum S., Hubacek, K., 2009. Conceptual foundations and applications of physical input-output tables, in: Suh, S. (Ed.), Handbook of Input-Output Economics in Industrial Ecology Spring Netherlands, Dordrecht, pp. 1-75.

Guo, Z.C., Fu, Z.X., 2010. Current situation of energy consumption and measures taken for energy saving in the iron and steel industry in China. Energy 35, 4356-4360.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H., Winiwarter, V., 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 21, 199-213.

Hamin, E.M., Gurran, N., 2009. Urban form and climate change: Balancing adaptation and mitigation in the U.S. and Australia. Habitat International 33, 238-245.

Harris, S., Pritchard, C., 2004. Industrial Ecology as a learning process in business strategy. Progress in Industrial Ecology, an International Journal 1, 89-111.

Hashimoto, S., Fujita, T., Geng, Y., Nagasawa, E., 2010. Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. Resources, Conservation and Recycling 54, 704-710.

Hashimoto, S., Moriguchi, Y., 2004. Proposal of six indicators of material cycles for describing society's metabolism: from the viewpoint of material flow analysis. Resources, Conservation and Recycling 40, 185-200.

Hayashi, Y., 2010. Can We Design the Future of Human Life and the Environment? Sustainability: Future Balance between Nature and Civilization Tokyo, Japan: Akashi Shoten.

Hertwich, E.G., Hammitt, J.K., Pease, W.S., 2000. A Theoretical Foundation for Life-Cycle Assessment. Journal of Industrial Ecology 4, 13-28.

Herva, M., Álvarez, A., Roca, E., 2012. Combined application of energy and material flow analysis and ecological footprint for the environmental evaluation of a tailoring factory. Journal of Hazardous Materials 237–238, 231-239.

Hoffrén, J., Luukkanen, J., Kaivo-oja, J., 2000. Decomposition Analysis of Finnish Material Flows: 1960–1996. Journal of Industrial Ecology 4, 105-125.

Holub, H.W., Schnabl, H., 1985. Qualitative input-output analysis and structural information. Economic Modelling 2, 67-73.

Hu, M.M., Pauliuk, S., Wang, T., Huppes, G., van der Voet, E., Muller, D.B., 2010. Iron and steel in Chinese residential buildings: A dynamic analysis. Resour Conserv Recy 54, 591-600.

Huber, J., 2000. Towards industrial ecology: sustainable development as a concept of ecological modernization. Journal of Environmental Policy and Planning 2, 269-285.

Jacobsen, N.B., 2006. Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and

Environmental Aspects. Journal of Industrial Ecology 10, 239-255.

Jensen, P.D., Basson, L., Hellawell, E.E., Bailey, M.R., Leach, M., 2011. Quantifying ‘geographic proximity’: Experiences from the United Kingdom's National Industrial Symbiosis Programme. Resources, Conservation and Recycling 55, 703-712.

JIS, 2011. Circular Economy Technology Report in Jinan iron and steel coorporation(in Chinese). Jinan iron/steel coorporation, Shandong: Jinan.

Johansson, M.T., Söderström, M., 2011. Options for the Swedish steel industry – Energy efficiency measures and fuel conversion. Energy 36, 191-198.

Kapil, A., Bulatov, I., Smith, R., Kim, J.-K., 2012. Process integration of low grade heat in process industry with district heating networks. Energy 44, 11-19.

Khoo, H.H., Lim, T.Z., Tan, R.B.H., 2010. Food waste conversion options in Singapore: Environmental impacts based on an LCA perspective. Science of The Total Environment 408, 1367-1373.

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H., 2014a. Review of LCA studies of solid waste management systems – Part I: Lessons learned and perspectives. Waste Management 34, 573-588.

Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen, T.H., Hauschild, M.Z., 2014b. Review of LCA studies of solid waste management systems – Part II: Methodological guidance for a better practice. Waste Management 34, 589-606.

Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., 2010. Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective. Resources, Conservation and Recycling 55, 246-259.

Lehmann, S., 2013. Low-to-no carbon city: Lessons from western urban projects for the rapid transformation of Shanghai. Habitat International 37, 61-69.

Leontief, W., 1936. Quantitative input-output relations in the economic system. Review of Economic Statistics, 18.

Li, H., Bao, W., Xiu, C., Zhang, Y., Xu, H., 2010. Energy conservation and circular economy in China's process industries. Energy 35, 4273-4281.

Liang, S., Wang, C., Zhang, T., 2010. An improved input–output model for energy analysis: A case study of Suzhou. Ecological Economics 69, 1805-1813.

Liang, S., Xu, M., Zhang, T., 2013. Life cycle assessment of biodiesel production in China. Bioresource Technology 129, 72-77.

Liang, S., Zhang, T., 2012. Comparing urban solid waste recycling from the viewpoint of urban metabolism based on physical input–output model: A case of Suzhou in China. Waste Management 32, 220-225.

Liang, S., Zhang, T., 2013. Investigating Reasons for Differences in the Results of Environmental, Physical, and Hybrid Input-Output Models. Journal of Industrial Ecology, n/a-n/a.

Liang, S., Zhang, T., Xu, Y., 2012. Comparisons of four categories of waste recycling in China’s paper industry based on physical input–output life-cycle assessment model. Waste Management 32, 603-612.

Lin, C., Huang, C.-L., Shern, C.-C., 2008. Recycling waste tire powder for the recovery of oil spills. Resources, Conservation and Recycling 52, 1162-1166.

Liu, H., Chen, J., Mei, J., Jia, J., Shi, L., 2014a. A view of iron and steel making technology in the Yan region during the Warring States period and the Han dynasty: scientific study of iron objects excavated from Dongheishan site, Hebei province, China. Journal of Archaeological Science 47, 53-63.

Liu, H., Gallagher, K.S., 2010. Catalyzing strategic transformation to a low-carbon economy: A CCS roadmap for China. Energy Policy 38, 59-74.

Liu, H., Zhou, G., Wennersten, R., Frostell, B., 2014b. Analysis of sustainable urban development approaches in China. Habitat International 41, 24-32.

Liu, Z., Liang, S., Geng, Y., Xue, B., Xi, F., Pan, Y., Zhang, T., Fujita, T., 2012. Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: The case of Beijing, Tianjin, Shanghai and Chongqing. Energy 37, 245-254.

Lowe, E., 1993. Industrial ecology—an organizing framework for environmental management. Environmental Quality Management 3, 73-85.

Ma, S.-h., Wen, Z.-g., Chen, J.-n., Wen, Z.-c., 2014. Mode of circular economy in China's iron and steel industry: a case study in Wu'an city. Journal of Cleaner Production 64, 505-512.

Marvuglia, A., Benetto, E., Rege, S., Jury, C., 2013. Modelling approaches for consequential life-cycle assessment (C-LCA) of bioenergy: Critical review and proposed framework for biogas production. Renewable and Sustainable Energy Reviews 25, 768-781.

Mattila, T.J., Pakarinen, S., Sokka, L., 2010. Quantifying the Total Environmental Impacts of an Industrial Symbiosis - a Comparison of Process-, Hybrid and Input−Output Life Cycle Assessment. Environmental Science & Technology 44, 4309-4314.

METI, 2006. Eco-Town Projects/Environmental Industries in Progress-, in: The Ministry of Economy, T.a.I. (Ed.).

Meylan, G., Ami, H., Spoerri, A., 2014. Transitions of municipal solid waste management. Part II: Hybrid life cycle assessment of Swiss glass-packaging disposal. Resources, Conservation and Recycling 86, 16-27.

Michaelis, P., Jackson, T., 2000. Material and energy flow through the UK iron and steel sector. Part 1: 1954–1994. Resources, Conservation and Recycling 29, 131-156.

Mirata, M., 2004. Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges. Journal of Cleaner Production 12, 967-983.

Mirata, M., Emtairah, T., 2005. Industrial symbiosis networks and the contribution to environmental innovation: The case of the Landskrona industrial symbiosis programme. Journal of Cleaner Production 13, 993-1002.

Molenaar, A.A.A., 2013. Durable and Sustainable Road Constructions for Developing Countries. Procedia Engineering 54, 69-81.

Moriguchi, Y., 2000. Industrial Ecology in Japan. Journal of Industrial Ecology 4, 7-9.

Moriguchi, Y., 2001. Rapid Socio-Economic Transition and Material Flows in Japan. Population and Environment 23, 105-115.

Nan Zhou, Gang He, Williams, C., 2012. China's Development of Low-Carbon Eco-Cities and Associated Indicator Systems. China Energy, ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY.

NBS, 2011. China Statistical Yearbook. National Bureau of Statistics, Beijing,China.

Newton, P., Bai, X., 2008. Transitioning to Sustainable Urban Development. Springer Publishing.

OECD, 2009. Eco-Innovation Policies in The People's Republic of China.

Oh, D.-S., Kim, K.-B., Jeong, S.-Y., 2005. Eco-Industrial Park Design: a Daedeok Technovalley case study. Habitat International 29, 269-284.

Ohnishi, S., Fujita, T., Chen, X., Fujii, M., 2012. Econometric analysis of the performance of recycling projects in Japanese Eco-Towns. Journal of Cleaner Production 33, 217-225.

Paquin, R.L., Howard-Grenville, J., 2012. The Evolution of Facilitated Industrial Symbiosis. Journal of Industrial Ecology 16, 83-93.

Park, H.-S., Behera, S.K., 2014. Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks. Journal of Cleaner Production 64, 478-485.

Park, H.-S., Rene, E.R., Choi, S.-M., Chiu, A.S., 2008a. 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.

Park, H.-S., Rene, E.R., Choi, S.-M., Chiu, A.S.F., 2008b. 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.

Pearce, D.W., Turner, R.K., 1990. Economics of Natural Resources and the Environment. Harvester Wheatsheaf.

Qu, L., Zhang, T., Liang, S., 2013. Waste management of urban agglomeration on a life cycle basis. Resources, Conservation and Recycling 78, 47-53.

R. Ayres, R., L. Ayres, L., 1996. Industrial Ecology: Closing the Materials Cycle. Edward Elgar, Cheltenham, UK and Lyme, MA.

R.Ayres, R., L.Ayres, L., 2002. A handbook of Industrial Ecology. Edward Elgar Publishing Limited, Massachusetts,USA.

RecycleChina, http://www.cjtr.com.cn/.

Reh, L., 2013. Process engineering in circular economy. Particuology 11, 119-133.

Rigamonti, L., Falbo, A., Grosso, M., 2013. Improvement actions in waste management systems at the provincial scale based on a life cycle assessment evaluation. Waste Management 33, 2568-2578.

Rodr ǵuez, M.T.T., Andrade, L.C., Bugallo, P.M.B., Long, J.J.C., 2011. Combining LCT tools for the optimization of an industrial process: Material and energy flow analysis and best available techniques. Journal of Hazardous Materials 192, 1705-1719.

Rotterdam-Climate-Initiative, 2011. CO2 capture and storage in Rotterdam:A network aproach.

Schaffartzik, A., Eisenmenger, N., Krausmann, F., Weisz, H., 2014. Consumption-based Material Flow Accounting. Journal of Industrial Ecology 18, 102-112.

Schiller, F., 2009. Linking material and energy flow analyses and social theory. Ecological Economics 68, 1676-1686.

Schmidt, M., 2010. Material and Energy Flow Analysis. Chemical Engineering & Technology 33, 551-551.

Sendra, C., Gabarrell, X., Vicent, T., 2007. Material flow analysis adapted to an industrial area. Journal of Cleaner Production 15, 1706-1715.

Shi, H., 2010. Industrial Symbiosis from the Perspectives of Transaction Cost Economics and Institutional Theory. Yale University.

Shi, H., Chertow, M., Song, Y.Y., 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.

Shu, X., Huang, B., Recycling of waste tire rubber in asphalt and portland cement concrete: An overview. Construction and Building Materials.

Siitonen, S., Tuomaala, M., Ahtila, P., 2010. Variables affecting energy efficiency and CO2 emissions in the steel industry. Energy Policy 38, 2477-2485.

Song, H.-S., Hyun, J.C., 1999. A study on the comparison of the various waste management scenarios for PET bottles using the life-cycle assessment (LCA) methodology. Resources, Conservation and Recycling 27, 267-284.

Soratana, K., Landis, A.E., 2011. Evaluating industrial symbiosis and algae cultivation from a life cycle perspective. Bioresource Technology 102, 6892-6901.

Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: moving from rhetoric to implementation. Journal of Cleaner Production 42, 215-227.

Su, M.R., Chen, B., Xing, T., Chen, C., Yang, Z.F., 2012. Development of low-carbon city in China: Where will it go? Procedia Environmental Sciences 13, 1143-1148.

Subramanian, P.M., 2000. Plastics recycling and waste management in the US. Resources, Conservation and Recycling 28, 253-263.

Suh, S., 2005. Theory of materials and energy flow analysis in ecology and economics. Ecological Modelling 189, 251-269.

Teresa Torres, M., Carmen Barros, M., Bello, P.M., Casares, J.J., Miguel Rodríguez-Blas, J., 2008. Energy and material flow analysis: Application to the storage stage of clay in the roof-tile manufacture. Energy 33, 963-973.

Tian, J., Liu, W., Lai, B., Li, X., Chen, L., 2014. Study of the performance of eco-industrial park development in China. Journal of Cleaner Production 64, 486-494.

Tunesi, S., 2011. LCA of local strategies for energy recovery from waste in England, applied to a large municipal flow. Waste Management 31, 561-571.

UN, 2012. World Urbanization Prospects The 2011 Revision United Nations, Department of Economic and Social Affairs,Population Division, New York, United States.

Vázquez-Rowe, I., Marvuglia, A., Rege, S., Benetto, E., 2014. Applying consequential LCA to support energy policy: Land use change effects of bioenergy production. Science of The Total Environment 472, 78-89.

van Beers, D., Bossilkov, A., Corder, G., van Berkel, R., 2007. Industrial Symbiosis in the Australian Minerals Industry: The Cases of Kwinana and Gladstone. Journal of Industrial Ecology 11, 55-72.

Van Berkel, R., 2010. Quantifying Sustainability Benefits of Industrial Symbioses. Journal of Industrial Ecology 14, 371-373.

Van Berkel, R., Fujita, T., Hashimoto, S., Geng, Y., 2009. Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. Journal of Environmental Management 90, 1544-1556.

van Berkel, R., Marinova, D., Annandale, D., Phillimore, J., 2007. The International Handbook of Environmental Technology Management.

Wang, H., Hashimoto, S., Moriguchi, Y., Yue, Q., Lu, Z., 2012a. Resource Use in Growing China. Journal of Industrial Ecology 16, 481-492.

Wang, L., Templer, R., Murphy, R.J., 2012b. A Life Cycle Assessment (LCA) comparison of three management options for waste papers: Bioethanol production, recycling and incineration with energy recovery. Bioresource Technology 120, 89-98.

White, R., 1994. The Greening of Industrial Ecosystems. National Academy Press, Washington, DC.

WRI, 2008. MATERIAL FLOWS IN THE UNITED STATES:A Physical Accounting of the U.S. Industrial Economy. World Resources Institute, Washington,DC.

Wu, B., Zhou, M.H., 2009. Recycling of waste tyre rubber into oil absorbent. Waste Management 29, 355-359.

Wu, F., 2012. China's eco-cities. Geoforum 43, 169-171.

Xu, M., 2009. EVALUATING SUSTAINABILITY AND RESILIENCE OF COMPLEX SYSTEMS USING NETWORK THEORY. Arizona State University, Phoenix.

Xu, M., 2010. Development of the Physical Input Monetary Output Model for Understanding Material Flows within Ecological-Economic Systems. Journal of Resources and Ecology 1, 123-134.

Xu, M., Weissburg, M., Newell, J.P., Crittenden, J.C., 2012. Developing a Science of Infrastructure Ecology for Sustainable Urban Systems. Environmental Science & Technology 46, 7928-7929.

Xu, M., Zhang, T., 2007. Material Flows and Economic Growth in Developing China. Journal of Industrial Ecology 11, 121-140.

Xu, M., Zhang, T., Allenby, B., 2008. How Much Will China Weigh? Perspectives from Consumption Structure and Technology Development. Environmental Science & Technology 42, 4022-4028.

Yang, L., Li, Y., 2013. Low-carbon City in China. Sustainable Cities and Society. DOI:http://dx.doi.org/10.1016/j.scs.2013.03.001.

Yang, W., Deng, W., 2013. "Building related KPIs in Sino-Singapore Tianjin Eco-City". APCBEE Procedia 5, 112-115.

Yi, H., Xu, G., Cheng, H., Wang, J., Wan, Y., Chen, H., 2012. An Overview of Utilization of Steel Slag. Procedia Environmental Sciences 16, 791-801.

Zeng, S., Lan, Y., Huang, J., 2009. Mitigation paths for Chinese iron and steel industry to tackle global climate change. International Journal of Greenhouse Gas Control 3, 675-682.

Zhang, H., Dong, L., Li, H.-q., Chen, B., Tang, Q., Fujita, T., 2013a. Investigation of the residual heat recovery and carbon emission mitigation potential in a Chinese steelmaking plant: A hybrid material/energy flow analysis case study. Sustainable Energy Technologies and Assessments 2, 67-80.

Zhang, H., Dong, L., Li, H., Fujita, T., Ohnishi, S., Tang, Q., 2013b. Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park: A case study with carbon flow analysis. Energy Policy 61, 1400-1411.

Zhang, J., 2007. The research on circular economy project design and evaluation of Iron and Steel enterprises, School of Management. Tianjin University, Tianjin,China, pp. 1-75.

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

Zhou, L., Hu, S.-y., Li, Y., Jin, Y., Zhang, X., 2012. Modeling and Optimization of a Coal-Chemical Eco-industrial System in China. Journal of Industrial Ecology 16, 105-118.

Zhu, Q., Geng, Y., Lai, K.-h., 2010. Circular economy practices among Chinese manufacturers varying in environmental-oriented supply chain cooperation and the performance implications. Journal of Environmental Management 91, 1324-1331.