Eco-Benefits Assessment on Urban Industrial Symbiosis based on Material Flows Analysis and Emergy Evaluation Approach: A Case of Liuzhou City, China

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Abstract

Chinese government promotes ecological civilization in the "13th five year planning" (2016-2020) period. As a result, ecological impacts become highlight in the national circular economy practices. To apply the eco-industrial development strategy to address the intertwined industrial and regional economic development, as well as related environmental and ecological challenges is key point. Urban industrial symbiosis provides a novel approach to realize the above expectation. Traditional evaluation on circular economy provided critical environmental insights, while to date, ecological evaluation has been rather few for urban industrial symbiosis promotion. With this circumstance, this paper developed an integrated material flows analysis (MFA) and emergy evaluation model to investigate the environmental and ecological benefits of urban industrial symbiosis implementation in one typical industrial city in China. Local oriented urban industrial symbiosis network was analyzed. Inter flows and related environmental benefits of symbiotic network were quantified with MFA, and further ecological impacts were evaluated with emergy approach and the designed emergy index. From the environmental perspective, results highlighted, in general, urban industrial symbiosis generated significant life cycle environmental benefits, especially the reduction of upstream resource mining and downstream waste disposal within the regional metabolism. In total, around 204.7 million tons ore mining, 6.9 million ton solid waste and 2.3 million tons CO_2 emissions were reduced per year. From the ecological perspective, total emergy input was reduced by 1.3×10^{22}sej, which reflected the reduction of ecological burden. Particularly, as a key indicator for ecological lost caused by pollution, dilution emergy was decreased by 2.5×10^{16}sej, resulting from carbon mitigation co-benefit of urban industrial symbiosis. This paper provided modeling approach to understand the ecological benefits and trade-offs of circular economy practices, and critical insights on regional eco-industrial development. It will shed a light on ecological civilization construction in China in the new national planning period.

Key words

Ecological civilization; Emergy; Urban industrial symbiosis; Regional eco-industrial development; China

1. Introduction

After nearly 15 year's practice, China's circular economy practice has entered a new era. With noteworthy achievements in the promotion of cleaner production and eco-industrial parks, China aims to construct an overall regional circular economy development mode in the 13th five year planning (FYP) period (2016 to 2020) (Dong et al., 2016b; Dong et al., 2014b; Dong et al., 2013b). Especially, different from traditional concerns on resource and energy conservation and pollutants reduction, China is sparing no efforts to develop "ecological civilization", via launching a wide-ranging set of ecological reforms in 2015[1].

With this circumstance, harmonious development between industrialization, urbanization, as well as economic growth is critical challenge (Dong et al., 2013a; Fujii et al., 2016). As a result of the "world factory", as well as the engine for surging industrialization and urbanization, China's large scale energy intensive industries (EII) have brought significant environmental and ecological impacts, contributing a lot to the surging increase of energy consumption and related greenhouse gas emissions (GHGs). It was reported that, in 2009, the CO_2 emission from Chinese iron/steel sector amounted to 1.17 billion tons[2](Zeng et al., 2009), almost equivalent to half of the world's steel industry CO_2 emission(Liu and Gallagher, 2010). Meanwhile, China owns accelerating urbanization process, the urbanization rate already reached to 51% in 2011 and was expected be 60%[3] by 2020 (Chen et al., 2013; NBS, 2011; UN, 2012). Therefore, among a series of policies packages, regional eco-industrial development is vital importance and key component of national circular economy practice. And it is required not only addressing concerns on environmental benefits, but also ecological benefits.

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[1] Source: http://thediplomat.com/2015/09/chinas-new-blueprint-for-an-ecological-civilization/

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

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

The concept of urban industrial symbiosis (also called industrial and urban symbiosis in some literatures) provides a novel approach for China's industry fighting for the environmental challenges and promoting regional eco-industrial development (Dong et al., 2016a; Dong et al., 2014a). Industrial symbiosis (IS) emphasizes to enhance resource efficiency, reduces waste generation and GHG emissions via material, energy, by-products exchange between different processes and industries (Chertow, 2000, 2007; Chertow and Lombardi, 2005; Eckelman and Chertow, 2009; Hashimoto et al., 2010; Jacobsen, 2006). As an extended concept of IS, the so called "urban symbiosis" further explores synergies in urban and industrial areas, via utilizing municipal solid waste into industrial area, and meanwhile, applying industries as providers for living resources, e.g. waste heat and hot water. In spatial perspective, urban industrial symbiosis optimizes the regional metabolic network through resources and infrastructures allocation, so as to reduce resource consumption and emissions, and coordinate the interaction between industries and urban development (Dong et al., 2013a; Dong et al., 2013b; Gibbs and Deutz, 2007).

A numerous case studies had verified the environmental and economic benefits of urban industrial symbiosis. To our best knowledge, the enlightening studies included but not limited to: case study on Kalundborg, Denmark (Jacobsen, 2006); Puerto Rico, USA (Chertow and Lombardi, 2005); "eco-town project" in Japan (Berkel et al., 2009) as well as "circular economy pilot" in China (Zhang et al., 2010). From the perspective of analytical approaches, the prevailing methodology was environmental evaluation methods, mainly based on the material flow analysis (MFA) (Berkel et al., 2009; Chertow and Lombardi, 2005; Jacobsen, 2006) and life cycle assessment (LCA) (Eckelman and Chertow, 2009; Hashimoto et al., 2010; Mattila et al., 2010). The methodological limitations include the lacks of life cycle view via only MFA. The advantages of LCA can fill this gap, but it was much more difficult to gain the data. The other big challenge is, both methodologies have the limitation on reflecting the impacts on the ecosystem (Geng et al., 2014; Geng et al., 2010). Under the big picture of ecological civilization promotion in China, feasible analytical approaches for evaluation on ecological performance of circular economy practice is critical (Geng et al., 2013).

Emergy approach provides potential solution to address this challenge. Established by Odum in late 1980s (Odum, 1996), it provided a new way to quantitatively evaluate the ecological impacts of socioeconomic metabolism on ecosystem (Geng et al., 2014; Geng et al., 2010; Liu et al., 2011; Yuan et al., 2011). The advantage of emergy methodology is to identify and quantify the contribution of nature systems in the material forming process, and unify different kinds of energy, material, goods and services into emergy unit (solar emjoules, sej), thus making it available to evaluate the ecological impacts by natural resources mining and processing, consumption of goods and or services (Campbell et al., 2014). In emergy theory, energy and material originated from the sun directly or indirectly, solar emergy has been widely used as the benchmark to measure the value of one energy (Hau and Bakshi, 2004). It is particularly valuable to China, where mining and process industries cause considerable negative impacts on the ecosystem, and urban industrial symbiosis can be an effective way to reduce such impacts from a life cycle perspective.

To date, there have been emerging studies focusing on emergy evaluation on urban metabolism (Huang et al., 2006; Zhang et al., 2011b), waste recycling (Giannetti et al., 2013; Song et al., 2013; Yuan et al., 2011; Zhang et al., 2011a), forest ecosystem (Lu et al., 2011; Tilley and Swank, 2003), eco-industrial park (Geng et al., 2014; Geng et al., 2010), circular economy (Geng, 2011; Geng et al., 2013), etc. Some research works have also been carried out to analyze the industrial system (Geng et al., 2010; Yang et al., 2003; Yang et al., 2011). However, in general, to our best knowledge, emergy has been still rarely applied in evaluation urban industrial symbiosis, especially in industrial cities. Under this circumstance, this paper aims to develop an integrated material flows analysis (MFA) and emergy evaluation model to evaluate the environmental and ecological benefits of urban industrial symbiosis implementation in one typical industrial city in China, named Liuzhou. Policy insights are revealed with consideration on both environmental and ecological perspectives. This study represents the first of a series of researches exploring the emergy evaluation approach application in urban industrial symbiosis in China, and the results are critical to Chinese policy makers to address a set of ecological reforms and ever-improvements on circular economy promotion.

The remainder of this paper is organized as: after this introduction part, section 2 presents the materials and methods; section 3 describes the case city and urban industrial symbiosis scenarios; section 4 presents and discusses the analytical results as well as policy insights; finally, section 5 draws the conclusions.

2. Materials and methods

To analyze the environmental impacts as well as ecological impacts of urban industrial symbiosis, this study develops the analytical approach integrating MFA and emergy method.

2.1 System boundary

The research boundary in this study is an urban industrial symbiosis, which is illustrated in *Figure 1*. For the urban material flows, it is analyzed with the help of urban statistics. While for the urban industrial symbiotic network, the flows are quantified with micro level material flow analysis.

In this way, the industrial metabolism is linked with urban metabolism.

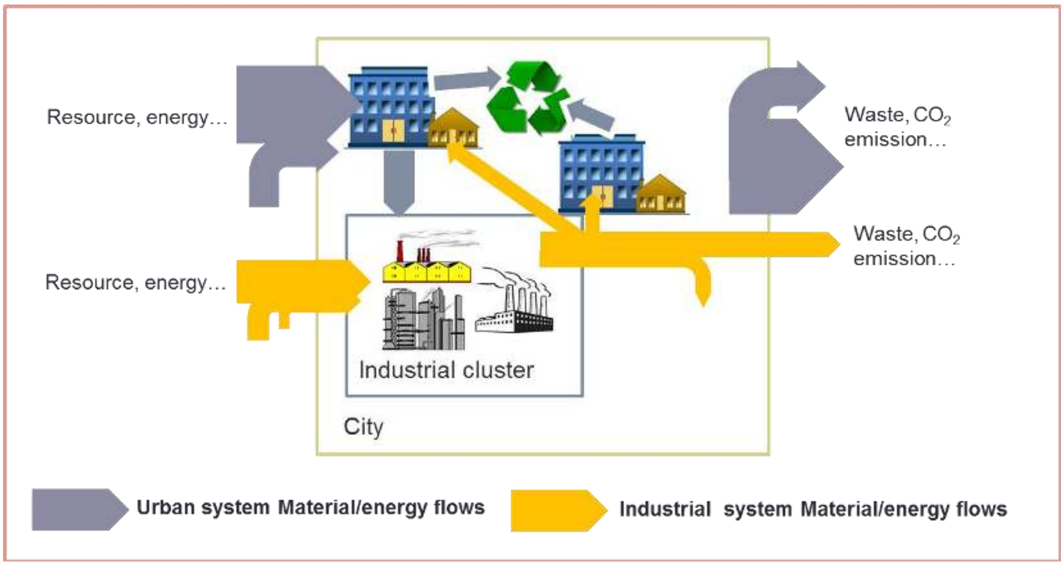

Figure 1 System boundary of urban industrial symbiosis

2.2 Model integration

The model integration framework is presented in *Figure 2*. Material and energy flows are analyzed with urban statistics (urban level input and output flows), and micro level material and energy flow analysis (input and output flows within symbiotic network). Furthermore, emergy flow analysis is applied to transform the physical material and energy flows into unified emergy flows with unit emergy value (UEV). According to emergy theory, emergy flows incorporate the ecological services, in this way, impacts on eco-system can be analyzed. Finally, this paper designs emergy evaluation index to assess the impacts in detail.

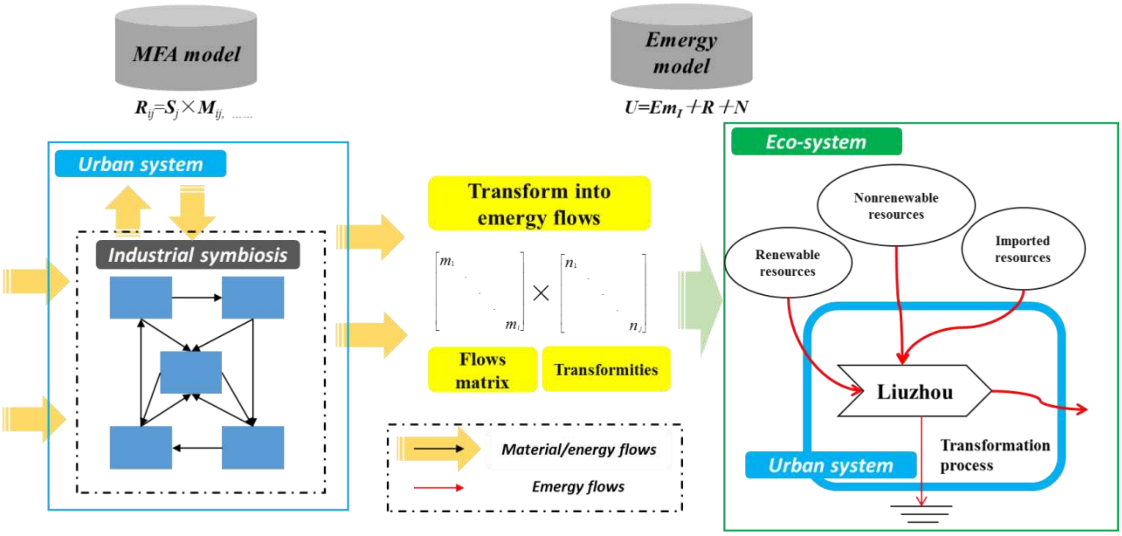

Figure 2 MFA-emergy model framework

2.3 MFA on the urban industrial symbiosis

MFA (in this paper also includes energy flows analysis) is basic approach to identify and quantify the flows in the symbiosis network. MFA is applied to calculate the different kind of material/energy flows (such as raw material, energy and waste) in various urban industrial symbiosis scenarios (Dong et al., 2013b). This part provides the values of avoided consumption on resources and emissions change of wastes for the follow-up emergy evaluation.

In detail, avoided consumption and emissions ($EnvG_i$) for company i engaged in the symbiotic network can be calculated by Eq.(1) and (2).

$$EnvG_i = \sum_j R_{ij} + \sum_k W_{ik} \qquad (1)$$

$$R_{ij} = S_{jk} \times W_{ik} \qquad (2)$$

R_{ij} is the conservation of resource j; W_{ik} is the quantity of the recycled or reduced waste k. Particularly, .R_{ij} can be directly gain from the data provided by survey, or indirectly calculated by the multiplication of the substitution rate (S_{jk}) for resource j and the quantity of reused/recycled waste (W_{ik}).

CO_2 emission reduction (CR_{ij}) can be further calculated. Cof_j is the CO_2 emission coefficient of the resources or waste *j*. The Cof_j are referred from literatures (Dong et al., 2014b; Zhang et al., 2013).

$$CR_i=\sum_j Cof_j \times EnvG_{ij} \tag{3}$$

Finally, apart from the direct material and waste exchange in the symbiosis network, we also need to consider from the life cycles perspectives. The concerns include how the reduction of raw materials reduction can result in up-stream mining activities and down-stream tailings, from the reduction of ore mining. This research applies the material coefficients to calculate such impacts. The basic calculation is according to the resource/waste reduction and the material co-efficient of ore and tailings summarized in *Table 1*.

Table 1 Material co-efficient for key materials

Materials	Value of co-efficient	Note
Tailings from iron ore (t/t)	1.7	Bulky solid waste (scrap rock and tailings) generated with the iron ore mining process.
Iron ore for steel (t/t)	1.6	Average amount of iron ore required to produce unit ton of steel.
Limestone for cement (t/t)	1.2	Average amount of limestone ore required to produce unit ton of cement.
Tailings from non-metal ore (t/t)	0.4	Bulky solid waste (scrap rock and tailings) generated with the cement manufacturing process.

2.4 Emergy evaluation

2.4.1 Basic theory

Emergy is applied to account for the values of ecosystem service embodied in the energy and resources coming from natural ecosystems. Emergy and transformiy are the two important concepts in emergy theory. Emergy is a measure of real wealth, defined as "the sum of available energy of one kind previously required directly and indirectly through input pathways to make a product or service" (Odum, 1996). Transformity, which represents unit emergy value (UEV), is an indirect measure of the activity of the environment, either directly or indirectly, has been required to manufacture a given product. (Brown and Ulgiati, 1997). Eq. (4) and (5) presents the calculation methods.

$$\text{Solar Emergy} = \text{Energy (Joules or grams)} * \text{UEV} \tag{4}$$

$$\text{UEV} = \text{Input Emergy (sej)/Output (Joules or grams)} \tag{5}$$

2.4.2 Emergy flow diagram

Within the defined system boundary and the above emergy concept and basic calculation, the emergy flow diagram can be drawn, which helps to understand and analyze emergy flows in the given system. *Figure 3* presents a simplified illustration of the input and output emergy flows throughout a city and related urban industrial symbiosis. It is emphasized that the urban ecosystem is divided into three subsystems: natural ecosystem, living system, and industry system. Emergy flows are categorized into renewable resource, nonrenewable resource, import resource and wastes.

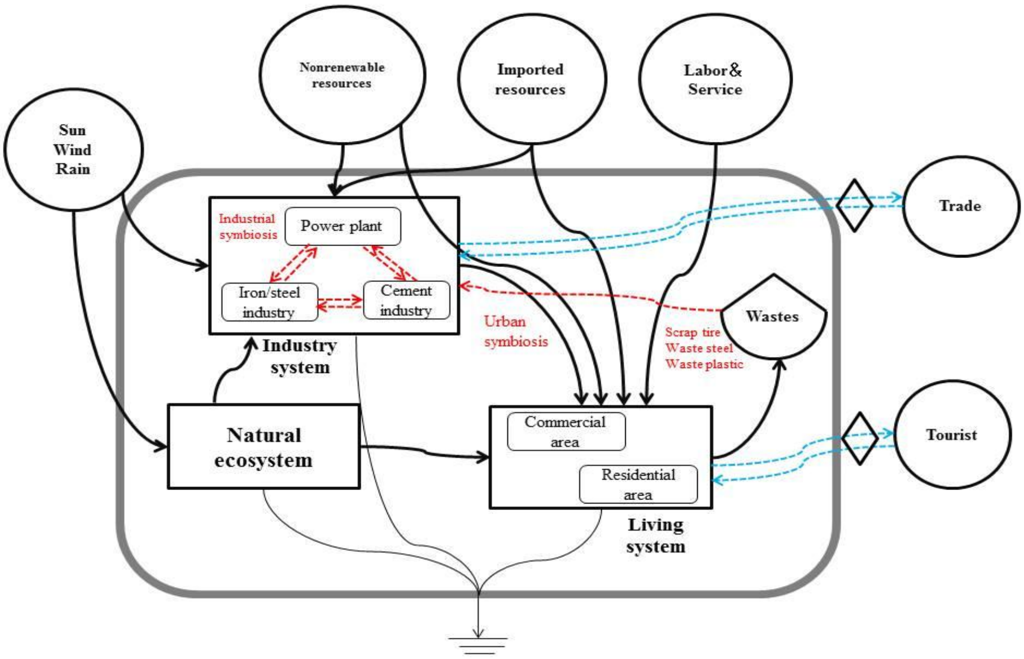

Figure 3 Emergy flow diagram of urban industrial symbiosis

2.4.3 Establish Emergy evaluation index

According to the flows of material, labor and energy in the given city, as well as emergy flows analysis, emergy evaluation index was further built to assess the performance before and after urban industrial symbiosis implementation. The basic emergy indicators are listed in *Table 2*. To facilitate the understanding of the indicators, some explanations are addressed in detail in the following.

The emergy yield ratio (EYR) is the ratio of total emergy used in the city divided by the imported emergy, it reflects the dependency of the economy on imports. The environmental loading ratio (ELR) is the ratio of nonrenewable and imported emergy divided by renewable energy, the bigger the value is, the more environmental pressure the city has. Emergy sustainable indices is the indicator to evaluate the sustainability of the city (Brown and Ulgiati, 1997).

Table 2 Emergy evaluation index at the urban level

Classification	**Index**	**Description**
Structural index	R	Renewable emergy
	N	Nonrenewable emergy
	EMI	Imported emergy
	W	Wastes emergy
	EMO	Export emergy
Efficiency index	ERS	Emergy of resource saving
	U=EMI+R+N	Total emergy
	EYR=U/ EMI	Emergy yield ratio
Overall index	EBR＝ERS/U	Ecological beneficial ratio
	ELR=(EMI +N)/R	Environment loading ratio
	ESI=EYR/ELR	Emergy sustainable indices

Based on the concept of ecosystem services (benefits), in this paper, a new emergy indicator, ecological beneficial ratio (EBR), is designed to measure the environmental benefits resulting from energy and material conservation. It can be expressed by following equation.

$$\mathrm{EBR} = \mathrm{ERS}/\mathrm{U} \tag{6}$$

Where ERS is the ratio of resource saving emergy, which could have positive effect on the whole urban system.

2.4.4 Dilution emergy

In production activities, even if the exhaust emissions have reached the industry emission standards, they still contain certain concentrations of harmful substances and require environmental self-purification services. Therefore, the related environmental services provided by the local ecosystem to absorb and dilute missions needed to be considered. With this consideration, this paper applies the dilution emergy, which stands for emergy input required by the eco-system to dilute pollutions:

$$M_a = d \times \frac{w}{c} \qquad (7)$$

Where M_a represents the mass of dilution air, *d* represents the air density with a value of 1.29E+03 g/m^3； *w* represents the annual emission amounts from production processes, *c* represents the acceptable emission concentrations based upon official standards.

Particularly, this paper addresses concerns on CO_2 emissions. Environmental services needed to dilute CO_2:

$$E_a = \frac{1}{2} \times M_a \times V^2 \qquad (8)$$

$$Em_a = E_a \times UEV_a \qquad (9)$$

Where *V* represents average wind velocity, E_a represents the kinetic energy of the dilution air, UEV_a represents wind transformity.

2.5 Data

The main data was gained through the governmental project of "12th five-year plan for the energy conservation in Liuzhou city" in 2011. In which, the author conducted a survey on 15 companies, including the iron and steel, chemicals, cement, power plant and so on. The company and sector level economic and environmental data was collected and verified. The dataset included the material and energy flows data, waste emissions, as well as the material, energy and waste exchanges among the companies. We selected 2009 as the base year. In addition, in 2011, the National Development and Reform Commission (NDRC) launched a "Circular Economy Technology Inventory" project, in which, key waste recycling and utilization technologies in key sectors (e.g. iron/steel, cement, chemicals, power plants, textile and so on) were collected and reviewed in detail. These technologies are helpful for us to design and simulate the urban industrial symbiosis scenarios.

3. Case introduction and scenarios design

3.1 General description of Liuzhou city, China

Liuzhou city is a typical industrial city located in the middle north part of the Guangxi Zhuang Autonomous Region, with a total area of 18707 km^2, and a population of 3.76 million in the year of 2009. The manufacturing industry dominates the local GDP. In 2009, the iron and steel industry and automobile industry accounted for 13.82% and 26.93% of the total industrial added value, respectively. For cities like Liuzhou, the environmental and ecological impacts generated by the resource mining and processing industries are considerable problems and therefore require smart solution to green their heavy industries. The location information is presented in *Figure 4*.

For this sake, the idea of urban industrial symbiosis is fit to Liuzhou. The city has advantages to establish urban industrial symbiosis. The existing large scale iron and steel company, Liuzhou iron/steel integrated corporation, can act as the hub of the symbiosis network. In the industrial complex, the iron and steel plant is surrounded by other industries with high potential of energy and material synergies, like the cement industry, chemical plants, power plant, etc.

With above condition, the Liuzhou city provides an ideal laboratory to test and verify how urban industrial symbiosis can have impacts from both environmental and ecological perspectives. The analytical results will provide critical insights to similar industrial city to transform into eco-city.

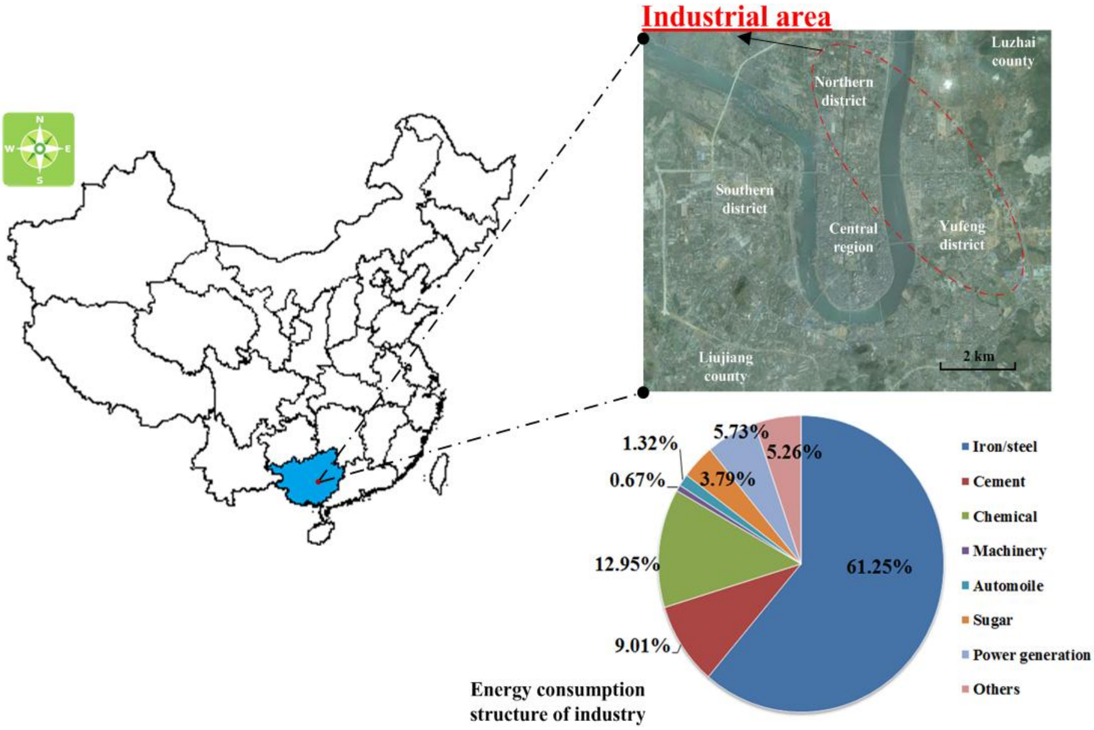

Figure 4 Location of Liuzhou City in China

Data source: Liuzhou Economic Statistical Yearbook, 2010

3.2 Urban industrial symbiosis scenarios

Local urban industrial symbiosis is analyzed first as the foundation of scenarios setting. A supply and demand matching potential is investigated, illustrated as *Figure 5*. Based on the industrial features, in general, nine categories of materials, energy sources and wastes can be exchanged, including slag from blast furnace and steel slag, slag power as a second processing products from slag, metallurgical gas and waste heat from iron and steel company; waste heat from iron and steel company and power plants; desulfurization byproduct from iron and steel company and power plant; waste steel, waste plastics and scrap tires from urban area; as well as coal flying ash from power plant.

With urban industrial symbiosis design, they can act as the sources for the substitution of raw materials and fossil fuels in other companies or sectors, including: BF slag and steel slag can be directly utilized by cement company, or utilized by cement or construction material manufacturing companies in the way of slag power, to produce cement or other construction materials (① and ②); desulfurization byproduct can be made into power, and further be utilized to produce fertilizer (③); waste heat from power plant and iron and steel company, as well as metallurgical gas (such as coke oven gas, COG) can be used as energy source to substitute fuels in ammonia production(④); steel scrap generated in the society can be recycled and transported to the iron/steel plant for reproduction. This is an effective way of reducing life cycle energy consumption and carbon emissions per unit of steel production (⑤); as metallurgical gas also contains H and C element, thus is an ideal raw material for hydrogen production, which is key substance to further produce methanol in chemical industry (⑥); Waste heat from power plant could be used as heat supply and transported to certain factories or residential area, or as the preheating in the production process (⑦); combustion characteristics of municipal waste plastics and scrap tires enable them can be recycled and used as fuel source in cement or iron/steel industry. In this way, fossil fuels are saved. Especially, Liuzhou city is famous for the auto mobile city, with high potential of waste tires recycling (⑧ and ⑨); finally, coal flying ash, which contains high value-added element could be recycled and reused for producing cement products and construction materials (⑩). Based on above analysis, in total, ten symbiosis scenarios (synergies) can be identified.

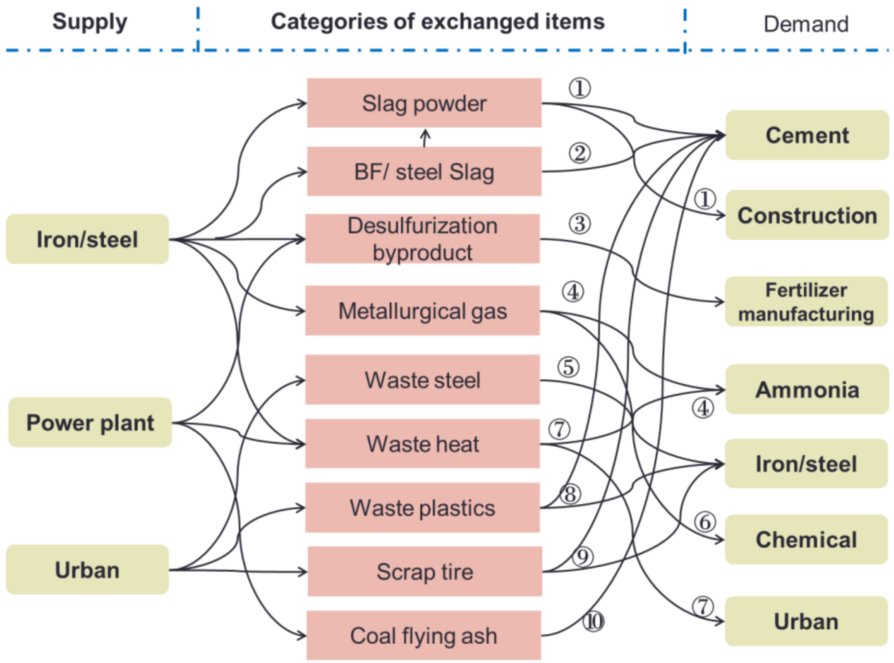

Figure 5 Supply and demand matching analysis for the symbiosis network design in Liuzhou city

It is noted that, in reality, not all the urban industrial symbiosis scenarios are implemented currently (baseline year in this research is 2009, and we have monitored the projects by 2012). As a result, this paper summarizes the symbiotic network in term of existing ones and planned ones. The network is finally illustrated in *Figure 6*.

In detail, through survey, the existing synergies are mainly bulky solid industrial waste exchanges, includes: No.①, slag power for cement production with a scale of 1.2 million ton per year; No.②, BF and steel slag for cement and construction materials production, the total exchanged amount is 1.2 million ton per year; No.③, desulfurization byproduct used for fertilizer production (8100 ton per year); No.⑤, waste steel recycling, with a scale of 700 thousand on per year. The other six synergies are planned and the key circular economy pilot projects in Liuzhou city in 12th and 13th five-year planning period (2011-2020). They include: No.④, the power plant, iron and steel company and chemical company establish a symbiotic network, in which, waste heat from power plant and iron and steel company, and metallurgical gas from iron and steel company is provided as energy source to substitute fuels in ammonia production (substituting 20 thousand ton's ammonia production per year); No.⑥: in the iron and steel company, part of metallurgical gas contains rich H and C elements (e.g. BOG and COG). They are provided as material sources for hydrogen production (a production line with 30 Mm^3/y), which is key substance to further produce higher added value methanol in chemical industry; No.⑦: waste heat from power plant and iron and steel company, is used for the central heating for the residential sector, and preheating heat source in the production process. The pilot project is with a total amount of 200 ton steam per year; No.⑧, certain amount of waste plastics is recycled into the furnaces in iron and steel and cement company, as substitution for fossil fuels (about 25 thousand ton per year). It is key circular economy pilot project managed by the city government. It is noted that, due to the difficulty of plastics collection, and technical features of furnace, there is only small percentage of total waste plastics amount (about 100 thousand ton per year); No.⑨, scrap tires is recycled and used as fuel source in cement or iron/steel industry (30 thousand ton per year). It is also the key circular economy project emphasized by the city government. Liuzhou city is the famous automobile city, thus this project is expected to generate significant environmental benefit in the near future; finally, No.⑩, as the key circular promotion not only in Liuzhou city, but also national wide, coal flying ash is recycled and reused for producing cement and construction materials. The pilot project is 240 thousand per year. Currently, it is mainly stockpiling, which not only cause land occupation, but also environmental risk generated by the potential toxic elements in the coal flying ash.

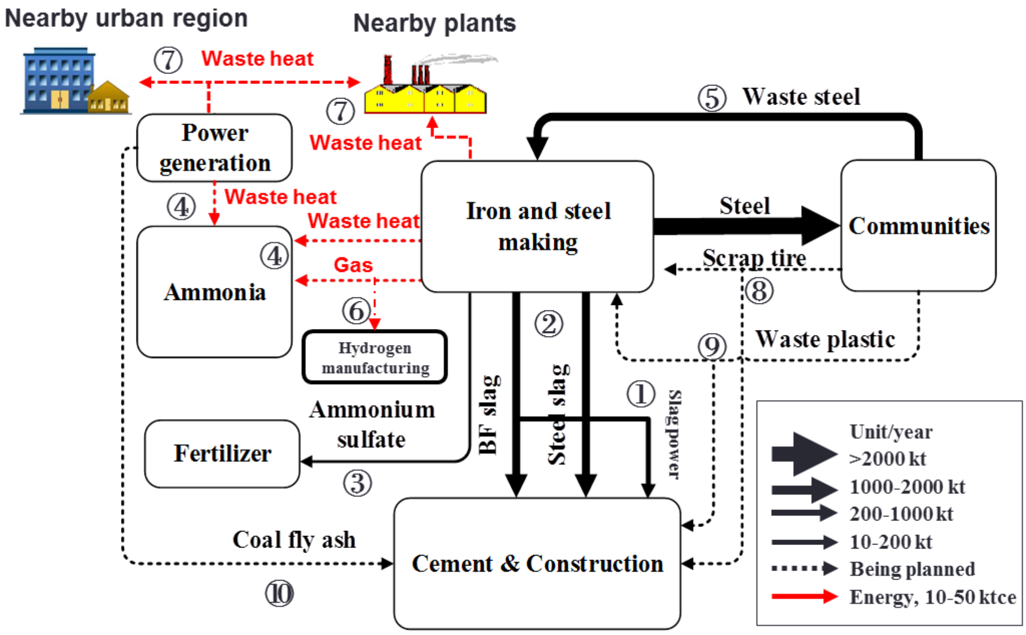

Figure 6 Quantitative material and energy flows of local urban industrial symbiosis

Note: Solid line: existing IS. Dotted line: planned IS. The number is in line with the numbers in *Figure 5*.

tce-ton coal equivalent. 1 tce =29.27 GJ; Gas-incudes BOG (blast furnace gas) and COG (coke oven gas) and other low quality metallurgical gas.

Source: revised from (Dong et al., 2014b)

4. Results and discussion

4.1 Environmental benefit

Based on above analysis on urban industrial symbiosis network and the developed approach, direct resource saving and emission reduction effects are summarized in *Table 3*. They acts as the basis for further emergy evaluation. In general, urban industrial symbiosis generated significant environmental benefits. In the whole urban industrial symbiosis system, there is more than 2.5 million ton material and 45.0 thousand tce energy is exchanged. As a benefit, approximately more than 2.4 million ton raw material and 0.9 million tce energy is directly saved, and about 3.4 million ton solid waste is directly mitigated.

Especially, significant low-carbon benefit is achieved. In total, CO_2 emission can be reduced by 2.3 million ton CO_2 per year. *Figure 7* highlights the CO_2 mitigation by each synergy. Due to the large amount, industrial solid waste exchanges and the waste steel recycling own much higher carbon mitigation effects. However, it is noted that, energy network, also has significant potential contribution to carbon mitigation, if extended in the future. In addition, even though the new planned urban industrial symbiosis don't present higher environmental benefits, mainly due to the project scale, but they significantly improve the utilization ratio of underused material and energy, e.g. waste plastics and exhausted heat. In a long term, with the ever-improvement on the related infrastructures and waste management system, it is expected to generate much more environmental benefits.

Table 3 Symbiotic activity and environmental benefit in Liuzhou

Urban industrial symbiosis	**Yearly environmental benefit**		
	Energy saving	**Air pollutants and CO_2 emission reduction**	**Resource saving and solid waste mitigation**
① Slag powder use as raw material of cement	200.0 thousand tce	520.0 thousand ton CO_2	1.2 million ton slag stock-pilling
② BF and steel slag reuse	253.8 thousand tce	660.0 thousand ton CO_2	1.2 million ton clinker
③ Fertilizer production from desulfurization byproduct	-	4.0 thousand ton SO_2	Reduce waste stock-pilling
④ Alternative fuels for ammonia production	25.1 thousand tce.	25.1 thousand ton CO_2	-
⑤ Waste steel recycling	292.9 thousand tce	761.1 thousand ton CO_2	1750.0 thousand ton iron ore
⑥ Alternative hydrogen production	47.9 thousand tce	47.3 thousand ton CO_2	-
⑦ Waste heat utilization	12.5 thousand tce	12.6 thousand ton CO_2	-
⑧ Waste plastics recycling	30.0 thousand tce	78.0 thousand ton CO_2	Reduce 25 thousand ton waste plastics
⑨ Scrap tires recycling	1.0 thousand tce	2.5 thousand ton CO_2	Save 19.5 thousand ton raw rubber and reduce 30.0 thousand ton scrap tires
⑩ Coal flying ash recycling	-	240.0 thousand ton CO_2	Solid waste mitigation. Save 240.0 thousand ton raw material for cement production

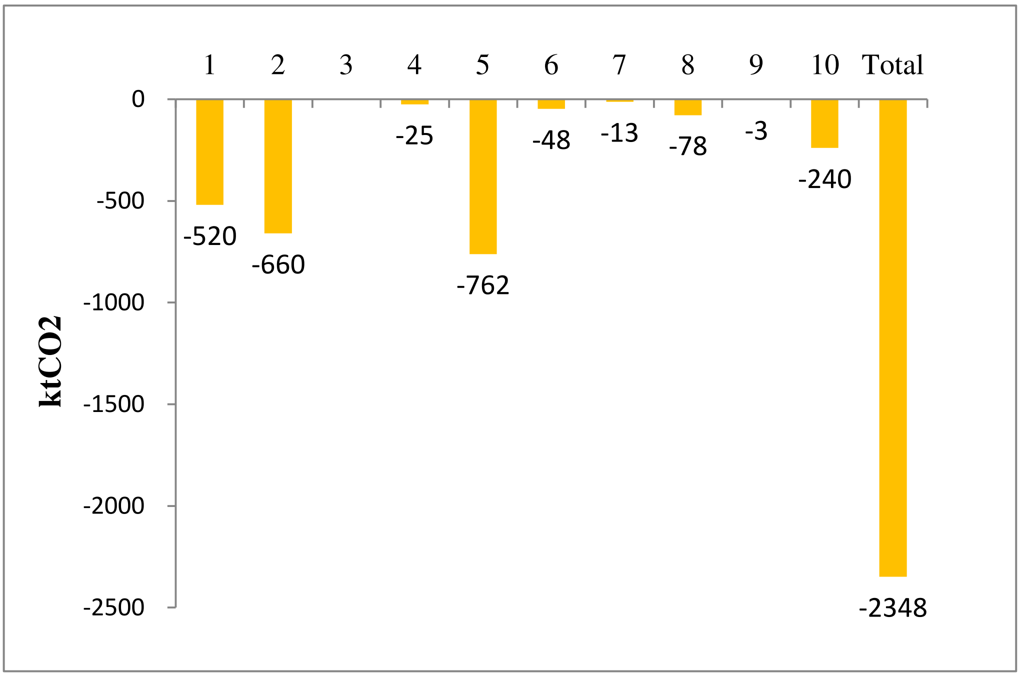

Figure 7 The effect on CO2 reduction through urban industrial symbiosis

Note: The number is in line with *Table 3*.

What is more, the urban industrial symbiosis also contributes to the reduction of upstream resource mining and downstream waste disposal within the regional metabolism. we express the effect of urban industrial symbiosis on resource efficiency in *Figure 8*. The basic calculation is according to the resource/waste reduction and the material co-efficient of ore and tailings summarized in previous *Table 1*. It is concluded that, in total, around 204.7 million tons ore mining is reduced per year, as a result of reduction on raw materials for steel and cement production. Related solid wastes are reduced by 6.9 million ton. Imports of fossil fuels (mainly coal) also decrease from 12.4 million ton to 11.1 respectively.

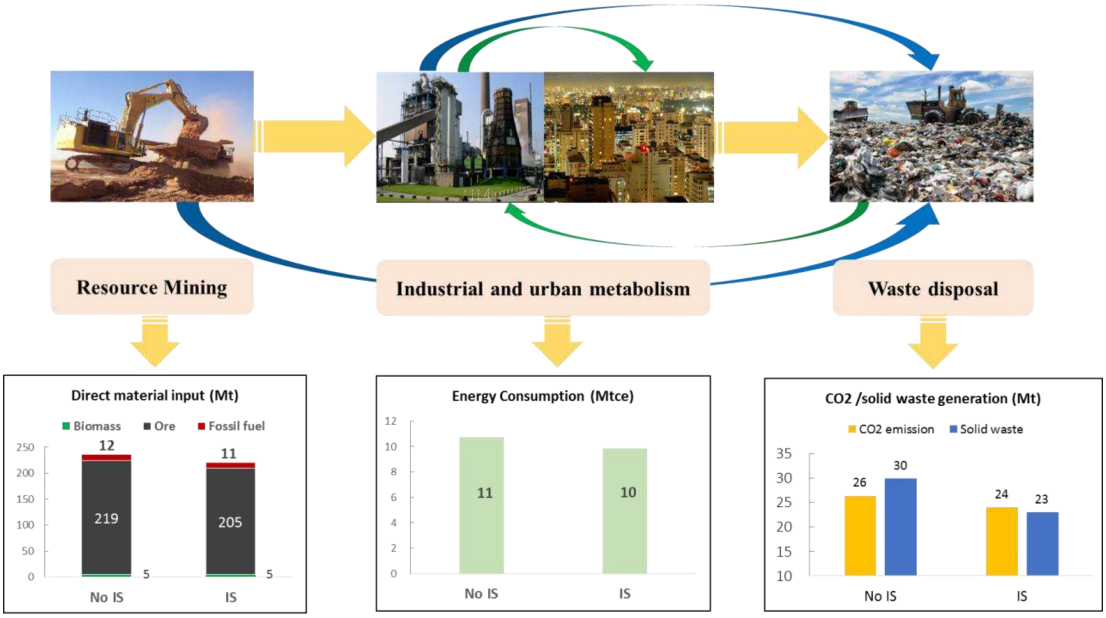

Figure 8 The effects on regional metabolism via urban industrial symbiosis in Liuzhou city

The above results highlight that the application of urban industrial symbiosis can improve the regional resource efficiency. The system efficiency can be improved by adjusting the material and energy flows appropriately in the whole supply and demand chain, from a life cycle perspective.

The other critical issue is the related ecological impacts accompanied with the mining and processing on raw materials, and bulky waste stock-pilling. As emphasized, Liuzhou city is typical industrial city, in which, mining and process industries are the pillars for local economy. Such industrial processes not only cause waste and emission problems, but also negative effects on eco-system, e.g. soil pollution, damage or even loss of eco service function, etc. Therefore, the contribution of urban industrial symbiosis is not limited to environmental benefits, but also ecological compensation. With more and more concerns on ecological civilization, critical insights on urban industrial symbiosis practice and their ecological contribution is highlighted. In next section, we will analyze the ecological benefits and trade-offs of the urban industrial symbiosis in Liuzhou city.

4.2 Ecological benefits

With the flows accounting for the symbiotic network as basis, ecological impacts with emergy as evaluation tool is presented. *Table 4* summarizes the emergy inputs change due to the resource conservation generated by the identified urban industrial symbiosis. Total emergy inputs saving 1.3×10^{22} sej. All the emergy flows calculation is presented in *Table S1* of "Supporting information". Among the most significant emergy saving effects, slag recycling and reuse, as well as slag power to substitute raw materials for cement generate 6.3×10^{21}sej (2.4×10^{21}sej for the former and 3.9×10^{21}sej for the latter) reduction, which accounting for 49.2% of the total ecological benefits. Waste recycling which reduces coal consumption presents a total amount of 2.7×10^{21}sej emergy input reduction. Flying ash recycling reduces 1.0×10^{21} sej. Finally, the ecological benefits of plastic and rubber reuse is 5.3×10^{20} sej, and fertilizer is 6.2×10^{18} sej. It is noted that bulky waste utilization within process industries generate significant ecological benefits.

Table 4 Ecological benefits of resource conservation regards to emergy inputs

Item	Amount	UEV sej/unit	Ref.	Saving Emergy (sej)
Slag power	1.2×10^{12}g	3.2×10^{9}	(Geng et al., 2014)	3.9×10^{21}
Slag recycling	1.2×10^{12}g	1.9×10^{9}	(Brown and Ulgiati, 2002)	2.4×10^{21}
Fertilizer	8.1×10^{9}g	7.7×10^{8}	(Odum et al., 2000)	6.2×10^{18}
Steel	7.0×10^{11}g	3.2×10^{9}	(Brown and Ulgiati, 2002)	2.2×10^{21}
Plastic and Rubber	5.5×10^{10}g	9.7×10^{9}	(Buranakarn, 1998)	5.3×10^{20}
Flying ash	2.4×10^{11}g	4.3×10^{9}	(Geng et al., 2014)	1.0×10^{21}
Coal	4.1×10^{16}J	6.7×10^{4}	(Odum et al., 2000)	2.7×10^{21}
Total saving			**1.28×10^{22}**	

Emergy indicators are analyzed further to explore other insights. *Figure 9* illustrates the emergy flow change with and without urban industrial symbiosis in Liuzhou. It is highlighted that with symbiotic network formation, the total renewable inputs remain stable while both total nonrenewable inputs and total imported resources decreases, indicating that the energy and material saving benefits are significantly. Nonrenewable resources (coal) saving amounts to 2.7× 10^{21}sej, indicating that 6.2 % nonrenewable resources can be saved after industrial symbiosis. Imported resources saving amounts to 1.0×10^{22}sej, meaning that 17.8 % of imported resources can be saved due to waste and material recycling.

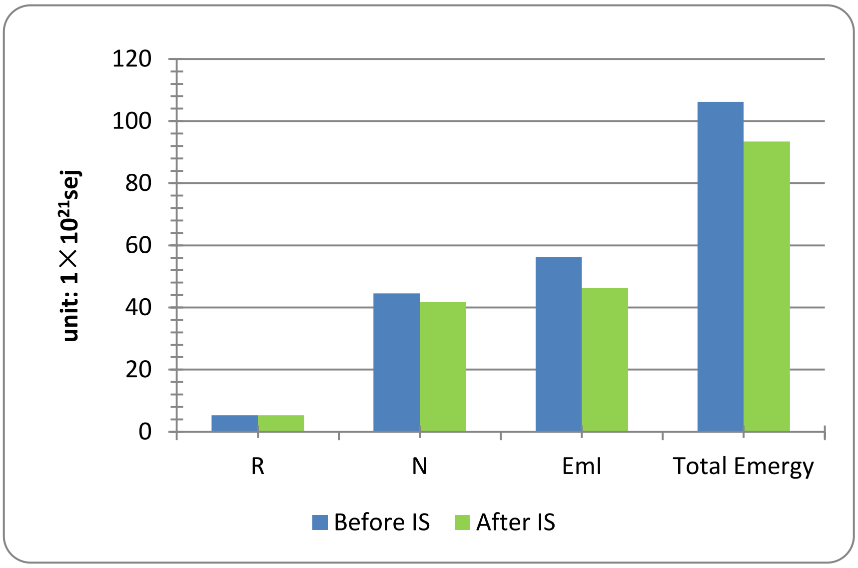

Figure 9 Comparison of Emergy flows (before and after urban industrial symbiosis) in Liuzhou

Table 5 lists the results of emergy indicators under scenarios with and without urban industrial symbiosis in Liuzhou. The environmental beneficial ratio is 12.0%, which indicates that urban industrial symbiosis will save 12.0% of total emergy consumption The value of EYR increases from 1.9 to 2.0, mainly because the value of EMI is reduced a lot when implementing urban industrial symbiosis. It highlights that symbiosis generates the benefit of reducing imported resources and therefore enhances the systematical ecological efficiency. ELR decreases from 18.9 to 16.5, indicating less pressure on the local ecosystem. Finally, industrial symbiosis can bring positive impact on the improvement of the sustainability of the city, reflected by a higher value of ESI, which increases by 20 %.

Table 5 The results of emergy indicators in Liuzhou (unit: sej)

	U	ELR	EYR	ESI	EBR
Without urban industrial symbiosis	1.1×10^{23}	18.8	1.9	10.0×10^{-2}	-
With urban industrial symbiosis	9.3×10^{22}	16.5	2.0	12.0×10^{-2}	12.0%

Finally, the results of ecological benefits from CO_2 emission reduction in Liuzhou are evaluated and summarized in *Table 6*. The total amount of environmental services required for diluting this reduced amount of CO_2 emission is 2.5×10^{16} sej, thus it can be seen as the ecological benefits from CO_2 reduction in Liuzhou. The benefits of CO_2 emission reduction in waste steel recycling is 8.1×10^{15}sej, also, dilution emergy reduced by steel slag reuse and recycling amounts to 7.0×10^{15}sej. They are remarkably higher than others, indicating that for Liuzhou, iron and steel making process as well as cement manufacturing process has significant potential to reduce ecological impacts among the industrial sectors.

Table 6 Ecological benefits of CO_2 emission reduction in Liuzhou

Item	CO_2 reduction (kt)	Dilution Emergy (sej)
Production of slag powder	520.0	5.6×10^{15}
Substitute cement material	660.0	7.0×10^{15}
Alternative fuels for ammonia production	25.1	2.7×10^{14}
Waste steel recycling	761.7	8.1×10^{15}
Alternative hydrogen production	47.9	5.1×10^{14}
Heat exchange	12.6	1.3×10^{14}
Waste plastics recycling	78.0	8.3×10^{14}
Scrap tires recycling	2.5	2.7×10^{13}
Coal flying ash recycling	240.0	2.6×10^{15}
Total Amount	**2347.9**	$\mathbf{2.5\times10^{16}}$

4.3 Insights and implications

With above analysis, urban industrial symbiosis is verified with the significant environmental an ecological benefits. Different from the previous studies that mainly focus on analyzing the economic, environmental, and social benefits of urban industrial symbiosis, this study consists not only the analysis on the benefits through material flow analysis, but also the improvements on sustainability performance through emergy synthesis. Based on the analytical results, several critical insights are highlighted.

a. Significance of applying urban industrial symbiosis: analytical results present that, in environmental perspective, industrial and urban symbiosis is able to reduce the resource exploration in upstream, resource processing and waste disposal in downstream, as well as the related CO_2 emissions. Such environmental benefit can further generate ecological benefits. Emergy evaluation verifies that ELR decreases, indicating less pressure on the local ecosystem. Such benefit is particularly important to industrial cities and resource dependent cities, which resource mining and processing industries dominates the local GDP. Urban industrial symbiosis provides a pathway to optimize the supply demand chain and the material and energy flows embodied in the total life cycles of supply chains.

b. Importance of reforming current evaluation system on circular economy: currently wide applied circular economy indicators in China lack a consideration on an aggregated index for measuring sustainability. Emergy sustainability index as a single aggregated index can represent the sustainability performance of the whole ecosystem. The users of this methodology easily judge the effects of urban industrial symbiosis on sustainability improvements and enhancement compared to business-as-usual scenario. As we all know, there are usually many different network configuration for symbiosis, thus, this methodology can help the users make better decision on selecting the scenarios among many alternative candidates that can significantly improve sustainability of the business-as-usual scenario.

c. Further investigation on the life cycle ecological impacts of natural resource utilization: as a world factory, China gains a lot from lower price of natural resources, but meanwhile, suffers from significant ecological lost. If we trace the natural resources utilization in their life cycles, from mining, processing to manufacturing and disposal, there is some mismatching between ecological impacts and market economic values. They own much lower market value in mining stage, but with higher ecological impacts, such as vegetation destruction, soil and air pollutions. While when come to the products stage, it becomes more economic “expensive” and with lower impacts on eco-system and environment. One key reason causing such unreasonable condition is the failure on internalize the ecological impacts into economic system. With this circumstance, approaches and results in this research provide some fundamental information to help decision makers to improve the current economic system with more consideration on internalizing the externality of ecological impacts. In the future, there is a need to combine with holistic life cycle assessment, better localized transforming coefficients, to better investigate the life cycle ecological impacts from economic perspective.

d. Finally, integration of city and industry in ecosystem perspective. China will promote ecological civilization in national wide, especially, will attach great importance on the accounting for natural resources capital. With this regard, quantifying ecological impacts within urban and industry process is critical. This research lays the methodological foundation to emphasize managing the city, industry and the ecosystem as a whole.

To address the above insights and challenges, several implications are proposed:

First of all, with large scale and integrated industrial system, as well as surging urbanization process, China provides an ideal laboratory to practice urban industrial symbiosis. To facilitate the progress, both hardware and software technologies are needed to be strengthened. Some symbiosis options are difficult to be achieved due to technology immaturity, and some options can be employed (e.g. coal flying ash utilization in the case of Liuzhou) but present very low efficiency. Thus, we urge China's authority to set special research and development funding for developing the core technologies in industrial and urban symbiosis, and to highlight this in some high level national projects. From software technologies perspective, mature and integrated waste management is required to be improved. Urban industrial symbiosis usually involves multiple stakeholders, taking the case of Liuzhou as an example, the symbiosis network is quite complex, different companies have been involved, and they may have different preferences and willingness on economic, environmental and social aspects, thus, it is usually difficult to participate in the symbiosis spontaneously as some companies just pursue the immediate interests;

however, the activities, i.e. energy recycling and waste reuse, sometime are high-invested and low-return in a short term. Thus, the local government should coordinate them as an ordered and harmonious consortium. Establishing special administrative sectors which can play a coordinator role for managing and planning the industrial and urban symbiosis in China, and resisting the external threats and risks, will be beneficial. And, to provide subsides, low-interest loan, and tax exemptions measures for the companies that participate in the symbiosis activities.

Secondly, guide the stakeholders revisit the eco-system and reform on the price mechanism of natural resources. We suggest China’s decision-makers to emancipate the mind, and they should consider not only the direct effects on economic, environmental and social aspects, but also the negative impacts on “nature”. In one words, China’s decision-makers should make decision in an ecosystem perspective, especially when designing and planning. On the other hand, practical economic measures should be made to forward such mind change. Applies proper resource tax, carbon tax, ecological compensation policies to better internalize the ecological externality, so that the market price of natural resources can be more close to their “real price”. In this way, ecological impacts can be better reflected in our current economic system. As a final point to this regard, current assessment mechanism for government is also needed to reformed. To incorporate ecological values into current assessment mechanism, of which, GDP is one key indicator, is helpful to guide the policy makers pay more attention on eco-system. China already began to conduct the accounting on natural capital (accounts the economic value of ecological services into current GDP accounting system), but in general, it is still in conception promotion stage. As a result, in the next national planning period, how to effectively practice the national and local accounting on natural capital is rather important.

Finally, to support the above discussed decision making, evaluation tools that can fully reflect the ecological impacts from our economic system is needed. Emergy theory can provide basic methodology and useful indicators to quantify the ecological impacts, but to combine them with prevailing life cycle assessment, input-output model and footprint tools is necessary. In addition, how to interpret the results from emergy evaluation into user-friendly formation to stakeholders is also critical. With these concerns, it is suggested to further improve the emergy approach and develop integrating index that link emergy indicators with current socioeconomic indicators and environmental indicators.

5. Conclusions

This paper developed a generic approach for evaluation on environmental and ecological benefits of urban industrial symbiosis, based on the hybrid methodology by combining material flow analysis and emergy approach. The developed approach was tested with application in an urban industrial symbiosis in Liuzhou city in China. Local urban industrial symbiosis network was analyzed, and related environmental benefits of symbiotic network were quantified with MFA, further ecological impacts were evaluated with emergy approach and emergy indicators. Results highlighted that, urban industrial symbiosis generated significant life cycle environmental benefits on the reduction of upstream resource mining and downstream waste disposal within the regional metabolism. In total, around 204.7 million tons ore mining, 6.9 million ton solid waste and 2.3 million tons CO_2 emissions were reduced per year. In ecological perspective, total emergy input which reflected the reduction of ecological burden was reduced by 1.3×10^{22}sej. This paper provided useful modeling approach to understand the ecological benefits and trade-offs of local circular economy practices and fundamental insights on natural capital accounting, which will be one of the core highlights of ecological civilization promotion in China, in the 13th FYP period (2016-2020).

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References

Bargigli, S., Ulgiati, S., 2003. Emergy and life-cycle assessment of steel production in Europe. Emergy Synthesis. Theory and Applications of Emergy Methodology–2. MT Brown, HT Odum, D. Tilley, and S. Ulgiati (Editors), published by the Center for Environmental Policy, University of Florida, Gainesville, FL, 141-155.

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.

Brandt-Williams, S., 2001. Handbook of Emergy evaluation: A compendium of data for emergy computation issued in a series of folios. Folio# 4. Emergy of Florida Agriculture, 32611-36450.

Brown, M., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecological engineering 9, 51-69.

Brown, M., Ulgiati, S., 2002. Emergy evaluations and environmental loading of electricity production systems. Journal of Cleaner Production 10, 321-334.

Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: HT Odum's contributions to quantifying and understanding systems. Ecological Modelling 178, 201-213.

Buranakarn, V., 1998. Evaluation of recycling and reuse of building materials using the emergy analysis method. University of Florida Gainesville.

Campbell, D.E., Lu, H., Lin, B.-L., 2014. Emergy evaluations of the global biogeochemical cycles of six biologically active elements and two compounds. Ecological Modelling 271, 32-51.

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.

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

Chertow, M.R., 2007. "Uncovering" Industrial Symbiosis. Journal of Industrial Ecology 11, 11-30.

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

Dong, H., Fujita, T., Geng, Y., Dong, L., Ohnishi, S., Sun, L., Dou, Y., Fujii, M., 2016a. A review on eco-city evaluation methods and highlights for integration. Ecological Indicators 60, 1184-1191.

Dong, H., Ohnishi, S., Fujita, T., Geng, Y., Fujii, M., Dong, L., 2014a. Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. Energy 64, 277-286.

Dong, L., Fujita, T., Dai, M., Geng, Y., Ren, J., Fujii, M., Wang, Y., Ohnishi, S., 2016b. Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China. Journal of Cleaner Production 114, 387-400.

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., 2014b. 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.

Fujii, M., Fujita, T., Dong, L., Lu, C., Geng, Y., Behera, S.K., Park, H.-S., Chiu, A.S.F., 2016. Possibility of developing low-carbon industries through urban symbiosis in Asian cities. Journal of Cleaner Production 114, 376-386.

Gaudenzi, B., Borghesi, A., 2006. Managing risks in the supply chain using the AHP method. The International Journal of Logistics Management 17, 114-136.

Geng, Y., 2011. Eco-indicators: improve China's sustainability targets. Nature 477, 162-162.

Geng, Y., Liu, Z., Xue, B., Dong, H., Fujita, T., Chiu, A., 2014. Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone. Environmental Science and Pollution Research 21, 13572-13587.

Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China's Circular Economy. Science 339, 1526-1527.

Geng, Y., Zhang, P., Ulgiati, S., Sarkis, J., 2010. Emergy analysis of an industrial park: the case of Dalian, China. Science of the total environment 408, 5273-5283.

Giannetti, B.F., Bonilla, S.H., Almeida, C.M.V.B., 2013. An emergy-based evaluation of a reverse logistics network for steel recycling. Journal of Cleaner Production 46, 48-57.

Gibbs, D., Deutz, P., 2007. Reflections on implementing industrial ecology through eco-industrial park development. Journal of Cleaner Production 15, 1683-1695.

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.

Hau, J.L., Bakshi, B.R., 2004. Promise and problems of emergy analysis. Ecological Modelling 178, 215-225.

Huang, S.-L., Chen, C.-W., 2005. Theory of urban energetics and mechanisms of urban development. Ecological Modelling 189, 49-71.

Huang, S.-L., Lee, C.-L., Chen, C.-W., 2006. Socioeconomic metabolism in Taiwan: Emergy synthesis versus material flow analysis. Resources, Conservation and Recycling 48, 166-196.

Jacobsen, N.B., 2006. Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. Journal of Industrial Ecology 10, 239-255.

Jiang, M., Zhou, J., Chen, B., Chen, G., 2008. Emergy-based ecological account for the Chinese economy in 2004. Communications in nonlinear science and numerical simulation 13, 2337-2356.

Liu, G., Yang, Z., Chen, B., 2011. Emergy-based Ecological Economic Evaluation of Beijing Urban Ecosystem. Procedia Environmental Sciences 5, 18-24.

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

Lou, B., Ulgiati, S., 2013. Identifying the environmental support and constraints to the Chinese economic growth—An application of the Emergy Accounting method. Energy Policy 55, 217-233.

Lu, H., Wang, Z., Campbell, D., Ren, H., Wang, J., 2011. Emergy and eco-exergy evaluation of four forest restoration modes in southeast China. Ecological Engineering 37, 277-285.

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.

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

Odum, H., Brown, M., Brandt-Williams, S., 2000. Handbook of emergy evaluation: a compendium of data for emergy computation in a series of folios, Folio.# 1. Center for Environmental Policy, University of Florida: Gainesville, FL, USA.

Odum, H., Diamond, C., Brown, M., 1987. Emergy analysis and public policy in texas, policy research project report. Ecology and Economy 12, 54-65.

Odum, H.T., 1996. Environmental accounting. Wiley.

Rugani, B., Benetto, E., 2012. Improvements to emergy evaluations by using life cycle assessment. Environmental science & technology 46, 4701-4712.

Song, Q., Wang, Z., Li, J., 2013. Sustainability evaluation of e-waste treatment based on emergy analysis and the LCA method: A case study of a trial project in Macau. Ecological Indicators 30, 138-147.

Tilley, D.R., Swank, W.T., 2003. EMERGY-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. Journal of environmental management 69, 213-227.

Ulgiati, S., Odum, H., Bastianoni, S., 1994. Emergy use, environmental loading and sustainability an emergy analysis of Italy. Ecological modelling 73, 215-268.

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

Vega-Azamar, R.E., Glaus, M., Hausler, R., Oropeza-García, N.A., Romero-López, R., 2013. An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada. Landscape and Urban Planning 118, 18-28.

Yan, M., Odum, H.T., 1998. A study on emergy evaluation and sustainable development of Tibet eco-economic system. J Nat Res 13, 116-125.

Yang, H., Li, Y., Shen, J., Hu, S., 2003. Evaluating waste treatment, recycle and reuse in industrial system: an application of the emergy approach. Ecological Modelling 160, 13-21.

Yang, Z., Li, S., Zhang, Y., Huang, G., 2011. Emergy synthesis for three main industries in Wuyishan City, China. Journal of Environmental Informatics 17, 25-35.

Yuan, F., Shen, L.-y., Li, Q.-m., 2011. Emergy analysis of the recycling options for construction and demolition waste. Waste Management 31, 2503-2511.

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., 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.

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.

Zhang, X., Deng, S., Zhang, Y., Yang, G., Li, L., Qi, H., Xiao, H., Wu, J., Wang, Y., Shen, F., 2011a. Emergy evaluation of the impact of waste exchanges on the sustainability of industrial systems. Ecological Engineering 37, 206-216.

Zhang, Y., Yang, Z., Liu, G., Yu, X., 2011b. Emergy analysis of the urban metabolism of Beijing. Ecological Modelling 222, 2377-2384.

Supporting Information

This file will provide complementary information and data related to the calculation.

Table S1. Emergy flow of Liuzhou

Item	**UEV**(sej/unit)	**Reference**	**Amount**	**Emergy** (sej)
Renewable inputs （R）				
Sunlight (J)	1.0E+00	(Odum et al., 2000)	1.2E+19	1.3E+19
Wind (kinetic energy) (J)	2.5E+03	(Odum et al., 2000)	4.6E+16	1.2E+20
Geothermal Heat (J)	5.8E+04	(Odum et al., 2000)	4.0E+16	2.3E+21
Earth cycle (thermal energy) (J)	2.9E+04	(Odum et al., 2000)	3.5E+16	1.0E+21
Rain (chemical potential energy) (J)	3.5E+04	(Odum et al., 2000)	5.7E+16	2.0E+21
Rain (geo-potential energy) (J)	1.8E+04	(Odum et al., 2000)	1.3E+16	2.3E+20
Nonrenewable inputs from within the city				
Piped water from aqueduct (g)	2.3E+04	(Geng et al., 2010)	4.7E+14	1.1E+19
Top soil loss (J)	1.2E+05	(Odum et al., 2000)	6.1E+14	7.5E+19
Cement (g)	2.0 E+09	(Odum et al., 2000)	5.3E+12	1.0E+22
Gasoline (g)	1.0E+05	(Brown and Ulgiati, 2002)	1.2E+15	1.2E+20
Disel (J)	1.1E+05	(Brown and Ulgiati, 2002)	1.7E+15	1.9E+20
Coal (J)	6.7E+04	(Odum et al., 2000)	2.8E+17	1.9E+22
Imports				
Grain(J)	1.1E+05	(Yan and Odum, 1998)	1.1E+16	1.3E+21
Beans(J)	3.7E+05	(Brandt-Williams, 2001)	9.9E+13	3.6E+19
Oil crop(J)	8.9E+04	(Odum et al., 1987)	6.0E+14	5.3E+19
Corn(J)	1.1E+06	(Brandt-Williams, 2001)	1.0E+15	1.1E+21
Vegetable(J)	7.4E+04	(Odum et al., 1987)	4.0E+15	3.0E+20
Fruit(J)	8.9E+04	(Ulgiati et al., 1994)	6.6E+15	5.9E+20
Meat(J)	5.3E+06	(Yan and Odum, 1998)	1.5E+15	7.8E+21
Milk(J)	3.3E+06	(Yan and Odum, 1998)	4.3E+12	1.5E+19
Fisheries production (J)	2.0E+06	(Odum et al., 2000)	2.6E+14	5.2E+20
Hydroelectric (J)	3.4E+05	(Odum et al., 2000)	9.2E+15	3.1E+21
Electricity (J)	1.7E+05	(Odum et al., 2000)	1.4E+16	2.5E+21
Iron ore (J)	3.2E+09	(Brown and Ulgiati, 2004)	7.9E+12	2.5E+22
Foreign investment ($)	2.7E+12	(Lou and Ulgiati, 2013)	3.9E+09	1.1E+22
Tourism ($)	2.7E+12	(Lou and Ulgiati, 2013)	2.5E+07	6.7E+19
Services in imports ($)	2.7E+12	(Lou and Ulgiati, 2013)	1.3E+09	3.6E+21
Exported commodities (o)				
Steel and iron (g)	3.2E+09	(Bargigli and Ulgiati,	8.2E+12	2.7E+22

		2003)		
Copper(g)	3.4E+09	(Brown and Ulgiati, 2004)	4.3E+08	1.4E+18
Zinc (g)	3.0E+09	(Rugani and Benetto, 2012)	1.7E+09	5.2E+18
Plumbum (g)	4.7E+09	(Odum et al., 2000)	1.2E+09	5.9E+18
Fertilizer(g)	7.7E+08	(Odum et al., 2000)	3.8E+11	3.0E+20
Glass (g)	2.8E+07	(Brown and Ulgiati, 2002)	1.6E+10	4.4E+17
Paper (g)	6.5E+09	(Vega-Azamar et al., 2013)	9.8E+09	6.4E+19
Rubber and plastic(g)	9.7E+09	(Buranakarn, 1998)	2.2E+10	2.2E+20
Export services ($)	1.2E+13	(Jiang et al., 2008)	4.4E+08	5.4E+21
Services to outside($)	1.2E+13	(Jiang et al., 2008)	1.7E+09	2.0E+22
Wastes（W）				
Waste water（J）	6.7E+05	(Huang and Chen, 2005)	3.3E+14	6.2E+21
Flying ash（g）	4.3E+09	(Geng et al., 2014)	1.4E+10	6.1E+19
Solid waste（J）	1.8E+06	(Huang and Chen, 2005)	1.4E+15	2.4E+21