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RESEARCH ARTICLE

Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone

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Abstract Industrial symbiosis is the sharing of services, utility, and by-product resources among industries. This is usually made in order to add value, reduce costs, and improve the environment, and therefore has been taken as an effective approach for developing an eco-industrial park, improving resource efficiency, and reducing pollutant emission. Most conventional evaluation approaches ignored the contribution of natural ecosystem to the development of industrial symbiosis and cannot reveal the interrelations between economic development and environmental protection, leading to a need of an innovative evaluation method. Under such a circumstance, we present an emergy analysis-based evaluation method by employing a case study at Shenyang Economic and Technological Development Zone (SETDZ). Specific emergy indicators on industrial symbiosis, including emergy savings and emdollar value of total emergy savings, were developed so that the holistic picture of industrial symbiosis can be presented. Research results show that nonrenewable inputs, imported resource inputs, and associated services could be saved by 89.3, 32.51, and 15.7 %, and the ratio of emergy savings to emergy of the total energy used would be about 25.58 %, and the ratio of the emdollar value of total emergy savings to the total gross regional product (GRP) of SETDZ would be 34.38 % through the implementation of industrial symbiosis. In general, research results indicate that industrial symbiosis could effectively reduce material and energy consumption and improve the overall eco-efficiency. Such a method can provide policy insights to industrial park managers so that they can raise appropriate strategies on developing eco-industrial parks. Useful strategies include identifying more potential industrial symbiosis opportunities, optimizing energy structure, increasing industrial efficiency, recovering local ecosystems, and improving public and industrial awareness of eco-industrial park policies.

Keywords Emergy analysis · Industrial symbiosis · Industrial park · China

Introduction

Industrial parks are characterized as a clustering of industries designed to meet compatible demands of different organizations within one location (Geng and Zhao 2009). By grouping various types of industrial activities within one designated area, firms can benefit from economies of scale in terms of land development, construction, and common facilities. Due to these advantages, many countries have chosen industrial parks as their main industrial development strategies, especially in emerging economies, such as China. For instance, a recent report released by Ministry of Commerce in China states that over 6,000 industrial parks are being operated across the whole country, including national economic and technological development zones, high-tech zones, and export processing zones (Song et al. 2014). However, rapid

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development of industrial parks also created a lot of problems, such as solid wastes, air pollution, water contamination, and noise, leading to a need of innovative management at the industrial park level. Under such a circumstance, the Chinese government has chosen eco-industrial parks as the main approach, aiming to reduce both resource consumption and pollutant emission through promoting industrial symbiosis (IS) (Geng and Doberstein 2008). Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products (Chertow 2007). The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (Chertow 2000). By promoting industrial symbiosis, industrial park managers can help their tenant firms reduce both the total consumption of virgin materials and the environmental emissions (Chertow and Lombardi 2005). Under such a circumstance, in order to encourage the application of industrial symbiosis at the industrial park level, both national eco-industrial park indicators (Geng et al. 2009) and national circular economy industrial park indicators (Geng et al. 2012) have been released by the Chinese ministries so that practitioners can find benchmarks for improving their industrial parks. However, these indicators were developed based upon material flow analysis (MFA). MFA-based indicators disregard flow quality and characteristics and the complexity of interactions between the natural environment and socioeconomic systems and cannot reveal the interrelations between economic development and corresponding environmental emissions (Geng et al. 2013a). Typical issues of such indicators include a lack of absolute material/energy reduction indicators, a lack of industrial symbiosis indicators and social indicators, a lack of prevention-oriented indicators, as well as barriers on implementation (Geng et al. 2009). Academically, many evaluation methods have also been applied at the industrial park level, such as carbon footprints (Dong et al. 2013), ecological footprints (Budihardjo et al. 2013), life cycle assessment (Yang et al. 2012), analytical hierarchy process (AHP) (Li 2013), and economic and energy evaluations (Yan and Chien 2013). However, these methods mainly focus on individual aspects of resource use and system metabolism within one industrial park but cannot address the systematic nature of industrial park development. Also, such methods do not account for local ecosystem services or the value of existing natural capitals. Such incomplete assessments may encourage the optimization of one individual resource and lead the policy makers to pay less attention on appropriate environmental management. They also do not have the ability to address industrial symbiosis (such as waste reuse and recycle) since they were not designed for the systemic, closed-looped features of industrial symbiosis. Therefore, it is critical to develop innovative indicators so that the holistic picture of industrial symbiosis can be illustrated.

Emergy analysis, a method rooted in ecology, thermodynamics, and general systems theory, has gradually been accepted by both academia and policy makers due to its innovative contribution on accounting for quantity and quality of input flows, keeping track of interactions among system components across scales, and identifying environmental costs and savings of loop-closing strategies at all levels (Odum 1988; Odum 2000; Geng et al. 2013b). It is a resource consumption accounting approach that is useful to evaluate the environmental profile of comparable systems (Ulgiati et al. 2011), such as one industrial park, and can provide additional aspects that other evaluation methods cannot address and should be seen as one complementary method, therefore, having been applied at the industrial park level. For instance, Wang et al. (2005) conducted their emergy analysis study at Shuozhou industrial park, in which they particularly studied how a local power plant played a key role on promoting industrial symbiosis within one eco-industrial park. Geng et al. (2010a) proposed their methodology on how to conduct emergy analysis within an industrial park by employing a case study in Dalian Economic and Technological Development Zone, especially raising their approach on calculating various waste transformities (transformity was defined as emergy input per unit of available energy output (Odum 1988)). Li (2010) applied emergy analysis at Tianye industrial park, a chlor-alkali-based industrial park in Xinjiang, and found that the overall performance of one industrial park can be improved through more efficient resource use and smart energy management. Taskhiri and his colleagues (2011) raised an emergy-based fuzzy optimization model for water reuse network in an industrial park so that the overall sustainability of one industrial park can be evaluated and policies to encourage the eco-industrial park development can be proposed. Mu et al. (2011) raised their improved emergy-based indicators on evaluating industrial ecosystems, specifically focusing on the interaction between a commercial polyethylene production process incorporating waste management and its surrounding environment. However, none of them focused on evaluating the overall eco-efficiency of industrial symbiosis, resulting in the lack of academic evidence on promoting industrial symbiosis at the industrial park level. Consequently, this paper aims to fill such a gap by evaluating the overall performance of industrial symbiosis by employing emergy analysis.

Methodology

Data collection and treatment

Similar to many other evaluation methods, such as life cycle assessment (LCA), input-output analysis (IOA), and exergy analysis, in order to evaluate industrial symbiosis by using emergy analysis method, various data and information should be collected and treated. Data availability and their reliability and quality are very important for accurate emergy analysis.

Thus, different data acquisition approaches should be performed in parallel, including direct surveys, document reviews, key informant interviews, and informal meetings. Particularly, the identification, collection, and review of primary and secondary documentation are very critical so that valuable information can be screened. During this process, invalid or inaccurate data should be deleted with careful analysis, while other data may be added or deleted based on thermodynamic and chemical evaluation of the process or even from direct measures. Additional interviews may be necessary in order to receive more accurate data and information.

Next step is to categorize these data into different groups, such as economic inputs, renewable resources, nonrenewable resources, and economic yields. Particularly, details on one industrial symbiosis activity should be appropriately described so that both quantitative and qualitative information of such a synergy can be reviewed and revised if necessary. All data should be coded and summarized into an analytical table (with clear reference to the source of data). In order to convert various inputs into common (solar) emergy units, different units for each flow should be multiplied by suitable transformities or specific emergies. The key issue here is to find more appropriate transformities from different sources. To date, there have been a large collection of emergy-related literatures, including papers available in international journals, a large collection of official reports, PhD dissertations, transformity database (http://www.emergysystems.org/nead.php), the official website of International Society for the Advancement of Emergy Research (http://www.isaer.org), national analyses of world countries, and finally books of proceeding of all the emergy conferences (available at http://www.cep.ees.ufl.edu/emergy/index.shtml).

Emergy system diagram

The following step is to draw an emergy system diagram of the whole industrial park so that input and output flows, system components, and interactions among components and final products can be presented. In such a diagram, flows should be organized clockwise from left to right according to their increasing transformities. This strategy helps in simplifying diagrams and preventing flows to cross each other, with a better picture of existing hierarchy of components (Geng et al. 2010a). It also builds up a solid foundation for evaluating the overall performance of this industrial park since various emergy-based indicators can be calculated by referring such a diagram, including emergy yield ratio (reflecting the net economic benefit), environmental loading ratio (reflecting the pressure of industrial activities on the local ecosystem), and emergy sustainability indicator (reflecting the sustainable level of one industrial park).

In order to better identify the key role of industrial symbiosis to improve the overall eco-efficiency of the whole park, it is encouraged to prepare another diagram, in which all the existing and potential industrial symbiosis scenarios are clearly marked with different colors. Such a diagram can clearly present how by-product exchanges occur between different firms so that potential savings on virgin materials and emission reduction can be quantified by using the same unit. Also, more specific waste-related emergy indicators can be calculated by referring this diagram, such as split indicators, co-product indicators, and by-product indicators (see (Geng et al. 2010a)), which can help evaluate the contribution of industrial symbiosis to the improvement of the whole industrial park. The detailed procedure for drawing such a diagram and calculating related indicators is referred to Geng et al. (2010a).

Emergy accounting for industrial symbiosis

First of all, in order to have a complete accounting on industrial symbiosis, emergy-based measurement of environmental services should be conducted. Environmental services provided by natural ecosystem can absorb and dispose of various wastes and therefore are of fundamental importance to a sustainable production pattern (Ulgiati and Brown 2002). Due to the intensive usage of fossil fuels for operating industrial processes within one industrial park, a large amount of environmental emissions from the combustion of fossil fuels, such as SO_2, NO_X, and CO_2, have been released to the local surroundings. In order to dilute such effects, it is necessary to maintain the functions of the local ecosystem. Thus, to accurately calculate environmental services provided by the local ecosystem cannot be ignored. The below procedures should be followed so that emergy accounting for environmental services (R_2) can be quantified:

1. The types and amounts of released emissions (i.e., SO_2, NO_X, CO_2, and dust) should be collected.
2. The volumes of fresh air needed to dilute the emissions to an accepted level can be determined by using Eq. (1):

$$M = \mathrm{d} \times \left(\frac{W}{\mathrm{c}}\right) \tag{1}$$

   where M represents the mass of dilution air, with a unit of gram (g); d represents the air density with a value of 1.29E+03 g/m^3; W represents the annual emission amounts from production processes, with a unit of gram (g); c represents the acceptable emission concentrations based upon official standards released by the Ministry of Environmental Protection (MEP) (GB16297-1996, available at http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjbh/dqgdwrywrwpfbz/199701/t19970101_67504.htm).
3. The energy value of required environmental services is determined by calculating the kinetic energy of the

dilution air, using average value of wind speed in the study area (here, the annual average value for wind speed is 1.40 m/s in the study area according to the local meteorological data (Shenyang Municipality 2011)).

4. Finally, measurement of environmental services can be calculated by multiplying wind transformity with energy value, in units of solar emergy (sej).

Second, specific emergy-based indicators for evaluating industrial symbiosis should be raised. Since industrial symbiosis encourages waste resources from one company being utilized by another neighboring company, both total consumption of virgin materials and total environmental emissions can be reduced. Therefore, specific industrial symbiosis indicators should address such advantages so that both economic and environmental benefits can be clearly quantified. By considering the special features of industrial symbiosis, several industrial symbiosis emergy indicators are proposed, including absolute emergy savings (ΔX, sej), relative emergy savings from different resources (*RES*, X%), emdollar values of total emergy savings (*ETS*, $).

Absolute emergy savings can be defined as the absolute emergy savings of nonrenewable resource, purchased resources, services associated with imported resource, and emergy of the total energy used (U) due to the use of by-products among different firms within the same park and can be calculated by Eq. (2). Relative emergy savings (*RES*) can be defined as the ratio of avoided inputs through all the industrial symbiosis activities to total emergy inputs without related industrial symbiosis activities and can be calculated by Eq. (3).

$$\Delta X = X_{without} - X_{with} \tag{2}$$

$$RES = \Delta X / X_{without} = (X_{without} - X_{with}) / X_{without} \tag{3}$$

where $X_{without}$ represents the total emergy inputs of nonrenewable resource (N), purchased resource (F), service associated with imported resource (S), and emergy of the total energy used (U) under the situation without any industrial symbiosis activities. X_{with} represents the total emergy inputs of nonrenewable resource (N), purchased resource (F), service associated with imported resource (S), and emergy of the total energy used (U) under the situation with industrial symbiosis activities. ΔX represents the absolute emergy savings.

Emdollar value of total emergy savings (*ETS*, $) represents the economic benefits of industrial symbiosis and should be calculated by using Eq. (4), with a unit of $.

$$ETS = \frac{\Delta U}{U/GRP} \tag{4}$$

where ΔU represents the difference of emergy of the total energy used before industrial symbiosis and after industrial symbiosis; *GRP* represents the gross regional product of one industrial park and can be obtained from the annual industrial park report (a request for all the Chinese industrial parks), with a unit of $.

Case study

A description of the case study site

Shenyang Economic and Technological Development Zone (SETDZ) was chosen as the case study industrial park. This industrial park locates in the west part of Shenyang city, the capital city of Liaoning Province in Northeast China. Figure 1 presents its geographical location in China and in Shenyang. This city is the largest city in Northeast China with a total population of over eight million and many heavy industrial sectors (Geng et al. 2013c). SETDZ was founded on June 22, 1988 as one of China's national economic and technological development zones and provides essentially the same preferential policies, incentives, and flexible measures as other special economic zones in China (Geng and Cote 2003). The original area for SETDZ was only 86 km^2 in 1988, but with its rapid development and functional expansion, the city of Shenyang decided to increase its total area through merging the famous Tiexi old industrial area in 2002 (Sun et al. 2013). At present, it has a planned area of 448 km^2, including separate sections for industrial development and mixed residential, financial, and commercial uses. The total population is 1.14 million, including over 300,000 workers and managers (SETDZ 2013).

Businesses in the zone cover a range of ownership types, including joint ventures, private companies, state-owned enterprises, and wholly foreign-owned enterprises. Numerous tenant sites, especially companies with a staff of more than 400 employees, have both manufacturing and residential buildings within their compounds. This is in keeping with Chinese government policy whereby businesses are expected to provide social benefits to employees, such as food and accommodation. Within SETDZ, there are over 1,300 enterprises, including 55 companies that are ranked among the Fortune 500 group. Total investment in the zone reached over US$13.7 billion in 2012 (SETDZ 2013). Through almost three decades of development, SETDZ has established five industrial pillars, including chemicals, equipment manufacturing, construction material industry, pharmaceuticals, and food processing. Examples of famous multinational companies include BASF, BMW motors, Coca-Cola, Pepsi-Cola, Tingyi food, Hino motors, GM motors, Bekaert, Michelin Tyres, Panasonic, Bridgestone Tyres, etc. In order to host these

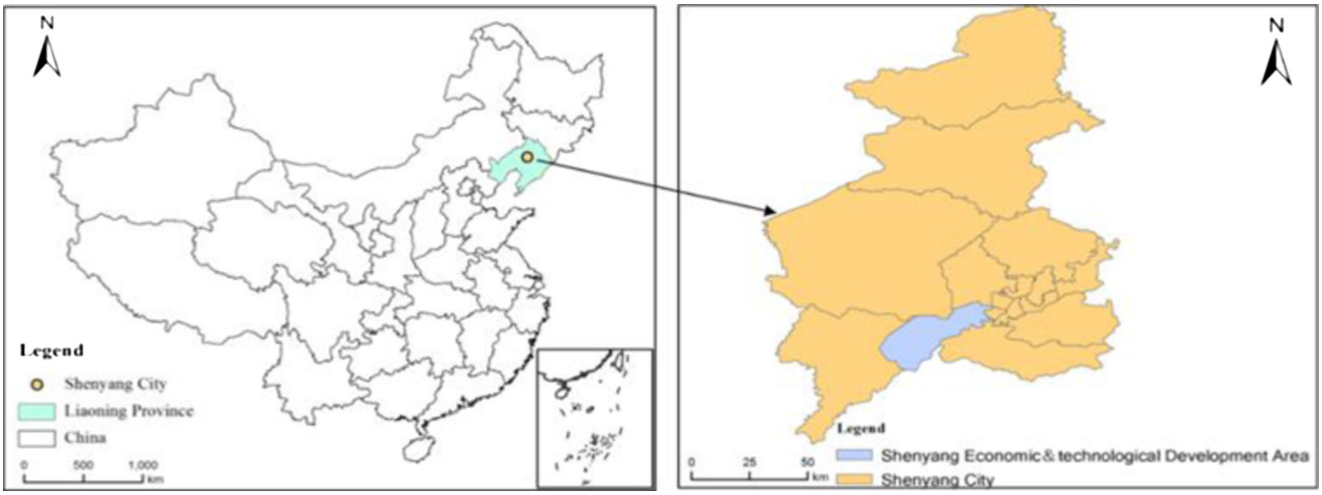

Fig. 1 Geographical location of SETDZ in China

foreign companies, the administrative commission (AC) of this industrial park invested a large amount of money for providing public services, including international schools and hospitals, stadiums, dental clinics, training labors, etc.

Data collection

A detailed survey was completed at SETDZ by the research team of the Institute of Applied Ecology at Chinese Academy of Sciences in early 2011 in order to collect necessary information and data for emergy analysis. Relevant reports, such as the local yearly statistics books, government planning documents, and environmental reports of key companies within SETDZ, were collected for extracting useful information and data. Knowledge experts and officials at the statistics, environmental protection and planning, and development bureaus within SETDZ and key managers in some local companies were interviewed. These interviews helped to validate data from archival and secondary sources and provided more background information on their environmental management efforts. Then, all the collected data were categorized into one emergy input table, namely Table 1. Table 2 lists air emissions and acceptable emission concentration data at SETDZ. All the data for this study are for the year of 2010.

Industrial symbiosis efforts at SETDZ

Since Shenyang is a famous tourist city and has several historical heritages, maintaining a pleasant and clean environment in Shenyang's largest industrial park (SETDZ) is thus beneficial to its economic well-being. Given these regional characteristics, the SETDZ AC has had a great desire to improve the zone's overall eco-efficiency and environmental quality and chose to apply the national eco-industrial park (EIP) title in 2011. On September 26, 2013, their EIP plan passed the national onsite evaluation organized by the MEP. Under this EIP project, 12 industrial plants have been closed because of economic inefficiency and environmental degradation, over 60 coal-burning boilers have been phased out due to their lower energy efficiency and higher emissions, and 105 companies have conducted cleaner production audits and implemented over 1,000 cleaner production options in order to identify the potential pollution prevention opportunities (SETDZ 2013).

More importantly, in order to develop an industrial symbiosis network, the AC at SETDZ determined to promote by-product exchanges based upon their five main industrial clusters (chemicals, equipment manufacturing, construction material industry, pharmaceuticals, and food processing). Several synergy opportunities have been identified and implemented through their EIP planning efforts. For instance, the local cogeneration power plants are producing various wastes, including boiler steam, flying ash, gypsum from desulfurization process, and slag. Such wastes have potential values for local construction material enterprises to produce gypsum boards and bricks. Another example is that local metallurgical enterprises can use the steel, iron, and lead scraps produced by local equipment manufacturing enterprises for their production. From energy point of view, many chemical enterprises at SETDZ can use the boiler steam from the local cogeneration power plants so that they can avoid using their own boilers. Figure 2 shows the detailed by-product exchanges within SETDZ. All these efforts were initiated after the AC decided to pursue EIP title.

Results

Emergy evaluation on SETDZ

Before a detailed evaluation on its industrial symbiosis at SETDZ, an emergy evaluation on the whole zone is crucial

Table 1 Emergy accounting data for SETDZ

Item	Unit	Amount (unit/year)	UEV (sej/unit)	Ref.	Solar emergy (sej/year)	
					Without IS	With IS
Renewable inputs						
1 Sunlight	J/year	1.60E+18	1.00E+00	(Mu et al. 2011)	1.60E+18	*1.60E+18*
2 Wind (kinetic energy)	J/ year	1.10E+15	2.51E+03	(Mu et al. 2011)	2.75E+18	*2.75E+18*
3a Rain (chemical potential energy)	J/ year	8.91E+14	3.50E+04	(Mu et al. 2011)	3.12E+19	*3.12E+19*
3b Rain (geopotential energy)	J/ year	2.67E+14	1.76E+04	(Mu et al. 2011)	4.69E+18	*4.69E+18*
4 Oxygen for combustion process	g/ year	1.12E+13	5.16E+07	(Li 2013)	5.77E+20	*5.77E+20*
5 Surface water	g/ year	1.50E+09	1.12E+06	(Odum 1988)	1.68E+15	*1.68E+15*
Internal electricity production						
6 Coal-fired power	J/ year	3.29E+15	2.87E+05	(Li 2013)	9.46E+20	*9.46E+20*
7 Wind power	J/ year	2.16E+13	1.04E+05	(Li 2013)	2.25E+18	*2.25E+18*
Nonrenewable inputs from within boundary						
8 Gravel	g/ year	3.33E+10	1.68E+09	(Mu et al. 2011)	5.59E+19	*5.59E+19*
9 Clay	g/ year	1.49E+11	3.36E+09	(Mu et al. 2011)	5.01E+20	*0*
10 Ground water	J/ year	5.94E+13	6.88E+04	(Geng et al. 2013b)	4.09E+18	*4.09E+18*
Imported resources						
Energy						
11 Coal	J/ year	5.42E+16	6.71E+04	(Geng et al. 2013b)	3.64E+21	*3.64E+21*
12 Crude oil	J/ year	2.64E+16	9.07E+04	(Geng et al. 2013b)	2.39E+21	*2.39E+21*
13 Gasoline	J/ year	3.28E+15	1.11E+05	(Geng et al. 2013b)	3.64E+20	*3.64E+20*
14 Diesel fuel	J/ year	2.07E+15	1.11E+05	(Odum and Nilsson 1996)	2.30E+20	*2.30E+20*
15 Natural gas	J/ year	1.30E+15	5.88E+04	(Odum 2000)	7.66E+19	*7.66E+19*
16 Steam	g/ year	3.93E+13	1.74E+08	(Hashimoto et al. 2010)	6.84E+21	*0*
17 Purchased electricity	J/ year	2.87E+09	2.87E+05	(Li 2013)	8.24E+14	*8.24E+14*
Metals						
18 Steel and pig iron	g/ year	2.53E+12	3.16E+09	(Ren et al. 2012)	8.00E+21	*7.20E+21*
19 Copper	g/ year	7.77E+10	3.36E+09	(Rugani and Benetto 2012)	2.61E+20	*2.61E+20*
20 Aluminum	g/ year	5.58E+10	1.44E+09	(Geng et al. 2013b)	8.03E+19	*8.03E+19*
21 Zinc	g/ year	1.71E+08	3.02E+09	(Rugani et al. 2012)	5.17E+17	*5.17E+17*
22 Lead	g/ year	1.19E+10	4.80E+11	(Rugani et al. 2012)	5.70E+21	*4.56E+21*
23 Titanium	g/ year	1.19E+09	6.42E+10	(Rugani et al. 2012)	7.66E+19	*7.66E+19*
24 Chromium	g/ year	1.51E+06	1.68E+09	(Geng et al. 2013b)	2.54E+15	*2.54E+15*
Nonmetals						
25 taped water	g/ year	7.87E+13	1.12E+06	(Odum 1988)	8.81E+19	*8.81E+19*
26 Quartz	g/ year	2.18E+08	1.68E+09	(Mu et al. 2011)	3.66E+17	*3.66E+17*
27 Gypsum	g/ year	2.13E+10	3.16E+09	(Geng et al. 2013b)	6.74E+19	*0*
28 Slag	g/ year	2.68E+11	6.61E+09	(Shenyang Municipality 2011)	1.77E+21	*0*
29 Timber	J/ year	1.16E+14	4.53E+04	(SETDZ 2013)	5.24E+18	*5.24E+18*
30 Glass	g/ year	2.91E+09	2.77E+07	(Sun et al. 2013)	8.05E+16	*8.05E+16*
31 Methanol	g/ year	1.66E+09	7.23E+09	(Ulgiati and Brown 2002)	1.20E+19	*1.20E+19*
32 Ethanol	g/ year	3.46E+09	8.26E+09	(Ulgiati et al. 2011)	2.86E+19	*2.86E+19*
33 Paint	g/ year	1.59E+09	1.50E+09	(Ulgiati and Brown 2013)	2.38E+18	*2.38E+18*
34 Rubber and plastic	g/ year	1.89E+11	9.68E+09	(Van Berkel et al. 2009)	1.83E+21	*1.83E+21*
35Resin	g/ year	4.20E+09	5.51E+09	(Van Berkel et al. 2009)	2.32E+19	*7.71E+19*
36 Paper	g/ year	1.24E+11	6.55E+09	(Odum and Nilsson 1996)	8.14E+20	*8.14E+20*
Food						
37 Vegetable	g/ year	2.08E+09	5.51E+05	(Ingwersen 2011)	1.14E+15	*1.14E+15*
38 Fruit	g/ year	4.82E+09	6.83E+09	(Ingwersen 2011)	3.29E+19	*3.29E+19*

Table 1 (continued)

Item	Unit	Amount (unit/year)	UEV (sej/unit)	Ref.	Solar emergy (sej/year)	
					Without IS	With IS
39 Meat	g/ year	1.49E+08	3.00E+10	(Wang et al. 2005)	4.46E+18	*4.46E+18*
40 Rice	g/ year	2.43E+08	4.47E+09	(Xi et al. 2011)	1.08E+18	*1.08E+18*
41 Soybean oil	g/ year	6.95E+07	1.35E+10	(Ingwersen 2011)	9.39E+17	*9.39E+17*
42 Egg	J/ year	5.10E+10	4.40E+06	(Yan and Chien 2013)	2.24E+17	*2.24E+17*
Labor and service						
43 Labor	$/ year	8.45E+08	5.88E+12	(Rugani et al. 2012)	4.97E+21	*4.97E+21*
44 Service	$/ year	2.05E+09	5.88E+12	(Rugani et al. 2012)	1.21E+22	*1.02E+22*
Output (main products)						
45 Construction materials						
Bricks	piece	3.92E+06				
Concrete	m^3	9.55E+04				
46 Machines						
Machine tools	piece	9.22E+04				
Blowers	piece	1.02E+03				
Transportation machineries	piece	3.10E+01				
47 Foods	ton	4.89E+03				
48 Chemicals	ton	1.04E+04				
Waste						
49 Wastewater	g/ year	2.61E+14	1.88E+07	(Yang et al. 2012)	4.91E+21	5.31E+20
50 Boiler steam	g/ year	5.90E+13	1.60E+07	[a]	9.46E+20	0
51 Flying ash	g/ year	2.20E+11	4.30E+09	[a]	9.46E+20	0
52 Slag	g/ year	2.92E+11	3.24E+09	[a]	9.46E+20	0
53 Gypsum from desulfurization	g/ year	3.83E+10	3.16E+09	(Geng et al. 2013b)	1.21E+20	0
54 Sludge	g/ year	2.76E+10	2.70E+09	[47]	7.45E+19	0
55 Steel and pig-iron scrap	g/ year	2.53E+11	3.16E+09	(Ren et al. 2012)	2.66E+21	0
56 Lead	g/ year	2.38E+09	4.80E+11	(Rugani et al. 2012)	7.31E+21	0

[a] The UEVs were calculated from this work

so that the holistic picture of this zone can be presented. Industrial symbiosis activities did not occur at SETDZ before 2010 but gradually expanded after the AC at SETDZ initiated their EIP efforts. Therefore, two emergy flow diagrams were drawn so that the differences before and after industrial symbiosis can be identified. Table 3 lists related emergy flow results, while Figs. 3 and 4 present two emergy flows at SETDZ (without and with industrial symbiosis activities), respectively. In both diagrams, cluster A represents heat and power supply enterprises; cluster B represents construction materials enterprises, including brick production, gypsum board production, and concrete and cement production; cluster C represents metallurgical enterprises; cluster D represents equipment manufacturing enterprises; cluster E represents chemical and pharmaceutical enterprises. In Fig. 4, $W_{A1,r}$ represents a portion of boiler steam reused by cluster A; $W_{A2,r}$ represents flying ash, desulfurization gypsum, and slag reused by cluster B; $W_{A3,r}$ represents the other portion of boiler

Table 2 Air pollutant emissions and accepted concentrations at SETDZ

Air pollutants	Emission (kg)	Acceptable concentration (kg/m^3)	Reference for acceptable concentration	Environmental services (R_2, sej)
W_{SO2}	1.07E+07	4.92E-10	[a]	3.78E+20
W_{NOx}	9.29E+06	4.31E-10	[a]	
W_{Dust}	2.05E+05	7.50E-08	[a]	

[a] Ministry of Environmental Protection of the People's Republic of China. Air Quality Standard of China (GB3095-2012). Available online at http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjbh/dqhjzlbz/201203/t20120302_224165.htm (in Chinese)

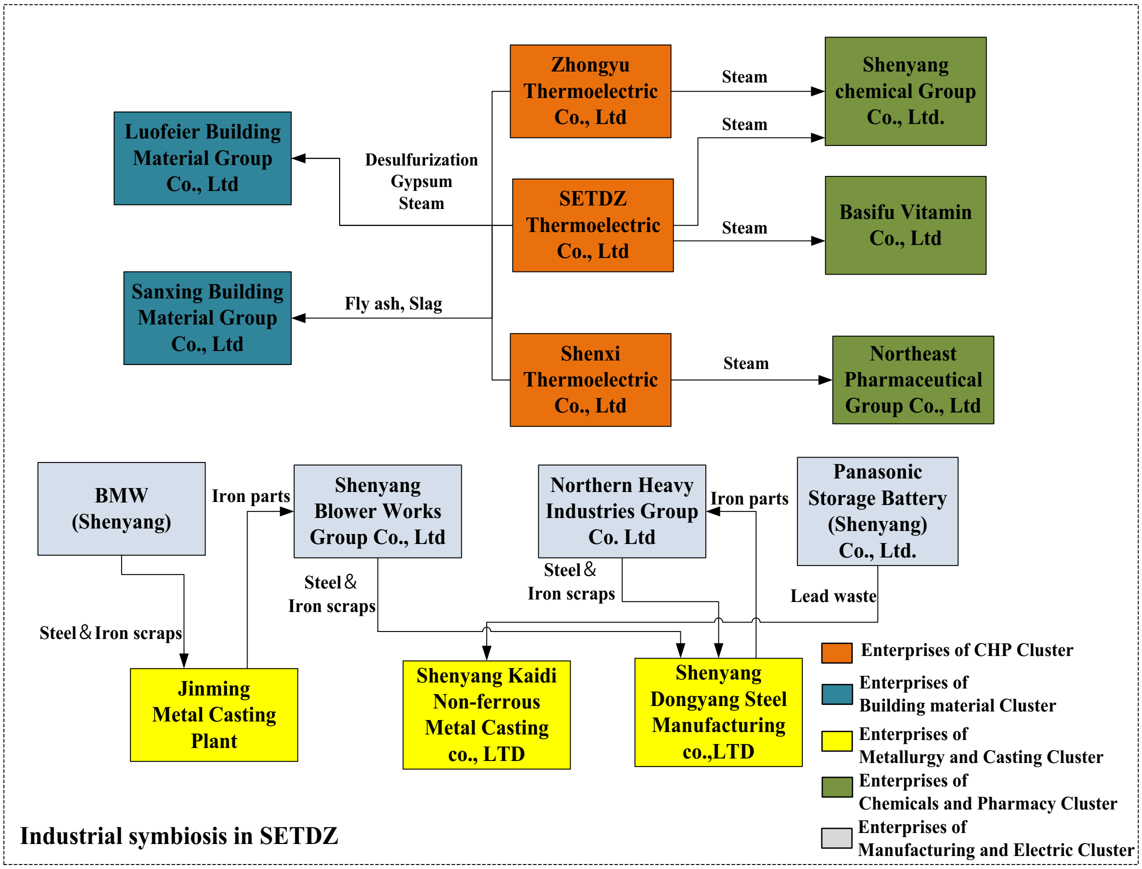

Fig. 2 Industrial symbiosis of SETDZ in 2010

steam reused by cluster E. $W_{C,r}$ represents iron, steel, and lead pig reused by cluster D; $W_{D,r}$ represents iron, steel scraps, and lead waste reused by cluster C; ES(R_2) represents environmental services for diluting air emissions.

Table 4 lists two sets of performance indicators for SETDZ. One set is for the real situation of 2010, namely, no industrial symbiosis activities occurred. The other set is for the assumption scenario of 2010, namely, the optimal scenario (if these industrial symbiosis activities occurred in 2010), although in the reality, these activities happened gradually after 2010. Such a comparison can help identify the key roles of industrial symbiosis. It is clear that with industrial symbiosis efforts, the total renewable inputs remain stable while both total nonrenewable inputs and total imported resources decrease, indicating significant resource saving benefits. The value of emergy yield ratio remains unchanged mainly because both values of R and N are still much smaller than the value of I even when industrial symbiosis activities occur, indicating that the magnitude of industrial symbiosis needs to be further expanded. Also, environmental loading ratio decreases from 83.71 to 62.04, indicating less pressure on the local ecosystem. Emergy money ratio decreases from 6.67E+12 sej/$ to 4.14E+12 sej/

Table 3 Aggregated emergy flows at SETDZ

Indicators and units		Without (IS)	With (IS)
Direct renewable input (sej)	R_1	6.08E+20	6.08E+20
Indirect renewable input (sej)	R_2	3.78E+20	3.78E+20
Local nonrenewable input (sej)	N	5.61E+20	6.00E+19
Imported resources (sej)	I	3.23E+22	2.18E+22
Direct labor input (sej)	L	4.97E+21	4.97E+21
Services associated to imported resources (sej)	S	1.21E+22	1.02E+22
Imported resources with labor and service (sej)	$F=I+L+S+W$	5.00E+22	3.73E+22
Total used emergy (sej)	$U=R_1+R_2+N+F$	5.15E+22	3.83E+22
Emergy used for waste transportation and disposal (sej)	W	5.88E+20	3.13E+20

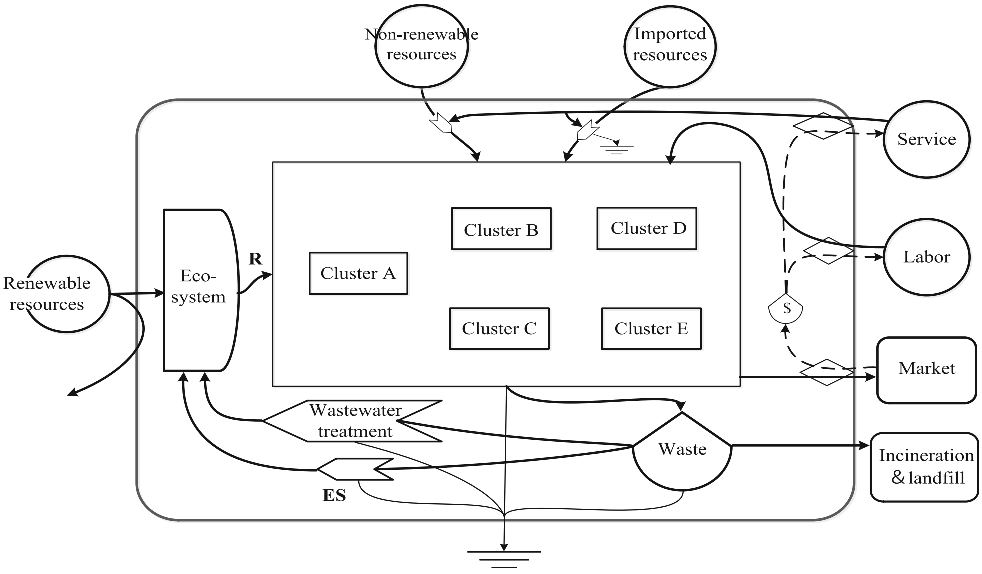

Fig. 3 Emergy system diagram of SETDZ without IS. *Cluster A* heat and power supply enterprises, *cluster B* construction material enterprises, *cluster C* metallurgical enterprises, *cluster D* equipment manufacturing enterprises, *cluster E* chemical and pharmaceutical enterprises

$, meaning that per dollar, emergy inputs decrease at SETDZ and its purchasing power at SETDZ increases. In general, industrial symbiosis can bring positive impacts to the overall eco-efficiency and improve the sustainable level of the zone, reflected by a higher value of EIS (increased by 34.2 % from 0.012223 to 0.016404).

Detailed analysis on industrial symbiosis

In SETDZ, wastes are mainly from the cogeneration power plants and equipment manufacturing and electronic enterprises, including waste steam, flying ash, desulfurization gypsum, slags, steel, pig iron, and lead scraps. Main industrial symbiosis activities occur between local cogeneration power plants and other tenant companies. For instance, waste steam from cogeneration power plants is being used for coke production, gypsum board production, and pharmacy production, with a total amount of 5.90E+07 t per year. Flying ash from cogeneration plants is being used for cement production, with a total amount of 2.20E+05 t per year, which can replace 1.50E+05 t of clay per year. And, the extracted gypsum from desulfurization process (with a total amount of 3.83E+04 t per year) is used for gypsum board production and can replace 2.13E+04 t of virginal gypsum per year. Finally, the slags from cogeneration power plants are being used for brick and cement production, with a total amount of 2.92E+05 t per

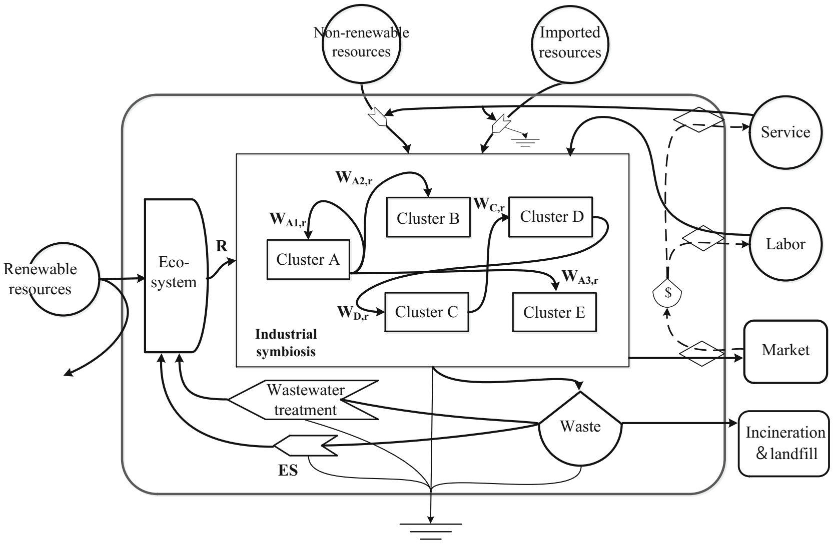

Fig. 4 Emergy system diagram of SETDZ with IS. *Cluster A* heat and power supply enterprises, *cluster B* construction material enterprises, *cluster C* metallurgical enterprises, *cluster D* equipment manufacturing enterprises, *cluster E* chemical and pharmaceutical enterprises. *WA1,r* a portion of boiler steam reused by cluster A, *WA2,r* flying ash, desulfurization gypsum, and slag reused by *cluster B*, *WA3,r* the other portion of boiler steam reused by *cluster E*. *WC,r* iron, steel, and lead pig reused by *cluster D*, *WD,r* iron, steel scraps, and lead waste reused by *cluster C*, *ES(R2)* environmental services for diluting air emissions

Table 4 Emergy-based indicators without IS and with IS at SETDZ

Indicators and units		Without (IS)	With (IS)
Ratio of renewable inputs to total used emergy (%)	R_1/U	1.18 %	1.59 %
Ratio of nonrenewable inputs to total used emergy (%)	N/U	1.09 %	0.16 %
Ratio of imported resources to total used emergy (%)	I/U	62.71 %	56.88 %
Emergy yield ratio	$EYR=U/(R_2+F)$	1.02	1.02
Emergy money ratio (sej/\$)	U/GRP	6.67E+12	4.14E+12
Environmental loading ratio	$ELR=(R_2+N+F)/R$	83.71	62.04
Emergy index of sustainability	$EIS=EYR/ELR$	0.012223	0.016404

year. Other industrial symbiosis efforts mainly include steel, pig iron, and lead scraps reuse and occur between local manufacturing and electronic enterprises and local metallurgical firms, with a total amount of 2.53E+05 t of steel and iron and 2.38E+03 t of lead per year. The reused wastes are then accounted by emergy analysis from the full life cycle perspective, which means that the total emergy for the extraction, refinement, and production of such replaced materials is considered so that the holistic picture on saving virgin materials can be presented.

Table 5 lists the detailed reusable waste flows from main industrial symbiosis activities that occurred between different tenant companies at SETDZ. It is clear if these industrial symbiosis efforts occurred in 2010, then significant benefits on saving virgin materials and avoiding environmental emissions can be achieved. Especially, boiler steam is the largest available reusable resource at SETDZ and can be reused by many firms so as to reduce both air pollutants and energy consumption. Without industrial symbiosis planning, such steam is being discharged into the local atmospheric environment, without any cascading application.

Another key element for evaluating industrial symbiosis is waste transportation and final disposal. Without the existence of industrial symbiosis pattern, these otherwise discarded wastes need to be delivered for final disposal, which requires additional emergy inputs. The emergy inputs for waste delivery and final disposal can be calculated by multiplying the mass of wastes (g) with per unit emergy for transportation and disposal (sej/g). In the case of SETDZ, such a value is 5.88E+20 sej under the situation without industrial symbiosis. For the scenario of industrial symbiosis, necessary emergy inputs (including pipeline construction and delivery of reused

Table 5 Reusable waste flows from industrial symbiosis activities at SETDZ

Wastes	Amounts (t)	Supply company	Demand company	Replaced items	Purpose of industrial symbiosis	Reduction amounts of virgin materials (t)
Boilersteam	5.90E+07	Zhongyupower plant; SETDZ power plant;	Shenyang chemical Group; Basf Vitamin Co., Ltd;	Steam	Coke production Gypsum board production	3.93E+07
		Shenxipower plant	Northeast Pharmaceutical Group; LuofeierConstruction Material Group		Pharmacy production	
Flying ash	2.20E+05	Zhongyupower plant; SETDZ power plant; ShenxiPower plant	SanxingConstruction Material Group	Clay	Cement production	1.50E+05
Gypsum from desulfurization	3.83E+04	ZhongyuPower plant; SETDZ Power plant; ShenxiPower plant	LuofeierConstruction Material Group	Gypsum	Gypsum board production	2.13E+04
Slags	2.92E+05	ZhongyuPower plant; SETDZ Power plant; ShenxiPower plant	SanxingConstruction Material Group	Slag	Brick production Cement production	2.92E+05
Steel and iron scraps	2.53E+05	BMW motors Shenyang Blowers Group; Northern Heavy Industries Group	Jinming Metal Casting Plant; Shenyang Dongyang Steel -Manufacturing	Iron and steel	Metallurgical production	2.53E+05
Lead waste	2.38E+03	Panasonic Battery Co., Ltd.	Shenyang Kaidi Nonferrous -Metal Casting	Lead pig	Metallurgical production	2.38E+03

wastes) are included. Thus, due to less wastes for final disposal through waste reuse and recycle, the aggregated emergy input value for waste transportation and final disposal is 3.13E+20 sej, 46.8 % lower than the one without industrial symbiosis, indicating clear economic and environmental benefits.

In order to further recover how industrial symbiosis improved the sustainable level of the whole zone, a more detailed emergy study on related industrial symbiosis activities is necessary. Table 6 lists the aggregated emergy flows for these industrial symbiosis activities and presents a comparison between two scenarios (with and without industrial symbiosis). Total emergy saving of nonrenewable resources (ΔN, sej) from industrial symbiosis is 5.01E+20 sej, indicating that 89.3 % nonrenewable resources can be saved for these industrial operations. Total emergy savings from imported resources (ΔI, sej), services (ΔS, sej), and total used emery (ΔU, sej) are 1.05E+22, 1.90E+21, and 1.32E+22 sej, respectively, meaning that 32.51 % of imported resources, 15.70 % of services, and 25.58 % of emergy of the total energy used can be saved due to by-product exchanges among involved firms. Such savings can bring a great economic benefit, with a value of 3.18E+09$ (equivalent to 34.38 % of total GRP of SETDZ in the year of 2010), calculated through the use of Eq. (4).

Figures 5 and 6 present two different components (without and with industrial symbiosis) of different emergy flows to emergy of the total energy used (*U*), respectively. From the whole industrial zone point of view, ratio of renewable emergy inputs (R_1) to emergy of the total energy used (*U*) increased from 1.18 to 1.59 %, mainly due to the decrease of *U*. Ratio of nonrenewable emergy input (*N*) to emergy of the total energy used (*U*) decreased from 1.09 to 0.16 % since clay is totally substituted by flying ash generated from local cogeneration power plants. The imported resources account for the largest part of emergy of the total energy used, which is up to 62.71 % without industrial symbiosis. But such a figure decreased to 56.88 % when all industrial symbiosis activities occurred, indicating that less imported resources are required due to by-product exchanges. Although labor emergy input is not changed (4.97E+21 sej), ratio of labor emergy input to emergy of the total energy used increases from 9.65 to 12.97 % due to the reduction of emergy of the total energy used. The services emergy associated to imported resources decreased from 1.21E+22 to1.02E+22 sej due to the reduction of imported resources. The emergy inputs for waste transportation and final disposal (*W*) decreased from 5.88E+20 to 3.13E+20 sej. The reason is that a large amount of emergy demand for waste transportation and disposal can be avoided due to industrial symbiosis and total emergy inputs for material reuse/recycling are quite small.

Table 6 The results of Δx and x% of SETDZ

	Before IS (sej)	After IS (sej)	Δx (sej)	x%
N	5.61E+20	6.00E+19	5.01E+20	89.3 %
I	3.23E+22	2.18E+22	1.05E+22	32.51 %
S	1.21E+22	1.02E+22	1.90E+21	15.70 %
U	5.15E+22	3.83E+22	1.32E+22	25.58 %

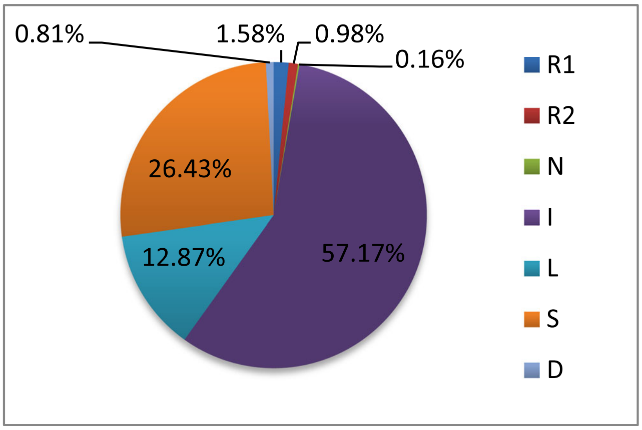

Fig. 5 Components of different emery flows to total used emergy (*U*) without industrial symbiosis

Figure 7 shows detailed emergy of energy inputs, metal inputs, nonmetal inputs, and food inputs in the imported resource. It is clear that the largest emergy input is metals, with values of 1.41E+22 and 1.22E+22 sej for scenarios of without industrial symbiosis and with industrial symbiosis, respectively. The second largest emergy input is energy, with values of 1.35E+22 and 6.70E+21 sej for scenarios of without industrial symbiosis and with industrial symbiosis, respectively. Figure 8 shows the detailed emergy inputs in the imported resources, covering all kinds of metals and energy sources. It is clear that steel and pig iron, steam, lead, coal, and crude oil account for the most inputs without industrial symbiosis activities occur, while industrial symbiosis efforts can

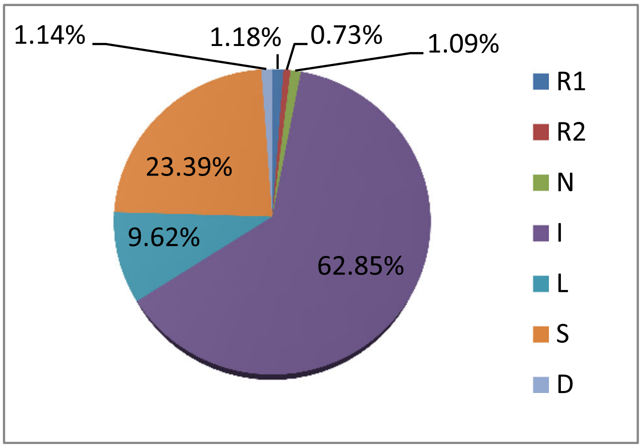

Fig. 6 Components of different emery flows to total used emergy (*U*) with industrial symbiosis

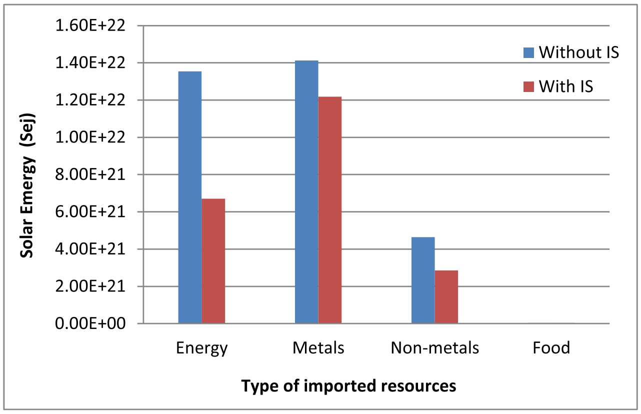

Fig. 7 Emergy inputs of energy, metals, nonmetals, and food in the imported resources

significantly reduce steam inputs and slightly reduce steel/iron and lead inputs. The related emergy inputs decreased from 2.77E+22 to 1.89E+22 sej, with a 31.8 % reduction.

Discussions

Industrial symbiosis uses an ecosystem metaphor and natural analogy to study industrial systems so that resource productivity can be improved and corresponding environmental burdens can be abated (Van Berkel et al. 2009). It advocates different companies to seek potential by-product exchanges so that industrial ecosystems can be created toward closing materials' cycles (Chertow 2000). By employing emergy analysis method at SETDZ, it is clear that industrial symbiosis efforts can bring significant economic and environmental benefits to this industrial zone. Our analysis contributes to this improved understanding with useful policy insights. Efforts to further identify potential industrial symbiosis opportunities, optimize energy structure, increase industrial efficiency, recover local ecosystems, and improve public and industrial awareness of EIP policies are direct and indirect implications from our study results.

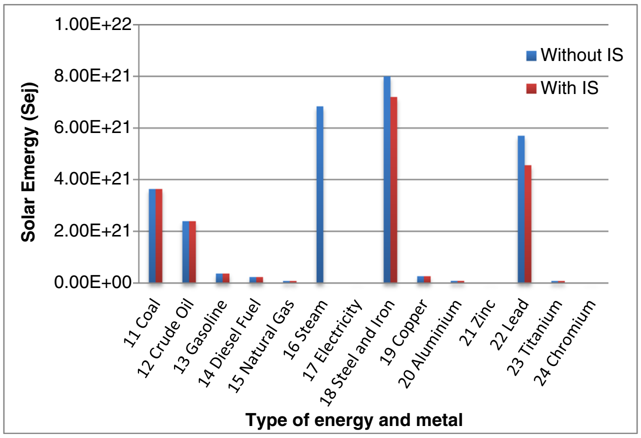

Fig. 8 Emergy values of all kinds of energy and metal inputs in the imported resources

First of all, current industrial symbiosis efforts should be further expanded. Although a large amount of wastes have been reused or recycled, total involved companies are still less and need to be increased. In order to investigate more potential industrial symbiosis opportunities, the research team conducted another in-depth study and identified more synergy options. Figure 9 presents more potential industrial symbiosis opportunities at SETDZ by considering the local realities. Particularly, treated wastewater from local wastewater treatment can be reused by many firms for different purposes, such as cooling, landscaping, and washing. Such a practice has been applied in several Chinese industrial parks with significant economic and environmental benefits. For instance, by encouraging water reuse both between large water users and between tenant companies and local wastewater treatment plant, the Tianjin Economic Development Area (TEDA) can save 16.9 % freshwater and 10.37 % water-related costs and reduce wastewater discharge by 45.6 % (Geng et al. 2007a). Another example is that sludge from wastewater treatment can be reused as a kind of artificial fertilizer for landscaping purpose, which has also been applied in TEDA for more than one decade (Geng et al. 2007b).

Second, energy structure optimization is one effective approach to reduce total energy consumption and energy-related emissions. Shenyang city relies on coal as its main energy source but suffers from coal-related air pollutions and was listed as one of top ten polluting Chinese cities in 1990s (Ren et al. 2012). As the main energy consumption district, SETDZ's carbon footprint reached 15.29 million tons in 2007, around 26.8 % of the whole city (Dong et al. 2013). Therefore, SETDZ has become a main focus for the local energy saving and emission reduction effort, a national initiative raised by National Development and Reform Commission (NDRC) in order to respond both climate change and environmental challenges (Geng and Sarkis 2012). Several approaches should be adopted in order to reduce its dependence on coal-dominated energy structure. For instance, Shenyang city is the largest Chinese city to apply ground source heat pumps, but most applications are for local residential communities, not for industrial operations (Geng et al. 2013d). Actually, surplus heat from wastewater treatment plant can be transferred to local tenant companies through the application of sewage heat pumps. Plus, many tenant companies can easily use ground source heat pumps for their own operations. In addition, wind power is available due to local weather conditions and should be promoted as well. Furthermore, the national project of "transferring natural gas from the west to the east" created a great opportunity to the city of Shenyang so that many industrial users at SETDZ can use such a cleaner energy source, rather than relying on coal (Geng et al. 2013d).

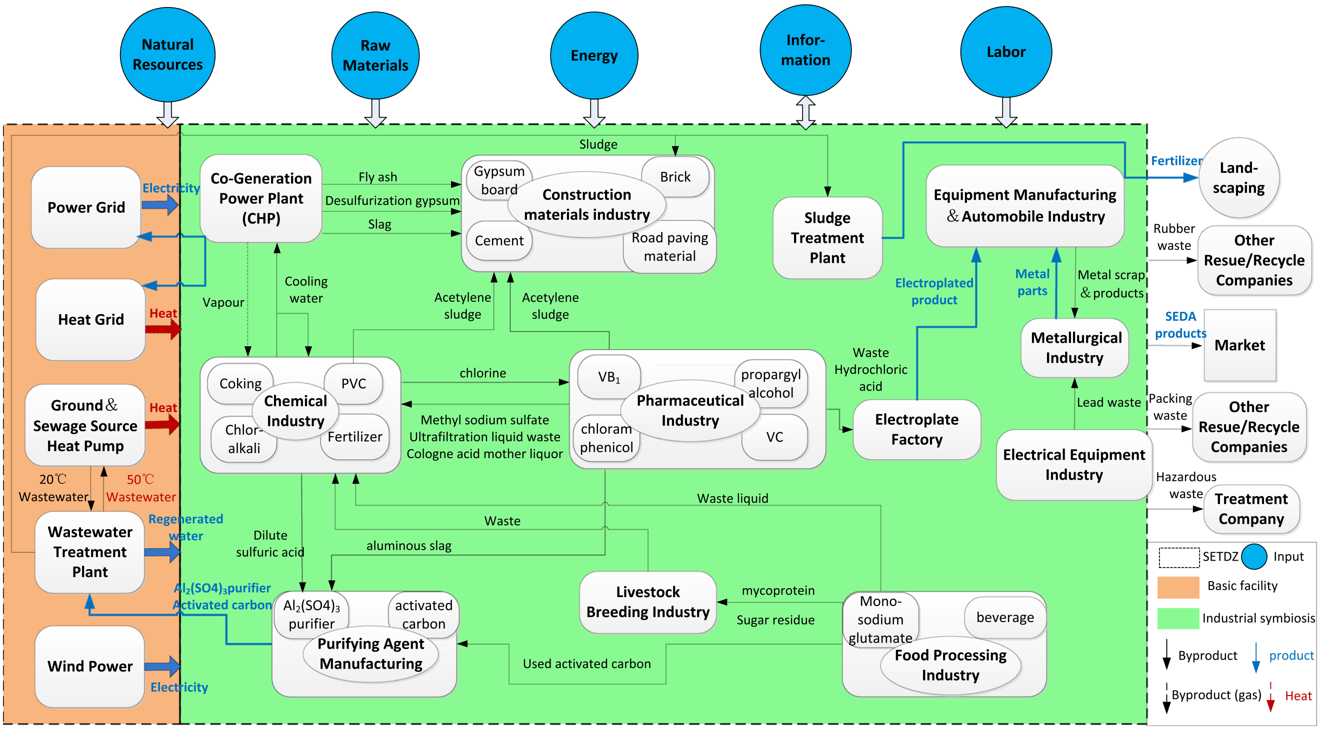

Fig. 9 Potential industrial symbiosis linkages at SETDZ

Third, to increase industrial efficiency is also functional and useful. Besides by-product exchanges among different companies, individual firm should seek internal synergy opportunities through eco-design, cleaner production, process integration, and appropriate waste treatment. In this regard, Liaoning province has been a leading province in China to promote cleaner production and has enacted several policies, including a cleaner production revolving fund to support the implementation of cleaner production (Geng et al. 2010b). Consequently, the AC of SETDZ should encourage all their tenant firms to initiate their cleaner production efforts and facilitate their application on such funds. Moreover, energy saving should be pursued in all tenant companies through energy audits so that potential saving opportunities can be identified and related benefits can be quantified. Such a measure can build up practitioners' confidence and reduce their energy consumption. It also advocates the application of more advanced energy efficiency technologies and equipment, such as energy cascading and pinch technologies, energy efficient boilers and engines.

Fourth, to pay more attention on recovering local ecosystem is necessary for sustainable operation of one industrial park. Comparing with conventional evaluation methods, emergy analysis can reflect the real contribution of local ecosystem by focusing on nature's investment, on the work performed by the biosphere to generate resources and services, not only the economic value or the mass of resources supplied to the economic system (Geng et al. 2013b). By doing so, it can help decision makers to understand the true value of local ecosystem and then pay more heed on protecting them. Also, by quantifying both the direct and indirect environmental costs of waste management and untreated waste disposal, as well as the advantage of recycling in closed loops, it can support multiple performance aspects in resource use and recovering local ecosystems.

Finally, to improve public and industrial awareness of EIP policies is very critical. Industrial symbiosis is still in its early stage in China, and many practitioners are not familiar with such a concept. Therefore, capacity building efforts should be initiated by considering the local realities. For instance, successful experiences and cases on applying industrial symbiosis should be regularly collected and disseminated by the AC so that more industrial managers at SETDZ can see the true stories and inspire their eagerness. Also, industrial park managers at SETDZ can prepare various programs to promote the concept, international and domestic cases, and lessons on industrial symbiosis through regular workshops, newspapers, TV programs, and outdoor bulletins. Particularly, international collaboration can play a key role. Shenyang city has been a sister city of Kawasaki city in Japan for more than three decades. The famous eco-town in Kawasaki has one of the best practices on promoting industrial symbiosis in the world (Van Berkel et al. 2009; Hashimoto et al. 2010; Geng et al. 2010c). Especially, industrial symbiosis efforts at Kawasaki have been expanded to urban symbiosis (referring to the use of by-products (wastes) from cities (or urban areas) as alternative raw materials or energy source in industrial operations), which can bring more adding values (such as resource saving, emission reduction, and climate change response) to the whole city (Van Berkel et al. 2009; Dong et al. 2014). These experiences and advanced symbiosis technologies should be shared by Shenyang city through their sister city partnerships.

From method point of view, we believe that emergy approach is an effective compliment to other indicators (Hau and Bakshi 2004), but not a panacea. For instance, transformity computation procedures and transferability have required significant standardization efforts (Bastianoni et al. 2005), which provided a solid foundation for its application. However, accurate calculations on transformities are based on very simplified models (in terms of structure) of the economic systems behind products and processes (Rugani and Benetto 2012) and case-specific. Although we have tried our best to collect the most relevant transformities from the existing sources, the unavoidable errors may still exist due to a lack of entirely localized data. Also, similar to most other biophysical aggregated metrics, emergy can be criticized for assuming that input resources are substitutable. This risk can be mitigated through transparent accounting for inputs, which may significantly increase the data collection and treatment time and accounting procedures. Moreover, emergy indicators are not all-encompassing measures of environmental and economic performances; their integration with other methods can complement understanding and management capabilities. For instance, emergy analysis has been linked with LCA method in order to help track the entire production cost (Rugani and Benetto 2012; Ingwersen 2011). In another case, Huang and Hsu (2003) combined MFA and emergy analysis together to investigate Taipei area's urban sustainability due to urban construction. This indicates that further research efforts for evaluating industrial symbiosis by employing emergy approach should focus on linking with other methods so that more complete and evolutionary picture of industrial symbiosis can be presented. In general, emergy is the only method that relates resources used in product life cycles back to the process in the environment necessary to replace those resources, and hence, it is the best potential measure of the long-term environmental sustainability of production (Ingwersen 2011) and can better evaluate the overall performance of one industrial park.

Conclusion

Industrial symbiosis provides strategies to achieve greater efficiency through "economies of systems integration," whereby partnerships between businesses meet common service, transportation, and infrastructure needs (Geng and Doberstein 2008). Such a concept adds value to businesses and communities by optimizing the use of energy, materials, and community resources and increases industrial competitiveness. Therefore, it becomes a key component for EIP development. However, convincible evaluation methods on industrial symbiosis are still lacking, leading to a crucial need of proposing an innovative evaluation method.

This paper fills such a research gap by presenting an emergy analysis-based method. Through a case study at Shenyang Economic and Technological Development Zone, a typical industrial park with an effort toward EIPs, we find that emergy analysis is one effective and efficient method on evaluating the overall efficiency of industrial symbiosis within one industrial park. Main emergy-based indicators, such as nonrenewable inputs, imported resource inputs and associated services, can be saved by 89.3, 32.51, and 15.70 %, respectively, with the implementation of industrial symbiosis. Meanwhile, the ratio of emergy savings to emergy of the total energy used is about 25.58 %, and the ratio of the emdollar value of total emergy savings to the total GRP of SETDZ is 34.38 %, indicating both resource efficiency and economic benefits. In order to further improve industrial symbiosis, several efforts need to be initiated at SETDZ, including identifying more potential industrial symbiosis opportunities, optimizing energy structure, increasing industrial efficiency, recovering local ecosystems, and improving public and industrial awareness of EIP policies.

From academic point of view, comparing with other evaluation methods, emergy analysis can account for quantity and quality of different input flows and recognize the complexity of interactions between the natural environment and industrial systems, leading to the full understanding of the value that free environmental services and resources offer to the industrial park. Moreover, it can provide an eco-centric view of ecological and human activities, which can be used for evaluating and improving industrial symbiosis activities. For instance, most conventional evaluation methods, such as MFA and energy analysis, do not account for labor and service's contribution to the economic development. In LCA practice, labor is often not accounted for as an energy input. When accounted for as an input, labor is cumulatively added as working hours, without any quality distinction (Rugani et al. 2012). However, it does not contribute to the final assessment of impact categories (Ulgiati and Brown 2013). In this regard, emergy analysis accounts for both labor and services so that the value of labor and services can be quantified in emergy terms although developing wage databases is necessary for such an application. In addition, when the decisions need to be made regarding sustainability, such a method can keep track of interactions among system components across scales and identify environmental costs and savings of industrial symbiosis strategies. However, such a method should be integrated with other methods in order to provide a complete picture of industrial symbiosis, such as LCA and MFA.

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