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Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on emergy analysis

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Abstract: Industrial parks have played a key role in promoting economic development around the world. However, rapid industrial park development has resulted in many challenges, including resource depletion, environmental emissions and increasing pressure for industries to respond to climate change. Under such circumstance, a solution to optimize resource utilization and reduce environmental impact is needed. One effective approach is to adopt an eco-industrial development strategy that not only contributes to economic profit and resource conservation, but also to greenhouse gas (GHG) emissions mitigation and environmental service. Such integrated benefits are often termed as co-benefits. However, at present, how to account for such co-benefits at the scale of an eco-industrial park (EIP) is still at an early stage. Therefore, this study aims to evaluate the co- benefits resulting from eco-industrial development and demonstrate how an emergy accounting-based approach can be applied. A case study involving the Dalian Economic and Technological Development Zone (DETDZ) was completed to verify the applicability of this approach. The results indicate that co-benefits go far beyond simple direct economic benefits. The policy implications of such strategies and the application beyond industrial development such as urban symbiosis are discussed within the context of the DETDZ demonstrating how multiple objectives can be achieved.

Keywords: Eco-industrial development strategies； Co-benefits；Accounting；Emergy analysis；Industrial park

1. Introduction

In order to respond to the extensive resource consumption and environmental pollution related to current industrial activities, by- product valorization or an ecologically-based cyclic approach to waste management is promising. The concept of the EIP was advanced by Cote and Hall in 1995 [11], and was defined later by the USAPCSD [50]) as “a community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and the local habitat) leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community” (PCSD, 1996). The features of an EIP should include: integrating ecological capacity into planning decisions; maximizing the use of renewable energy; green buildings design; industrial tenants based in part on their compatibility for symbiosis with other tenants; business “webs” that involve producers and consumers, scavengers and decomposers; material redundancy within the structure of the system; water and wastewater infrastructure that recovers and reuses; and information management systems which facilitates networking [12,10,8,9].

Through more than a dozen years’ development, eco-industrial development strategies have been adopted within industrial parks around the world. Even though the standards of such EIPs are not uniform across the globe, many countries have been pursing their own EIPs pathway development. For instance, in 1994, the United States Environmental Protection Agency (USEPA) announced the availability of $300,000 for EIP design and development and in 1995 it funded the preparation of the fieldbook for the Development of EIPs. Since that time, more than 60 eco-industrial networking projects have been identified in both the US and Canada. In Europe, there are several EIPs in various countries; the industrial symbiosis network in Kalundborg, Denmark for example is likely the most cited EIP case studies in the world. In Asia, countries like Japan initiated eco-towns as part of a national program by the Ministry of Environment (MOE) and Ministry of Economy, Trade and Industry (METI) in 1997. The Korean government established a three-stage, 15-year plan to retrofit existing industrial complexes into EIPs [38]. EIPs are also developed in South America. For instance, in Brazil, research was completed involving the Paracambi EIP (located in the state of Rio de

Janeiro), to develop by-products and waste synergies between the various industrial typologies [15]. Australia has been among the world's highest waste producers, annually disposing of more than 800 kg per capita of industrial, consumer and domestic waste to landfill and incineration. To start to address this issue, in 1996 the Australian state government and a local council supported a private business proposal to develop Australia's first eco-industrial estate, Synergy Park, on a site 22 km west of Brisbane. The following year, the Australian Housing and Urban Research Institute (AHURI) started a research project in southeast Queensland to investigate the concept of industrial ecology and its application to achieve more sustainable forms of industrial estate development [41]. However, in large measure it seems that African countries there have been left behind compared to other continents. Some progress has been made in the past dozen years in more industrialized nations such as Egypt. Even though there are no eco-industrial parks that exist yet, it is worth mentioning two im- portant national projects that targeted the improvement of environ- mental performance on the scale of an industrial estate: the Environmentally Friendly New Industrial Cities Program (NICs) and the Integrated Industrial Solid Waste Management in Egypt project (IISWM) [42].

Within academia, research focusing on EIPs can be categorized as follows: basic theory of EIP [10,11,29–31], strategies for optimizing resource efficiency and by-product/waste exchange [1,37,59,53,20] and evaluations of development outcomes such as eco-efficiency studies, material flow analysis, overall efficiency, carbon emission, etc. [18,21,22,48,49,55]. Such research mostly focuses on the benefits that EIP strategies bring about, but most only focus one specific perspective or system. The question of the collective benefits that can be gained by the eco-industrial development strategies and the con- nection between the co-benefits and direct benefits should be raised.

Co-benefits, also called ancillary benefits, are used to describe multiple, equally important rationales that could be achieved by a single policy or measure [45]. The term “co-benefits” has received significant attention in climate change discourse worldwide. The Clean Air Initiative for Asian Cities (CAI-Asia) has defined the concept of “co- benefits” as the various benefits that can be provided by managing climate change and air pollution [4]. Co-benefits were heralded as an important bridging tool to environmental and development issues [7]. In recent years, co-benefits researches have developed rapidly from the field of renewable energy [43] specific industries like power, steel and cement industries etc. [33,57,58], transportation [14,35] to the specific area like province, country [19,13] and even globally [2,54]. However, we were unable to find out the reference regarding co-benefits acquirement achieved by eco-industrial strategies in the scale of an industrial park. Industrial parks have been adopted by many countries as one way to promote industrial development. So far, there have been over 20,000 industrial parks around the world [42]. Especially, in China, industrial parks play a key role in the industrial development for the entire nation. For instance, in year 2011, industrial parks at national level completed a gross domestic production (GDP) with a value of 47 million US dollars per square kilometer, 59.2 times higher than the national average level and 7.9 times higher than the average level of 36 major cities. The overall contribution of the various industrial parks to the national economy would amount to about 60% of the total [44]. However, rapid development of industrial parks also created some problems, such as resource depletion and environ- mental pollution, and very recently increasing pressure on responding climate change. In order to respond such a challenge, The Chinese Ministry of Environmental Protection (MEP, the former State Environmental Protection Administration) initiated EIP projects in 2001 [23]. To date, MEP has approved 108 EIP projects [28]. Therefore, the effect of their co-benefits associated with eco-industrial strategies' implementation should be identified.

In this regard, there was a paucity of scholars' literature that took a dual approach to eco-industrial park development and investigating co- benefits. This study strives to address this gap to show how is the connection between co-benefits accounting and the other direct benefits under the implementation of eco-industrial development strategies in the scale of industrial parks. According to Jiang et al. [19], different institutions and organizations have different under- standings, definitions and interpretations for the term "co-benefits". In this context, we define co-benefits as the achieving of climate change mitigation, whilst also addressing local environmental and resource depletion challenges through the implementation of eco-industrial development strategies. This study will use emergy-based analysis demonstrating how it can be applied to quantitatively account for co- benefits in the scale of an industrial park. The framework of this paper is organized as follows; Section 2 will detail the methodology, while the introduction of case study is presented in Section 3. The results and discussions on co-benefits accounting of the adoption of eco-industrial development strategies at the scale of industrial park – as well as the limitation and future research – are described in Section 4. Finally, some policy implications and conclusions are drawn in Section 5.

2. Methodology

2.1 Emergy analysis background on the research of eco-industrial parks

Emergy, specifically solar emergy, is "the available energy of one kind (usually solar emergy joules) used up directly and indirectly to generate a service or product" [36]. Therefore, solar emergy (seJ) is the common units for emergy analysis. The emergy concept was first proposed in the late 1980s, which deals with an integrated evaluation of ecological economic systems, and was successfully applied to various systems at various scales such as national level, regional level, coastal systems, forest systems, farm systems, and industrial systems [3,32,39,40]. In recent years, research emerged that explored how emergy analysis could be applied at the scale of industrial parks. In particular research looked at four aspects of this application: (a) the as evaluation of eco-efficiency and quantitatively identifying the impact factors associated with adopting eco-industrial development strategies [17,27,52,26,24]; (b) optimizing efficiency of EIPs [46,47,5]; (c) influence on energy use and carbon emissions [16,26,51]; and (d) the longer term sustainability of EIPs [23,56,6]. However, in regards to co- benefits accounting within EIPs, we were unable to find any reference within the body of literature. Therefore, this study aims to demonstrate how the emergy-based model can be used to address such gaps in scientific understanding. Emergy analysis takes into account the quality of each form of energy, multiplying each quantity of energy by its solar transformity. Solar transformity is defined as the solar emergy required to make 1 J (or 1 g) of a service or a product. Its units are solar emjoule per Joule (se J/J or se J/g)。

2.2 Co-benefits accounting

2.2.1 GHG emission mitigation

In most recent research, emergy can be applied to the case of GHG emission [16]. This established an embodied carbon accounting frame-work based on emergy to identify the input-output structure and embodied carbon emission flows of an industrial park. In this study, the carbon emissions intensity factors refer to solar emergy per embodied carbon emissions in an industrial park, describing the embodied carbon emission intensity. Therefore, the emergy value of GHG emission mitigation accounts for the carbon emissions mitigation value embodied in the materials or energy incorporated into the implementation of eco-industrial development strategies. The equation is as follows:

the price disparities multiplying transformity of labor and service:

$$G = M * E_{CO_{2-eq}} \tag{1}$$

where G is the emergy value of GHG emission mitigation within the scope of the industrial park operations resulting from the implementation of eco-industrial development strategies. M is the mass of saved materials; $E_{CO_{2-eq}}$ represents the carbon emissions intensity factor embodied in materials or energy imports of the industrial park; when the mass of saved materials multiplied corresponding carbon emissions intensity factor, it gives a measure of the emergy value of GHG emission mitigation that is involved.

2.2. Environmental service

In this study, we focused on air and water environmental service. Air environmental service refers to how much air should be needed to dilute the air pollutant emissions to an acceptable level. Zhang et al. (2011) developed the air pollutant environmental service equation as follows:

$$M_{air} = d_{air}\left(\frac{w_{air}}{c_{air}}\right) \tag{2}$$

where M_{air} is the mass of dilution air in kg; d_{air} is air density (1.29E+03 g/m^3); w_{air} is the annual amount of air pollutant emission from the production process in kg; c_{air} is the acceptable concentration from agreed standard released by the Ministry of Environmental Protection of the People's Republic China [34]. In this study, we only considered SO_2, NO_X and dust as our targeted air pollutants due to data limitation. The acceptable concentrations are 0.02 mg/m^3, 0.08 mg/m^3 and 0.005 mg/m^3 respectively. The annual average wind speed is 4.5 m/s in the study area according to the statistical material of Dalian. The wind transformity is 2.45E+03 seJ/J, the emergy value of the air environmental service (AES) that is required is as follows:

$$AES = \frac{1}{2} M_{air} * 4.5^2 * 2.45E + 03 \qquad (3)$$

Due to data limitation, we could not get the data from DETDZ regarding the water quality indicators like chemical oxygen demand (COD), biological oxygen demand (BOD) etc directly induced by eco- industrial development. Under such circumstance, water environmen- tal service refers to how much emergy is needed to remediate waste water to fresh water in our study. The equation is as follows:

$$WES = M_{water} * (T_{regenerate} - T_{fresh}) \qquad (4)$$

where WES is water environmental service emergy; M_{water} is the mass of regenerated water in g; T_{fresh} is the emergy transformity of fresh water (1.66E+05 seJ/g) (Buenfil, 2001); $T_{regenerate}$ is the emergy transformity of regenerated water (1.12E+06 seJ/g) [52]. When the mass of water is multiplied by the disparity of emergy transformity value between fresh water and regenerated water, it gives a measure of the water environmental service (WES) that is required, in units of emergy.

2.3. Direct benefit accounting-economic benefit and material formation benefit

The economic benefit can be gained from the price disparities between raw material price and price of material collected for reused and recycling. The emergy value of economic benefit is calculated by the price disparities multiplying transformity of labor and service:

$$E = P * 1.42E + 13 \qquad (5)$$

where E is the economic benefit brought by eco-industrial development strategies; P is the price disparities between raw material price and second-hand material price; and 1.42E+13 seJ/$ (UFL, 2008) is the transformity of labor and service.

Regarding the material formation benefit, in this study, we follow the emergy accounting procedure proposed by Geng et al. [17]. Particularly, we focus on waste reutilization induced by eco-industrial development strategies to evaluate the waste efficiency of an industrial park. The transformity of the reutilized waste were equal to the raw materials, no matter if it is one by-product or co-product. For instance, if the selected material is wood, the calculation method for waste reutilization is as follows:

$$Transformity_{wood} = Transformity_{reusedwood} \quad (6)$$

Therefore, the equation of material formation benefit is as follows:

$$R = MT \quad (7)$$

where R is the material formation benefit induced by the implementation of eco-industrial development strategies; M is the mass of the reutilized materials; and T is the transformity of the reutilized materials.

2.4. Data collection

Boundary confirmation of an industrial park is the first step.Usually, we take the administrative boundary of an industrial park,which means that there is always a planned area for the development of an industrial park. Therefore, the geographic boundary of this planned area is considered the boundary of an industrial park. In this study, we did a field survey with the administration office of DETDZ, where we held informal meetings with the stakeholders including local officers, investors and even local citizens to acquire the necessary information on DETDZ. Also, we investigated the main tenant companies, collecting data regarding raw material consumption, product yield, etc. In addition, we collected useful data from local annual statistical documents and other associated governmental materials. After compiling all the data, we hosted another workshop to further verify the accuracy of these data and to collect additional information that could not be obtained from official documents, with the great help of local administrative officials. Next, the relevant data were categorized such as information on renewable resources, non-renewable resources, the amount of imported materials, and the cost of labor and services. In the final step, an emergy system diagram of the whole system was drawn to demonstrate how material and energy flow in the system [25,27].

3. Case study

3.1. A brief introduction of DETDZ

Dalian Economic and Technological Development Zone (DETDZ) was the first approved national industrial park by the State Council of China and was established in 1984. DETDZ is located in the southeast part of Liaoning province in Northeast China (See Fig. 1), having many transportation advantages due to its close proximity to the Dalian port, the biggest port in the northeast region of China. According to national statistics, DETDZ ranks No. 7 among all the national industrial parks in terms of its GDP. It includes primary industrial clusters involving petro-chemical, manufacturing, and metallurgy and had a GDP of 24.013 billion USD in 2012. At the administrative level, the DETDZ provides essentially the same preferential policies, incentives, and flexible measures as other special economic zones in China. In terms of climate condition, the average annual rainfall in DETDZ is 550–950 mm and the total annual length of sunlight on this site is 2500–2800 h.

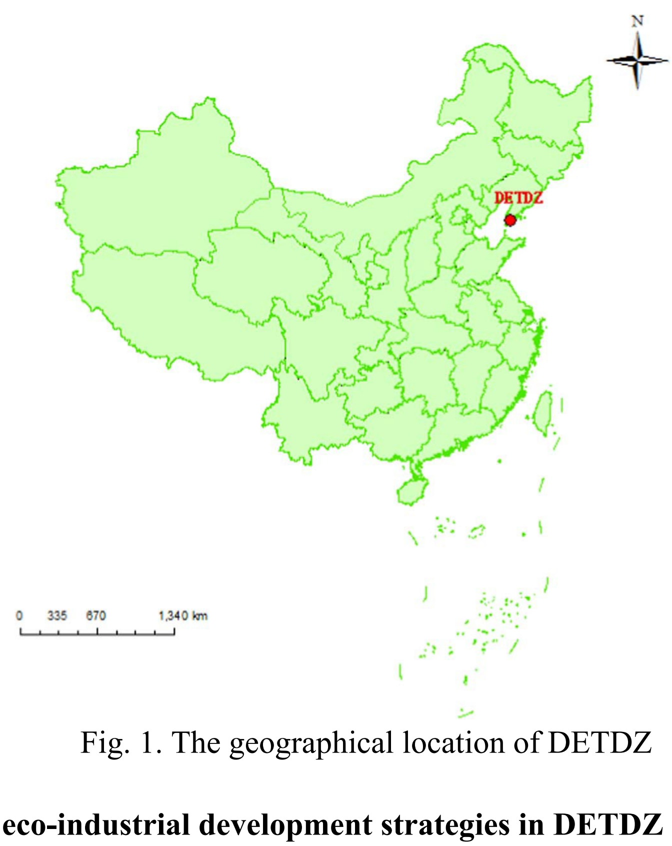

Fig. 1. The geographical location of DETDZ

3.2. Implementation of eco-industrial development strategies in DETDZ

Eco-industrial development strategies' implementation at DETDZ started in early 2000. The local government identified six strategies as follows:

1.Integrating the investment and developing circular economies together.

DETDZ altered the previous model for attracting the investment, which transitioned from only attracting general investment to selecting specific investment into the area. DETDZ considered high efficiency and low energy consumption industries as their investment priority. Also, DETDZ focused on establishing network for waste exchange among local industries. In doing so, the eco-industrial chains were created. Fig. 2 shows the emergy flow after the implement of eco- industrial development in DETDZ.

2.Optimizing industrial structure to promote the levels of sharing resources and energy

DETDZ implemented uniform management inside the area in the field of resource, energy, land use, solid waste as well as environ- mental protection to promote their utilization efficiency. For in- stance, from 2006 to 2010, energy yield ratio was improved by 65.5% while water yield increased by 99.1%.

3.Improving the basic infrastructure

DETDZ encouraged and supported the development of energy- saving industries. By doing so, DETDZ centralized processing for solid waste conduction, municipal waste water and water regeneration etc.

4.Carrying out national laws and regulations regarding circular economy development

In order to implement national laws and regulations regarding circular economy development, DETDZ established a foundation for supporting energy-saving and emission mitigation scientific projects as well as encouraging circular economy development in the key industries.

5.Implementing international cooperation

In order to learn the experience and advanced technology from other developed countries, DETDZ established international cooperation ties with the countries like Japan, USA, and Norway. Especially, DETDZ carried out an energy cooperation project with Norway to establish an "Energy Efficiency Center". Through this cooperation, DETDZ realized the demonstration and application in the field of public building energy- saving by combining the advanced technique from Norway with the local reality.

6.Carrying out energy saving activities and increasing the ratio of renewable resource

DETDZ carried out energy saving activities in key areas through

technological promotion and advancement. For instance, in construction field, DETDZ advocated energy saving buildings while improving efficiency for present buildings. In the field of transportation, DETDZ integrated renewable energy vehicles into park operations and planned to expand their application.

3.3. Impact of eco-industrial development strategies

During the five year plan from 2006 to 2011, the DETDZ made major advancements in the in the field of energy saving and emission mitigation through the implementation of eco-industrial development strategies. For instance, during that time, energy consumption per GDP decreased by 20.8% and water consumption per GDP decreased by 24.2%. The reutilization ratio of regenerated water to fresh water increased from 16% to 40%. The solid waste disposal increased from 81.8% to 98%. The comprehensive use of fly ash increased from 68% to 85% etc. In the regard of emission mitigation, total Chemical Oxygen Demand (COD) decreased by 51% between 2011 and 2012, while sulfur dioxide (SO_2) emission dropped by 41%. Table 1 shows the exact materials saving by the implementation of eco-industrial development strategies in DETDZ in 2006.

4. Results and discussions

4.1. Co-benefits

4.1.1. GHG emission mitigation

As previous mentioned, with the implementation of eco-industrial development strategies, DETDZ successfully reutilized a variety of resources within its system, offsetting the need for a considerable amount of raw materials. In addition, the GHG emissions associated with the production of raw materials were mitigated. Using Eq. (1), Table 2 presents the embodied carbon emission factors and GHG emission mitigation that had been transformed to the unit of solar emergy.

The results of GHG emission mitigation indicated that with the implementation of eco-industrial development strategies, the saved materials also contributed to GHG emission mitigation during the process from exploitation to manufacturing, which were previous ignored. Applying emergy analysis one can calculate the reduction in GHG emissions during the process with the unit of solar emergy. Results indicated that GHG mitigation caused by cement reutilization was the most remarkable (see Fig. 3).

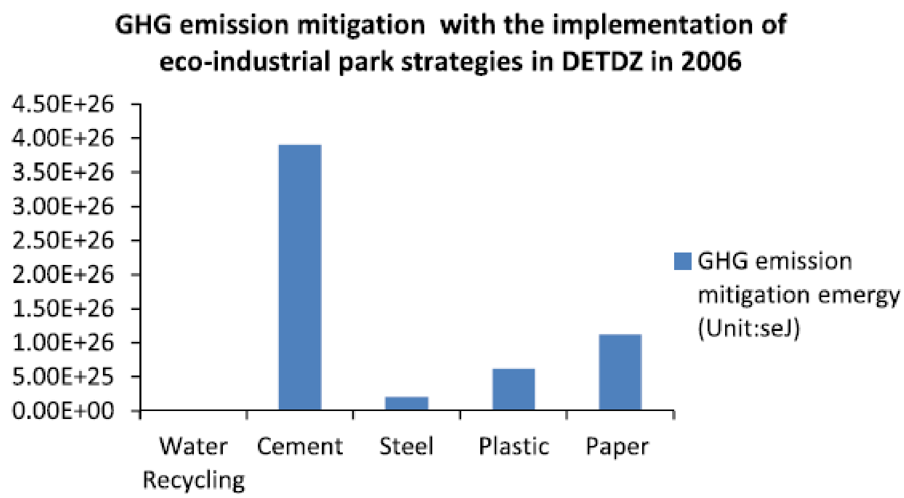

Fig. 3. GHG emission mitigation in DETDZ in 2006.

4.1.2 Environmental service

In the same way, we focus on calculating the environmental service contribution associated with the material saving resulting from the implementation of eco-industrial development strategies. The system of industrial activity, which develops industrial product from raw materials has been traditionally linked to environmental degradation due to the production of toxins and pollution and in turn; such outputs are linked to health damage in human beings. Eqs. (2)–(4) are used to analyze the emissions and the dust output during the industrial process. Emergy based analysis was applied to measure what emergy would be needed to dilute these toxic gases to the accepted level for the human body. In this regard, emergy value would reflect the environ- mental service contribution for diluting the toxic gases and even water to reduce the concentrations to non-harmful levels for environmental health. Through this approach, we can see the air environmental service benefit was greatest for cement generation in 2006 while air environmental service of dust was the most significant contribution compared with SO2 (see Fig. 4).

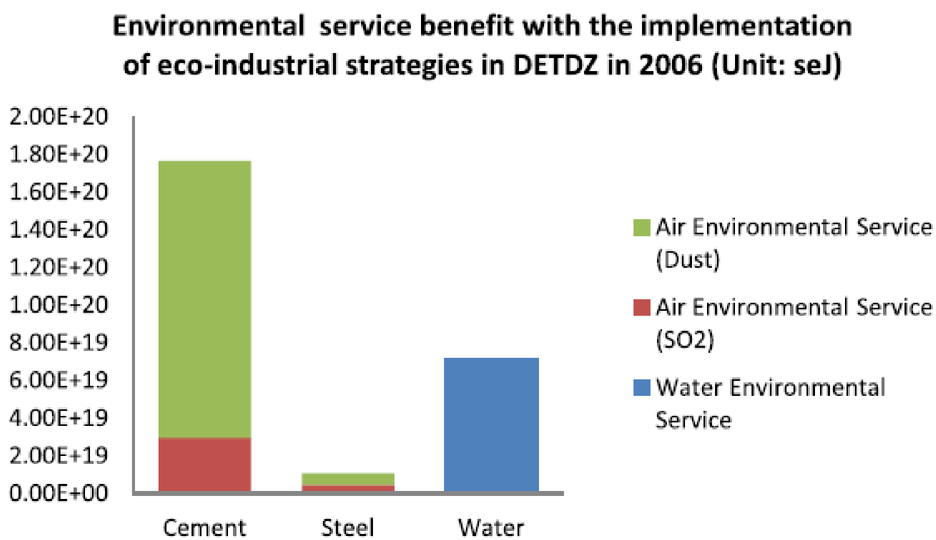

Fig. 4. Environmental service contribution in DETDZ in 2006.

4.2. Economic benefit

Eq. (5) was used to calculate the impact of water reutilization as well as paper and plastic. Fig. 5 presents the associated economic benefits resulting from the implementation of eco-industrial development strategies. Through the comprehensive re-utilization of byproducts, a lower price will be paid to purchase raw materials. Through proper manufacturing, the repurposed materials could be used as raw material, which would save considerable costs for the enterprises. The enterprises always prioritize economic benefit over any other benefits such as social benefit, environmental benefit, etc. These other benefits can be gained for society as a whole while enterprises benefit economically; however, from the whole picture of ecological system, the economic benefit was positioned the lowest among other benefits in this study.

4.3. Materials formation benefit

Eqs. 6 and 7 were used to calculate the material formation benefits linked to the implementation of eco-industrial development strategies (Table 3). For instance, plastics originate from the fossil oil materials; through exploration and manufacturing, such materials are transformed into the plastics used by society. However, before fossil oil materials are formed, it needs thousands of years from transforming the natural energy like sunshine, wind and rain etc to become the present fossil oil resource. Therefore, it should record the energy that from the natural system.

Table 3
Materials formation benefits in DETDZ in 2006.

Items	Amount (g)	Unit	Transformity (seJ/g)	Reference	Solar emergy (seJ)
Fresh water	7.50E+13	g/yr	1.66E+05	Buenfil, 2001	1.25E+19
Cement	4.13E+10	g/yr	1.97E+09	Brown and Bardi, 2001	8.14E+19
Metal	1.99E+10	g/yr	3.16E+09	Bargigli and Ulgiati, 2003	6.29E+19
Plastic	1.14E+10	g/yr	9.68E+09	Buranakarn, 1998	1.10E+20
Paper	1.71E+10	g/yr	6.55E+09	Brown and Arding, 1991	1.12E+20

The emergy-base analysis approach has the advantages of recording ecological contribution for materials formation. For instance, during the process of materials formation, it records the sun, wind, rain and tidal energy embodied in the formation of the materials. By multiplying the transformity, it reflects the embodied energy during the process of materials formation. From the results, it can be seen that in DETDZ in 2006, the solar emergy values of plastic and paper were bigger than metal and cement (see Fig. 6).

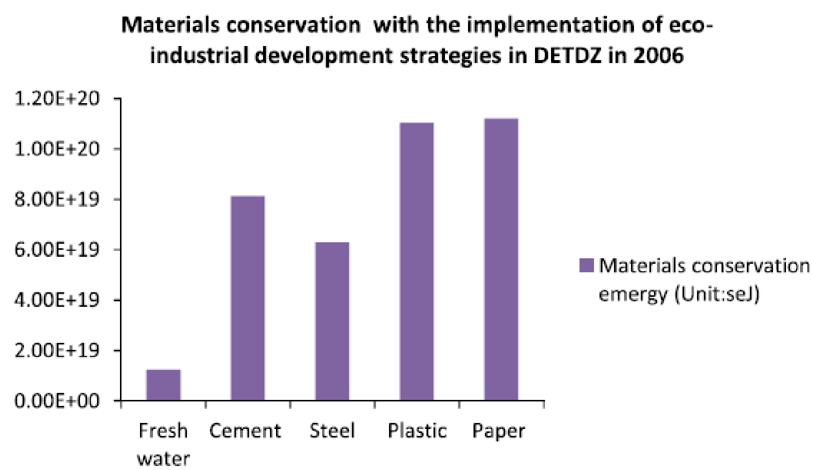

Fig. 6. Materials formation benefits in DETDZ in 2006.

As noted, we found that by applying eco-industrial development strategies, DETDZ reutilized the byproduct and saved raw materials during the industrial process, directly yielding an the economic benefit for the associated enterprises. However, we did find that compared with co-benefits, the economic benefit was much smaller. The advantage of emergy analysis is that it records the ecological contribution such that we can analyze the saved materials formation benefit. Through the analysis, it is noticeable that co-benefits and materials formation benefit were considerable; however, such co-benefits were typically ignored by the administrators of an industrial park (see Fig. 7).

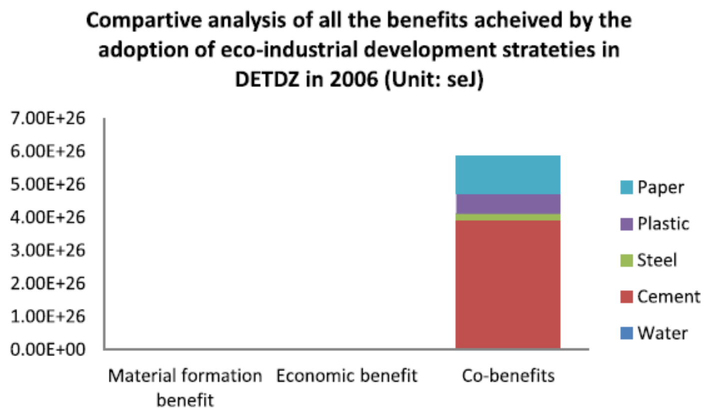

Fig. 7. Comparative analysis on the all benefits in DETDZ in 2006.

Through the study, we found that each material contributed differently to each corresponding benefits. For instance, the reduction in total cement used had a noticeable contribution to co-benefit and material formation benefit. However, it contributed the least to the economic benefit. Contrary to this, paper and plastic provided a considerable economic benefit, while water's formation benefit was the lowest among the other materials. Compared with GHG emission mitigation benefit, environmental service benefit, economic benefit and materials formation contribution were too small to register on Fig. 8. It would be valuable to identify the materials' benefit contribution for each sub-system so that policy maker could be informed that which materials would be the priority for reutilization so that the administrators could amend corresponding policies from a whole picture to foster the relevant industrial development.

4.4 Limitation and future research

This study focuses mainly on the co-benefits brought by the adopted the eco-industrial development strategies including GHG emission mitigation and environmental service. DETDZ was selected as our case study to verify our emergy-based analysis model. Through the comparative study at DETDZ, we found that co-benefits were typically higher than the direct benefit such as economic benefit. In this regard, this study not only investigated the co-benefits generated by the eco-industrial development strategies, but also uncovered other potential benefits value like economic benefit and materials formation value. However, this study still left some limitations. For instance, emergy-based analysis is of times critiqued for its preciseness in the scale of industrial park level. Secondly, acquiring data for industrial park operations is not always easy. This study only applied one year data of 2006 to validate this emergy-based model and lacked the ability to track trends.

In future research, improving the precision of emergy transformity at the scale of industrial park is a promising aspect. In addition, model improvements have much more potentials. Nonetheless, this study uncovered the different benefits brought by eco-industrial development strategies and enabled a comparison between traditional industrial systems and eco-industrial systems. This in and of itself is a breakthrough point. Policy makers can be informed which materials items should be eco-industrial developed according to their corresponding benefits so that the whole efficiency of system can be enhanced.

5.Policy implication and conclusion

Compared with similar industrial structure of industrial parks in northeastern regions in China, DETDZ is a pioneer in the field of energy saving. However, compared to other industrial parks in the developed regions like Tianjin, Guangzhou etc, it is a challenge for the DETDZ to meet similar levels of energy consumption to its nature as a heavy industrial based industrial park. For instance, in 2011, energy consumption per 10 thousand Chinese yuan GDP and water consumption per 10 thousand Chinese yuan GDP in DETDZ were lower than other regions like Northeast regions as well as lower than national average level. However, when compared to Tianjin Economic Development area (TEDA) and Guangzhou industrial park, energy consumption and water consumption for unit GDP generation were higher. The main reason of this was because the main industries in TEDA were electronic communication, vehicle equipment, medical industrial and food industry, while the industrial structure of Guangzhou industrial park was electronic communication, food industry and metal processing. Under such circum- stance, DETDZ should promote the eco-industrial efficiency of its industries. DETDZ should also take advantage of its transportation advantage to establish urban symbiosis network among the adjacent regions so that much more co-benefits can be realized in a bigger area.

This paper aims to uncover the co-benefits caused by the implementation eco-industrial development strategies in the scale of industrial park, not only limiting in co-benefits but also extending to other direct benefits. Therefore, this study also investigated the comparison between direct benefits and co-benefits. In this regard, this study established the model to measure the benefits from the whole system including economic system, environmental system (GHG emission mitigation and environmental pollution mitigation) as well as the ecological system (material formation). Emergy analysis has the advantage to merge the value of all the sub-systems. From this study, we can see that the economic benefit is the least benefit brought by eco-industrial development strategies. Although emergy analysis has its disadvantages, at least from this unified model, we can see all the benefits and their contrast relationship brought by eco-industrial development strategies. Eco-industrial development strategies have been adopted by many counties around the world. Many counties have claimed EIP projects in their own countries. However, there has been no agreed indicator system for an eco-industrial park around the world. Nevertheless, EIP pathway is the direction for the worldwide countries moving forward. In our modern commercial society, economic benefit is always dominated by the market rule, which plays a key role. However, behind the economic benefit, other co-benefits like environ- mental service, GHG emission mitigation as well as resource conservation also involve in the ecological contribution. This paper quantitatively interpreted how eco-industrial development strategies contribute to in these aspects in the scale of industrial park.

Eco-industrial development has been applied for about thirty years around the world. Its original goal is to reduce resource consumption during the industrial activity processes by simulating the natural world's material circulation. Through a dozen years' development, the benefits achieved by eco-industrial development strategies have been identified by academia. However, there are still many gaps that need to be filled in future study. For instance, given the current technological level, there is still lack of study regarding on the net benefits of waste materials recycling from a life cycle perspective especially including the natural energy input during materials formation. Therefore, in future research, a system or a database on waste material circulation benefits achieved by eco-industrial strategies should be established under current technological level. In addition, dynamic models of waste circulation benefit promotion with the technological improvements should be explored as well.

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