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RESEARCH ARTICLE

Emergy-based comparative analysis of energy intensity in different industrial systems

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Abstract With the rapid economic development, energy consumption of China has been the second place in the world next to the USA. Usually, measuring energy consumption intensity or efficiency applies heat unit which is joule per gross domestic production (GDP) or coal equivalent per GDP. However, this measuring approach is only oriented by the conversion coefficient of heat combustion which does not match the real value of the materials during their formation in the ecological system. This study applied emergy analysis to evaluate the energy consumption intensity to fill this gap. Emergy analysis is considered as a bridge between ecological system and economic system, which can evaluate the contribution of ecological products and services as well as the load placed on environmental systems. In this study, emergy indicator for performing energy consumption intensity of primary energy was proposed. Industrial production is assumed as the main contributor of energy consumption compared to primary and tertiary industries. Therefore, this study validated this method by investigating the two industrial case studies which were Dalian Economic Development Area (DEDA) and Fuzhou economic and technological area (FETA), to comparatively study on their energy consumption intensity between the different kinds of industrial systems and investigate the reasons behind the differences. The results show that primary energy consumption (PEC) of DEDA was much higher than that of FETA during 2006 to 2010 and its primary energy consumption ratio (PECR) to total emergy involvement had a dramatically decline from year 2006 to 2010. In the same time, nonrenewable energy of PEC in DEDA was also much higher than that in FETA. The reason was that industrial structure of DEDA was mainly formed by heavy industries like petro-chemistry industry, manufacturing industries, and high energy-intensive industries. However, FETA was formed by electronic business, food industry, and light industries. Although the GDP of DEDA was much higher than that of FETA, its energy intensity was higher as well. Through the 5-year development, energy consumption intensity in DEDA made a significant reduction from 3.90E+16 seJ/$ to 1.84E+16 seJ/$, which was attributed by the improvement of industrial structure, construction of eco-industrial park and circular economic industrial park. The proposed emergy indicator for demonstrating energy consumption intensity overcame the weakness that the indicator was only transformed from the heat burning. Therefore, this study shows an optional way to measure energy consumption intensity from the perspective of material ecological contribution.

Keywords Energy intensity · Emergy analysis · Industrial park · Primary energy

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Introduction

Energy is one of the most important physical bases for social and economic development in modern society, which has a major impact on the development of society and economy, as the production and consumption of energy are at the heart of economic development and social progress (Sun and Huang 2014). There are two kinds of energy which are renewable energy and nonrenewable energy. Renewable energy means natural energy including sunshine energy, wind energy, and rain energy. Nonrenewable energy includes the fossil fuels such as oil, natural gas, and coal. Almost 85 % of world consumption of energy is from nonrenewable energy resources (Odell 2004). Energy consumption especially nonrenewable energy in developing countries has risen rapidly as a result of economic growth in recent years (Deng et al. 2014). As the largest-developing country, China's energy consumption amounted to 1678 million tons coal equivalent (MTCE), making China the world's largest consumer next to the USA (Crompton and Wu 2005). Although China has achieved significant progress in economic development, China still relies on coal power for approximately 70–80 % of its energy consumption (Zhang et al. 2011) and this coal-based energy consumption structure can give rise to increasing serious environmental problems (Dong et al. 2013; Liu et al. 2014b). In order to respond this issue, Chinese government amended China's 11th Five-Year Plan, in which energy consumption per unit of gross domestic product (GDP) should reduce by 20 % between 2005 and 2010 (National Bureau of Statistics 2007).

The indicator for evaluating energy consumption intensity is always applied as coal equivalent per GDP. However, this indicator is oriented by conversion coefficient of heat burning not considering the ecological contribution and real value of resource materials during the process of formation in the world. Therefore, this study will fill the gap by demonstrating the indicator of emergy synthesis to perform energy consumption intensity combining economic system and ecological system. In order to validate this method, this study selected the scale of industrial parks as case study. As described by the United Nations Industrial Development Organization (UNIDO), an industrial park can be defined as a tract of land that is developed and subdivided into plots according to a comprehensive plan that makes provision for roads, transport, and public utilities for the use of a group of firms and industrial business oriented activities carried out in the park (UNIDO 1997). There are two main reasons to select the scale of industrial parks as case study. The first reason is that industrial park plays an important role in the economic development in China. In China, the central government planned and developed economic and technological zones as a way of industrial parks to stimulate economic development around the nation from the 1980s. Through nearly 30-year development, industrial parks in China has made a significant progress in the economic development. For instance, calculating economic contribution made by all levels' industrial parks, the percent of their economic yield value would reach over 60 % in national ratio (Shi and Wang 2010). The second reason is that industrial production is assumed as the main contributor of energy consumption compared to primary and tertiary industries. Although industrial park has achieved great success in economic domain, problems remain, such as intensive energy consumption as well as the concomitant effects of environmental pollution. Based on this, an appropriate indicator for evaluating energy consumption intensity would be needed. The framework of this paper is as follows: the background of emergy analysis would be introduced in "Methodology." Also, methodology of this study would be detailed in this part as well. The results and discussions would be performed in the section "Results and discussions." In the section "Conclusions and policy implications," there would be the conclusion of this study including critical analysis, including discussion of benefits, advantages and limitations of this method as well as political implications.

Methodology

Background of emergy synthesis approach

Emergy is the available energy of one kind (for instance solar energy) required directly and indirectly to make a product or service. Its unit is emjoule. When emergy is expressed as solar emergy, the units are solar emjoules (seJ) (Jorgensen et al. 2004). The theoretical and conceptual basis for the emergy methodology is grounded in thermodynamics and general systems ecology (Brown and Bardi 2001). Therefore, emergy analysis is concerned with quantifying the relationships between human-made systems and the biosphere. For instance, when this method is applied to a building, it quantifies all the natural resources used for building manufacturing, maintenance, and use. The emergy evaluation assigns a value to products and services by converting them into equivalents of one form of energy, solar energy, that is used as the common denominator through which different types of resources, either energy or matter, can be measured and compared to each other. In this sense, the unit for emergy is the solar emergy joule (seJ). The emergy of different products is assessed by multiplying mass quantities (kg) or energy quantities (J) by a transformation coefficient, namely transformity or specific emergy. Transformity is the solar emergy required, directly or indirectly, to make 1 J or kilogram of a product or service. Every time a process is evaluated, previously calculated transformities are used as a practical way of determining the emergy (seJ) of commonly used products or services (Pulselli et al. 2007).

Through nearly 30-year development, emergy indicators have been proposed for quantitatively evaluating ecological system, including which some original indicators such as renewable emergy ratio (RER), nonrenewable emergy ratio, emergy yield ratio (EYR), emergy load ratio (ELR), and emergy sustainability index (ESI) were proposed by Odum (1996), Ulgiati et al. (1995), and Brown and Ulgiati (1997)). In the following researchers, they proposed new emergy indicators subjective to the different targeted cases study in order to effectively perform ecological characterization of different objectives. For instance, a new emergy index for sustainable development (EISD) was proposed to demonstrate the sustainability for an urban ecological system (Lu et al. 2003). For eco-industrial system, the indicators of waste recycling rate (WRR), recycling benefit ratio (RBR) were applied to evaluate the waste efficiency(Geng et al. 2010). The index of circular indices, waste indices, buyer advantage, sustainability indices, etc. were proposed to measure the sustainability of policy scenarios for assessing the Chinese paper industry (Ren et al. 2010). Liu et al. (2014a) evaluated Shenyang Economic Technological Development Area to uncover the efficiencies among different industrial clusters by applying emergy analysis, etc. Besides these, in order to overcome the weakness by a single method, hybrid methods integrating emergy analysis with other methods were also studied by some researchers (Liu et al. 2015a; Liu et al. 2015b; Geng et al. 2013a; Wesley 2011). Based on the studies mentioned above, in order to explore an optional way for illustrating energy consumption intensity, this study aims to help fill this gap to show an optional way by proposing new emergy indicators to perform energy consumption intensity among different industrial systems.

Field survey and data collection

In order to get the original data for research work, field survey would be needed. Although much data are shared on the website in modern society, it is always very difficult to get the relevant data of industrial production for a kind of secrecy issue. Especially for the scale of industrial park, field survey is a necessary step. Nevertheless, the administrators are always reluctant to share the industrial data with us. In addition, in

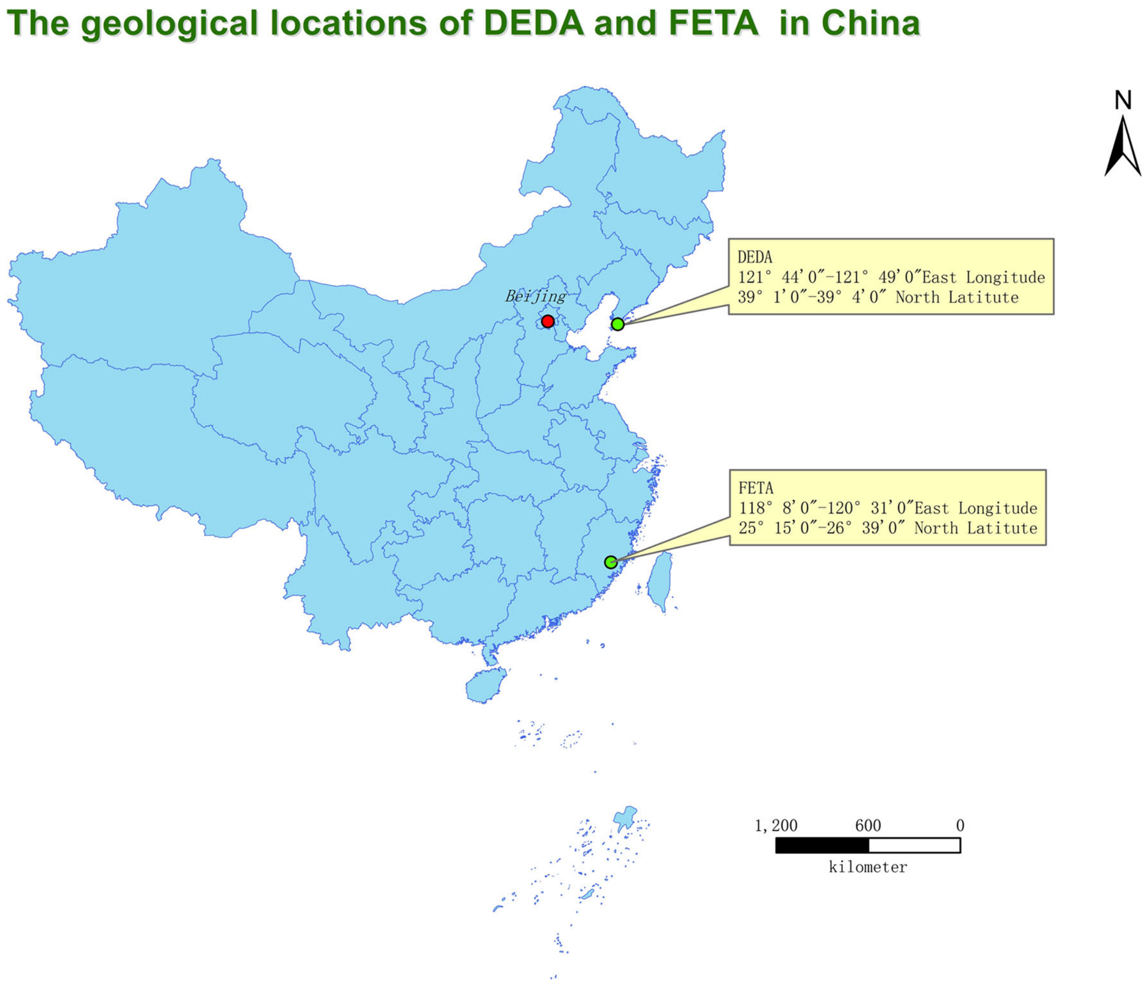

Fig. 1 The geological locations of DEDA and FETA in China

Table 1 Emergy calculating table of DEDA from year 2006 to 2010

Item	Amount					Unit	Transformity	Unit	Reference	Solar Emergy (seJ/year)				
	Year 2006	Year 2007	Year 2008	Year 2009	Year 2010					Year 2006	Year 2007	Year 2008	Year 2009	Year 2010
1.Renewable resource(R)														
Sunlight	5.44E+16	5.44E+16	5.44E+16	5.44E+16	5.44E+16	J/year	1.00E+00	seJ/J	By definition	5.44E+16	5.44E+16	5.44E+16	5.44E+16	5.44E+16
Wind (kinetic energy)	3.30E+14	3.30E+14	3.30E+14	3.30E+14	3.30E+14	J/year	2.51E+03	seJ/J	Odum et al. 2000	8.28E+17	8.28E+17	8.28E+17	8.28E+17	8.28E+17
Rain (chemical potential energy)	3.80E+13	3.80E+13	3.80E+13	3.80E+13	3.80E+13	J/year	3.50E+04	seJ/J	Odum et al. 2000	1.33E+18	1.33E+18	1.33E+18	1.33E+18	1.33E+18
Rain (geopotential energy)	6.25E+13	6.25E+13	6.25E+13	6.25E+13	6.25E+13	J/year	1.76E+04	seJ/J	Odum et al. 2000	1.10E+18	1.10E+18	1.10E+18	1.10E+18	1.10E+18
Waves	5.56E+14	5.56E+14	5.56E+14	5.56E+14	5.56E+14	J/year	5.12E+04	seJ/J	Odum et al. 2000	2.85E+19	2.85E+19	2.85E+19	2.85E+19	2.85E+19
Tidal	1.74E+15	1.74E+15	1.74E+15	1.74E+15	1.74E+15	J/year	2.82E+04	seJ/J	Odum et al. 2000	4.91E+19	4.91E+19	4.91E+19	4.91E+19	4.91E+19
Geothermal Heat	3.01E+13	3.01E+13	3.01E+13	3.01E+13	3.53E+13	J/year	5.80E+04	seJ/J	Odum et al. 2000	1.75E+18	1.75E+18	1.75E+18	1.75E+18	2.05E+18
2. Nonrenewable resource (N)														
Granite	8.73E+11	1.13E+12	1.41E+12	1.90E+12	9.71E+11	g/year	8.40E+08	seJ/g	Odum et al. 2000	7.33E+20	9.53E+20	1.18E+21	1.60E+21	8.17E+20
Shale	1.27E+11	1.65E+11	2.07E+11	2.79E+11	1.64E+11	g/year	1.68E+09	seJ/g	Odum et al. 2000	2.13E+20	2.77E+20	3.47E+20	4.69E+20	2.76E+20
Clay	1.79E+10	2.33E+10	2.92E+10	3.94E+10	2.01E+10	g/year	3.36E+09	seJ/g	Odum et al. 2000	6.01E+19	7.82E+19	9.80E+19	1.32E+20	6.75E+19
Quartz	8.43E+11	1.10E+12	1.38E+12	1.86E+12	9.45E+11	g/year	1.68E+09	seJ/g	Odum et al. 2000	1.42E+21	1.84E+21	2.31E+21	3.13E+21	1.59E+21
3.Imported source (F)														
Water	2.46E+13	2.48E+13	2.45E+13	2.92E+13	3.45E+13	g/year	1.66E+05	seJ/g	Buenfil 2001	4.08E+18	4.12E+18	4.07E+18	4.85E+18	5.73E+18
Coal	4.11E+17	4.02E+17	4.10E+17	4.11E+17	4.14E+17	J/year	2.88E+09	seJ/J	Brown et al. 2011	1.18E+27	1.16E+27	1.18E+27	1.18E+27	1.19E+27
Coke	2.50E+14	3.25E+14	3.90E+14	4.72E+14	3.61E+14	J/year	6.71E+04	seJ/J	Odum 1996	1.68E+19	2.18E+19	2.62E+19	3.17E+19	2.42E+19
Diesel fuel	5.39E+16	7.01E+16	5.97E+16	5.11E+16	5.82E+16	J/year	1.11E+05	seJ/J	Brown and Arding 1991	5.98E+21	7.78E+21	6.63E+21	5.67E+21	6.46E+21
Gasoline	1.49E+09	1.94E+09	2.40E+09	2.93E+09	3.20E+09	J/year	1.87E+05	seJ/J	Brown et al. 2011	2.79E+14	3.63E+14	4.49E+14	5.48E+14	5.98E+14
Crude oil	3.61E+17	3.47E+17	3.59E+17	3.77E+17	3.63E+17	J/year	6.53E+09	seJ/J	Brown et al. 2011	2.36E+27	2.27E+27	2.34E+27	2.46E+27	2.37E+27
Maize	1.69E+14	2.53E+10	2.30E+10	1.80E+10	1.87E+14	J/year	6.62E+05	seJ/J	Brandt-Williams 2002	1.12E+20	1.67E+16	1.52E+16	1.19E+16	1.24E+20
Bean	2.63E+14	2.94E+14	2.45E+14	2.43E+14	3.67E+14	J/year	3.66E+05	seJ/J	Brandt-Williams 2002	9.63E+19	1.08E+20	8.97E+19	8.89E+19	1.34E+20
Seafood	1.47E+15	1.85E+16	2.04E+16	2.06E+16	2.05E+15	J/year	8.51E+04	seJ/J	Geng et al. 2010	1.25E+20	1.57E+21	1.74E+21	1.75E+21	1.74E+20
Vegetable	3.20E+09	3.62E+10	3.20E+10	2.90E+10	5.40E+09	g/year	5.51E+05	seJ/g	Comar 2000	1.76E+15	1.99E+16	1.76E+16	1.60E+16	2.98E+15
Fruit	3.00E+11	2.49E+10	2.10E+10	1.78E+10	6.20E+11	J/year	8.51E+04	seJ/J	Geng et al. 2010	2.55E+16	2.12E+15	1.79E+15	1.51E+15	5.28E+16
Wood	1.27E+14	1.60E+15	1.30E+15	4.73E+14	3.48E+14	J/year	4.53E+04	seJ/J	Tilley 1999	5.75E+18	7.25E+19	5.89E+19	2.14E+19	1.58E+19
Cotton	2.96E+13	3.73E+14	3.88E+14	4.39E+14	3.45E+13	J/year	1.06E+06	seJ/J	Brandt-Williams 2002	3.14E+19	3.95E+20	4.11E+20	4.65E+20	3.66E+19
Wool	1.79E+12	2.26E+13	2.35E+13	2.66E+13	2.89E+12	J/year	7.39E+06	seJ/J	Odum et al. 2000	1.32E+19	1.67E+20	1.74E+20	1.97E+20	2.14E+19
Leather	2.07E+12	2.61E+13	2.71E+13	3.06E+13	3.80E+12	J/year	1.44E+07	seJ/J	Odum et al. 2000	2.98E+19	3.76E+20	3.90E+20	4.41E+20	5.47E+19
Steel	4.48E+08	8.96E+08	1.11E+09	1.35E+09	6.25E+08	g/year	3.16E+09	seJ/g	Bargigli and Ulgiati 2003	1.42E+18	2.83E+18	3.51E+18	4.27E+18	1.98E+18
Copper	1.62E+07	3.24E+07	4.01E+07	4.89E+07	3.42E+07	g/year	3.36E+09	seJ/g	Brown and Ulgiati 2004a, b	5.44E+16	1.09E+17	1.35E+17	1.64E+17	1.15E+17

Table 1 (continued)

Item	Amount					Unit	Transformity	Unit	Reference	Solar Emergy (seJ/year)				
	Year 2006	Year 2007	Year 2008	Year 2009	Year 2010					Year 2006	Year 2007	Year 2008	Year 2009	Year 2010
Aluminum	2.51E+06	5.02E+06	6.21E+06	7.58E+06	4.20E+06	g/year	1.44E+09	seJ/g	Odum 1996	3.61E+15	7.23E+15	8.94E+15	1.09E+16	6.05E+15
Plastic	1.54E+07	4.48E+08	5.54E+08	6.76E+08	4.32E+07	g/year	9.68E+09	seJ/g	Buranakarn 1998	1.49E+17	4.34E+18	5.36E+18	6.54E+18	4.18E+17
Ester	1.12E+10	3.26E+11	4.03E+11	4.92E+11	2.42E+10	g/year	5.51E+09	seJ/g	Buranakarn 1998	6.17E+19	1.80E+21	2.22E+21	2.71E+21	1.33E+20
Glass	1.16E+07	3.38E+08	4.18E+08	5.10E+08	3.46E+07	g/year	2.77E+07	seJ/g	Brown and Ulgiati 2002	3.21E+14	9.36E+15	1.16E+16	1.41E+16	9.58E+14
Paper	4.23E+10	1.23E+12	1.52E+12	1.85E+12	6.53E+10	g/year	6.55E+09	seJ/g	Brown and Arding 1991	2.77E+20	8.06E+21	9.96E+21	1.21E+22	4.28E+20
Electricity	6.12E+15	6.67E+15	7.99E+15	9.68E+15	8.12E+15	J/year	4.48E+05	seJ/J	Odum 1996	2.74E+21	2.99E+21	3.58E+21	4.34E+21	3.64E+21
4. Labor and service														
Labor	3.57E+08	3.75E+08	3.93E+08	4.31E+08	4.67E+08	$/year	1.42E+13	seJ/$	UFL (2008); Lou and Ulgiati 2013	5.07E+21	5.33E+21	5.58E+21	6.12E+21	6.63E+21
Service	5.30E+09	5.42E+09	5.66E+09	5.81E+09	5.90E+09	$/year	1.42E+13	seJ/$	UFL (2008); Lou and Ulgiati 2013	7.53E+22	7.70E+22	8.04E+22	8.25E+22	8.38E+22

order to guarantee the quality of acquired data, several data acquisition approaches are performed in parallel in order to validate the quality of data and information such as literature reviews, key-informant interviews, and informal meetings. In some circumstance, in order to further validate the collected data information, informal meetings with local stakeholders or some other kinds of actions are needed to validate the accuracy of the gathered information.

In this study, we investigated DEDA and FETA to hold face to face discussions with the administrators of the two different industrial parks in order to get the original research data. Besides this, visiting the local enterprises and reviewing some documents were carried out to validate the accuracy of the acquired data.

Data categorization and drawing emergy diagram

Data categorization is the following step after data collection. In order to satisfy the study of emergy analysis, relevant data should be classified by renewable resources (R), nonrenewable resources (N), the amount of imported materials (F), cost of labor and services (L&S), etc. Renewable resources refer to natural resources like sunlight energy, rain energy, wind energy, and even tidal or geothermal heat energy in the targeted area. Nonrenewable resources include materials which are needed much time to be transformed such as ore which involves in industrial production or soil erosion during the industrial process. Imported materials mean that the input from the outside to be part of raw materials for industrial production. Labor and service costs are always included in the calculation of emergy analysis.

An emergy system diagram of the whole system at this stage is necessary. Generally, an emergy diagram will include the sign of flows of input and output, system components, and interactions among components and final products. An emergy diagram are described as clockwise from left to right in order of their increasing transformity, which will help simplify the material and energy flows so that the existing hierarchy of components and flows in the picture can be seen easily understood.

Calculation of emergy indicators

In order to calculate the emergy indicators, transformities, and other emergy coefficient factors per unit values (UEV), which are the coefficients used to transform raw units, e.g., joules and grams, into solar energy are needed to be investigated. The transformities could be obtained by reviewing references and documents. In case of where suitable transformities are not available in the references or documents, they should be investigated and recalculated. The units of the UEVs are most often solar emjoules per joule (seJ/J) or solar emjoules per gram (seJ/g). After the transformities are confirmed, some

Table 2 Emergy calculating table of FETA from year 2006 to 2010

Item	Amount					Unit	Transformity	Unit	Reference	Solar Emergy (seJ/year)				
	Year 2006	Year 2007	Year 2008	Year 2009	Year 2010					Year 2006	Year 2007	Year 2008	Year 2009	Year 2010
1.Renewable resource (R)														
Sunlight	7.15E+17	7.15E+17	7.15E+17	7.15E+17	7.15E+17	J/year	1.00E+00	seJ/J	By definition	7.15E+17	7.15E+17	7.15E+17	7.15E+17	7.15E+17
Wind (kinetic energy)	2.78E+13	2.78E+13	2.78E+13	2.78E+13	2.78E+13	J/year	2.51E+03	seJ/J	Odum et al. 2000	6.99E+16	6.99E+16	6.99E+16	6.99E+16	6.99E+16
Rain (chemical potential energy)	1.00E+15	1.00E+15	1.00E+15	1.00E+15	1.00E+15	J/year	3.50E+04	seJ/J	Odum et al. 2000	1.47E+21	1.47E+21	1.47E+21	1.47E+21	1.47E+21
Rain (geopotential energy)	4.19E+16	4.19E+16	4.19E+16	4.19E+16	4.19E+16	J/year	1.76E+04	seJ/J	Odum et al. 2000	1.77E+19	1.77E+19	1.77E+19	1.77E+19	1.77E+19
Tidal	2.50E+17	2.50E+17	2.50E+17	2.50E+17	2.50E+17	J/year	2.82E+04	seJ/J	Odum et al. 2000	7.05E+21	7.05E+21	7.05E+21	7.05E+21	7.05E+21
Geothermal heat	3.95E+14	3.95E+14	3.95E+14	3.95E+14	3.95E+14	J/year	5.80E+04	seJ/J	Odum et al. 2000	2.29E+19	2.29E+19	2.29E+19	2.29E+19	2.29E+19
2.Nonrenewable resource (N)														
Granite	3.37E+11	3.37E+11	4.13E+11	6.76E+11	9.35E+11	g/year	8.40E+08	seJ/g	Odum et al. 2000	2.83E+20	2.83E+20	3.47E+20	5.67E+20	7.85E+20
3.Imported source (F)														
Water	3.70E+13	3.70E+13	3.95E+13	5.81E+13	6.27E+13	g/year	1.66E+05	seJ/g	Buenfil 2001	6.14E+18	6.14E+18	6.56E+18	9.64E+18	1.04E+19
Electricity	3.93E+10	3.93E+10	4.07E+10	3.73E+10	3.90E+10	J	4.48E+05	seJ/J	Odum 1996	1.76E+16	1.76E+16	1.82E+16	1.67E+16	1.75E+16
Natural gas					1.43E+02	M^3/year	1.78E+05	seJ/J	Brown et al. 2011	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.55E+07
Coal	1.46E+11	8.69E+10	5.60E+10	1.35E+10	5.48E+10	g/year	2.88E+09	seJ/J	Brown et al. 2011	4.20E+20	2.50E+20	1.61E+20	3.89E+19	1.58E+20
Oil	3.22E+14	3.98E+13	3.97E+13	5.10E+13	5.05E+13	J/year	6.53E+09	seJ/J	Brown et al. 2011	2.10E+24	2.60E+23	2.59E+23	3.33E+23	3.30E+23
Steel	3.25E+11	9.92E+11	6.23E+11	6.86E+11	8.00E+11	g/year	3.16E+09	seJ/g	Bargigli and Ulgiati 2003	1.03E+21	3.13E+21	1.97E+21	2.17E+21	2.53E+21
Aluminum	8.01E+10	1.02E+11	1.07E+11	1.35E+11	1.47E+11	g/year	1.44E+09	seJ/g	Odum 1996	1.15E+20	1.47E+20	1.54E+20	1.94E+20	2.12E+20
Plastic	7.14E+09	9.80E+09	1.09E+10	1.90E+10	2.32E+10	g/year	9.68E+09	seJ/g	Buranakarn 1998	6.91E+19	9.49E+19	1.06E+20	1.84E+20	2.25E+20
Glass	6.82E+11	3.18E+10	3.68E+11	4.61E+11	9.94E+11	g/year	2.77E+07	seJ/g	Brown and Ulgiati 2001	1.89E+19	8.81E+17	1.02E+19	1.28E+19	2.75E+19
Patrol	3.71E+10	2.01E+09	2.58E+09	6.87E+09	2.58E+09	g/year	9.07E+04	seJ/J	Odum 1996	3.36E+15	1.82E+14	2.34E+14	6.23E+14	2.34E+14
Chemicals	1.51E+09	1.60E+09	1.82E+09	1.71E+09	1.37E+09	g/year	6.38E+08	seJ/g	Odum 1996	9.63E+17	1.02E+18	1.16E+18	1.09E+18	8.74E+17
Wood	5.87E+11	5.74E+10	5.52E+10	1.08E+11	3.86E+12	g/year	1.68E+08	seJ/g	Brown and Arding 1991	9.86E+19	9.64E+18	9.27E+18	1.81E+19	6.48E+20
Fruit	1.19E+10	1.19E+10	1.24E+10	1.29E+10	1.40E+10	g/year	4.82E+05	seJ/J	Ulgiati et al. 1993	5.74E+15	5.74E+15	5.98E+15	6.22E+15	6.75E+15
Rice	1.28E+10	1.29E+10	5.98E+09	5.83E+09	4.67E+09	g/year	8.51E+04	seJ/g	Geng et al. 2010	1.09E+15	1.10E+15	5.09E+14	4.96E+14	3.97E+14
Honey	4.02E+08	4.03E+08	7.03E+08	2.16E+09	2.52E+09	g/year	1.43E+05	seJ/J	Ulgiati et al. 1993	5.75E+13	5.76E+13	1.01E+14	3.09E+14	3.60E+14
Meat	5.52E+09	5.70E+09	4.01E+09	4.00E+09	4.16E+09	g/year	5.11E+05	seJ/J	Calculated from Andresen et al. 1999	2.82E+15	2.91E+15	2.05E+15	2.04E+15	2.13E+15
Eggs	7.61E+09	8.16E+09	5.84E+09	5.94E+09	6.05E+09	g/year	8.97E+05	seJ/J	Calculated from Brandt-Williams 2002	6.83E+15	7.32E+15	5.24E+15	5.33E+15	5.43E+15
Floor	1.09E+08	5.80E+07	9.38E+07	2.54E+08	4.27E+08	g/year	8.51E+04	seJ/J	Geng et al. 2010	9.28E+12	4.94E+12	7.98E+12	2.16E+13	3.63E+13
Bean	9.65E+08	1.17E+09	1.38E+09	2.61E+09	3.23E+09	g/year	1.14E+05	seJ/J	Brown and Arding 1991	1.10E+14	1.33E+14	1.57E+14	2.98E+14	3.68E+14
Milk	2.57E+09	2.75E+09	2.93E+09	2.75E+09	2.68E+09	g/year	6.81E+05	seJ/J	Calculated from Brandt-Williams 2002	1.75E+15	1.87E+15	2.00E+15	1.87E+15	1.83E+15
Poultry	1.84E+09	1.94E+09	1.14E+09	1.17E+09	1.21E+09	g/year	1.33E+06	seJ/J	de Boer and Smit 2001	2.45E+15	2.58E+15	1.52E+15	1.56E+15	1.61E+15
Cement	2.35E+11	1.17E+11	1.34E+11	1.51E+11	2.51E+11	g/year	1.97E+09	seJ/g	Brown et al. 2000	4.63E+20	2.30E+20	2.64E+20	2.97E+20	4.94E+20

Table 2 (continued)

Item	Amount					Unit	Transformity	Unit	Reference	Solar Emergy (seJ/year)				
	Year 2006	Year 2007	Year 2008	Year 2009	Year 2010					Year 2006	Year 2007	Year 2008	Year 2009	Year 2010
Paper		2.93E+10	5.56E+10	6.88E+10	1.09E+11	g/year	6.55E+09	seJ/g	Brown and Arding 1991	0.00E+00	1.92E+20	3.64E+20	4.51E+20	7.14E+20
4. Labor and service														
Labor	3.39E+08	4.55E+08	9.35E+08	7.12E+08	6.20E+08	$/year	1.42E+13/7.0E+12	seJ/$	UFL (2008); Lou and Ulgiati 2013	1.66E+21	2.23E+21	4.58E+21	3.49E+21	3.04E+21
Service	7.71E+06	6.59E+06	6.56E+06	9.20E+06	1.01E+07	$/year	1.42E+13/7.0E+12	seJ/$	UFL (2008); Lou and Ulgiati 2013	3.78E+19	3.23E+19	3.22E+19	4.51E+19	4.97E+19

structural emergy indicators could be calculated such as R, N, F, L&S, and total emergy used and exploited by the process U (U=R+N+F+L&S).

In this study, in order to avoid double counting, we only calculate the primary energy consumption in our cases study. In this regard, primary energy emergy indicator (P) would be investigated, which refers to petrol emergy, coal emergy, and other primary energy emergy consumed during the industrial process. The equation could be performed as follows:

$$P = E_r + E_n \tag{1}$$

In the Eq. 1, P is the total primary energy emergy consumption. E_r represents renewable primary energy emery consumption, which refers to sunlight, tidal, and geothermal emergy. While E_n is the nonrenewable primary energy emergy consumption like petrol emergy, coal emergy, and natural gas emergy.

$$PECR = \frac{P}{U} \tag{2}$$

In the Eq. 2, primary energy emergy consumption ratio (PECR) means the energy ratio in an industrial system.

$$NER = \frac{N}{P} \tag{3}$$

In the Eq. 3, nonrenewable energy ratio (NER) is the ratio of nonrenewable primary energy emergy consumption ratio in the total primary energy consumption emergy, which could be an indicator for demonstrating energy structure in an industrial system.

$$E = \frac{P}{GDP} \tag{4}$$

In the Eq. 4, E is primary energy consumption intensity of an industrial system. The indicator E, which indicates how much primary energy emergy consumed by generating unit GDP in an industrial system, reflects the energy consumption intensity. The bigger the E, the lower efficiency of primary energy consumption is in an industrial system.

Results and discussions

Case study of DEDA and FETA

DEDA is the first industrial park at national level approved by the State Council of China. It is located in the southeast part of Liaoning province, which is of the continental monsoon climate of warm temperate zone (see Fig. 1). The average rainfall in DEDA region is 550–950 mm per year, and the total length of sunlight on this site is 2500–2800 h. DEDA has many advantages over the transportation condition for it is the

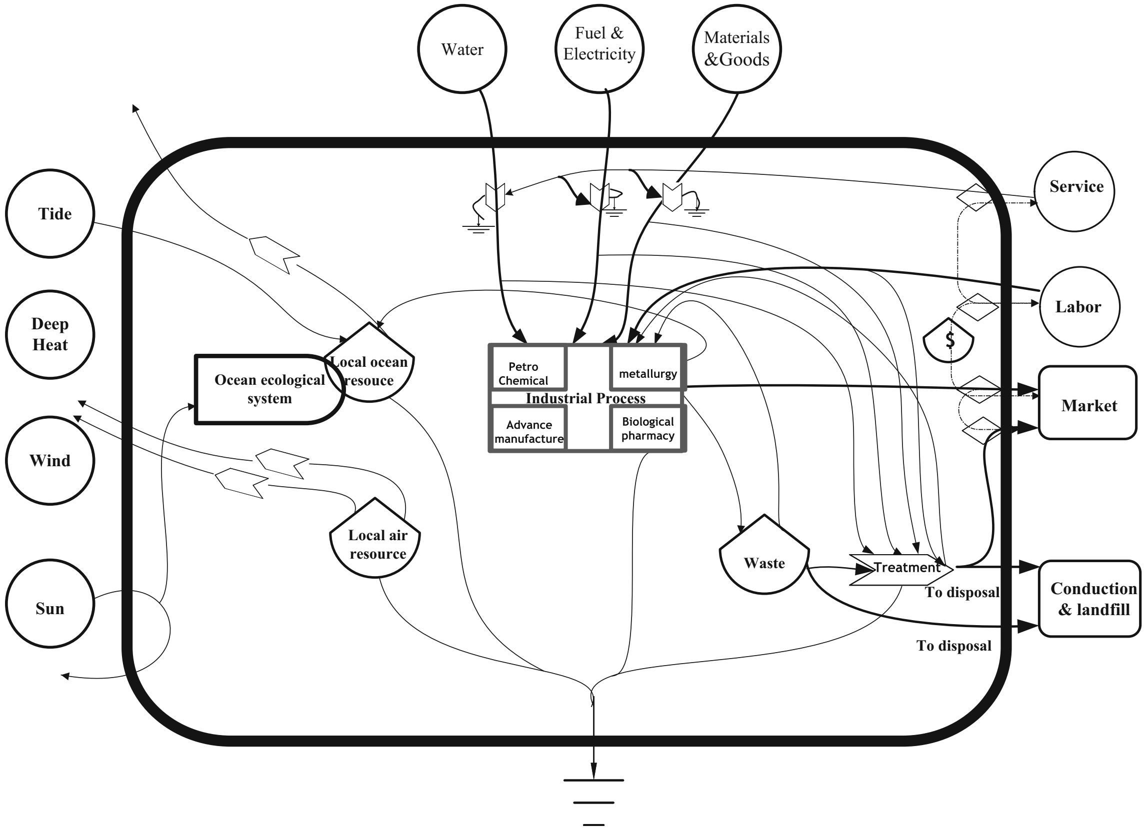

Fig. 2 Diagram of emergy flow in DEDA

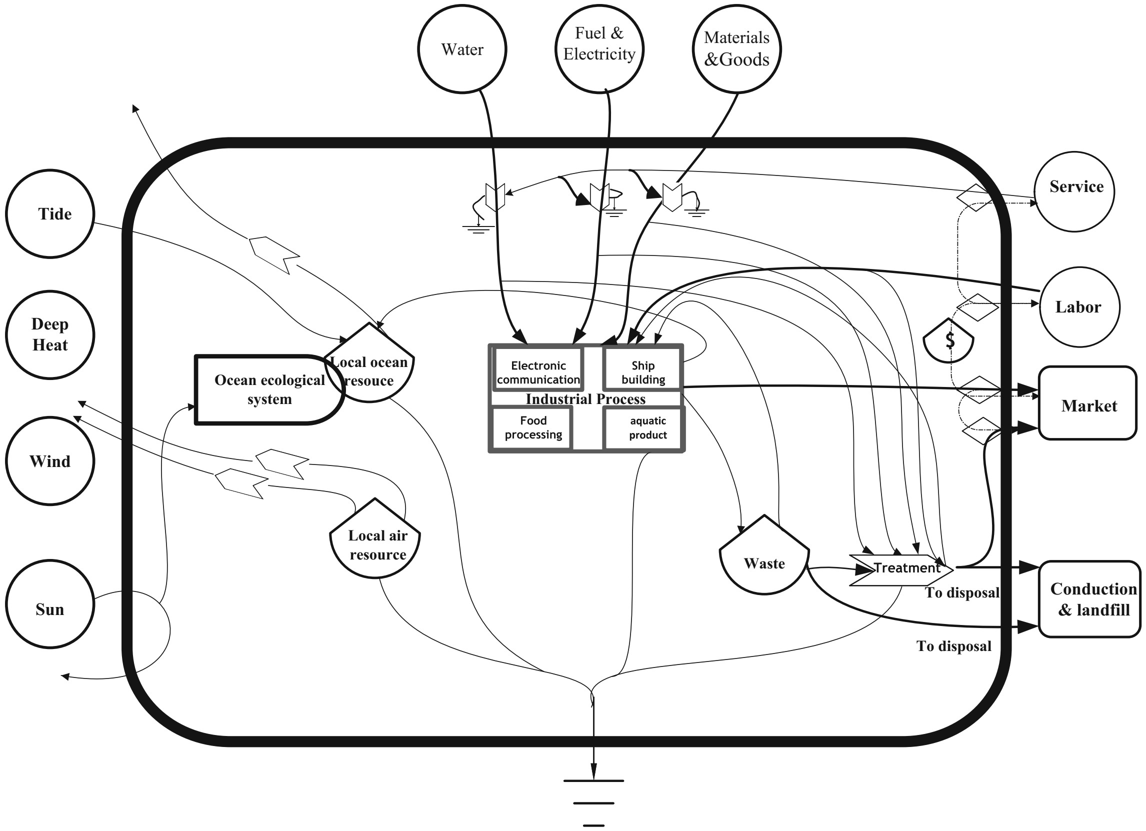

Fig. 3 Diagram of emergy flow in FETA

Table 3 The primary energy of DEDA and FETA (unit: seJ)

Year	2006	2007	2008	2009	2010
FETA	2.10E+24	2.60E+23	2.59E+23	3.33E+23	3.30E+23
DEDA	3.54E+27	3.42E+27	3.53E+27	3.65E+27	3.56E+27

Table 5 GDP of DEDA and FETA (unit: $)

Year	2006	2007	2008	2009	2010
FETA	2.12E+10	2.71E+10	3.19E+10	3.67E+10	4.19E+10
DEDA	9.07E+10	1.13E+11	1.34E+11	1.62E+11	1.94E+11

biggest port in the northeast region of China. The comprehensive assessment shows that DEDA ranks the seventh among the industrial parks at national level in China. There are six main industrial clusters in DEDA including petrol chemical industrial cluster, manufacturing industrial cluster, and metallurgy industrial cluster. Also, there are 75 companies in the top world 500 who set up business in DEDA like LG of Korea and Intel and Volkswagen of Germany. DEDA functions in a similar manner as a small municipality that is divided between three main areas—industrial, commercial, and residential—with some limited agricultural activities within its boundaries. In addition, a green corridor has been planned as a buffer zone within its boundary in order to improve the local ecological niche (Geng et al. 2010). In the development of circular economic perspective, DEDA has made a significant progress in the past 10 years. In 2004, DEDA was approved as industrial park of circular economy by the National Development and Reform Commission. The system has been established for saving energy consumption. The energy consumption and CO_2 emission per GDP in DEDA have been greatly reduced. In order to show the determination, almost 100 industrial plants have been closed because of economic inefficiency and environmental degradation (Geng et al. 2009a, b). The broad environmental goals and supportive administration of this municipality made it an especially attractive case study location.

FETA was established in the January of 1985 approved by the State Council of China, which is one of the 14 first batch industrial parks at national level. It is located in the southeast ocean region. The average rainfall of FETA region is 1382 mm per year. FETA occupied the area of 184 km^2, the population of which is 164,000. The advantage of transportation is evident for that it locates in the door of way to the world in the sea, which is 420 nautical miles to Hong Kong, 472 nautical miles to Shanghai, 200 nautical miles to Xiamen, respectively (see Fig. 1). Through nearly 30-year development, FETA has formed several main industrial clusters like electronic business, food industry, aquatic product, and shipbuilding. In 2010, the GDP of FETA was 3.74 billion US dollars. In recent years, with the development of circular economy carried out in the area, some environment-friendly projects have been implemented. For instance, the reutilization of waste oil and waste solid has been initiated by Zhong aluminum company. The technology of raw material saving energy of Shenghua company has been listed as the typical project of circular economy. FETA also promoted the capability of attracting the enterprises of cleaner production to strengthen the capability of saving energy and reducing emission. So far, the area has been approved as the national ecotown in China. Additionally, FETA also carried out the promotion of industries in the area to improve the industrial structure and develop green industries. At the same time, improving the traditional industries was another target. For instance, FETA developed high-tech industries like electronic industry, new material, and biological medical to increase the competitive capability in the market. The famous company like Xindalu, Huaying, and Guanlin were the leading examples.

Table 4 The total emergy (U) of DEDA and FETA (unit: seJ)

Year	2006	2007	2008	2009	2010
FETA	2.12E+24	2.75E+23	2.76E+23	3.49E+23	3.47E+23
DEDA	3.54E+27	3.42E+27	3.53E+27	3.65E+27	3.56E+27

The reason that this study selected these two industrial parks as case study can be summarized as follows: first, the targeted two industrial parks are two types of industrial parks. DEDA is an industrial park with heavy industries while FETA was formed mainly by light industries. From the case study, the characteristic of the two kinds of energy utilization trace could be clearly compared during the target period. Second, both of the two industrial parks are all along the ocean. However, one is located in the south and the other is located in the north. The different climate and regional characteristic and even national strategy attributed to different industrial structures and patterns. The reasons behind these should be highlighted.

Results and discussions

Statistical data from the year 2006 to 2010 including materials data, energy data, and even natural resource data of the two

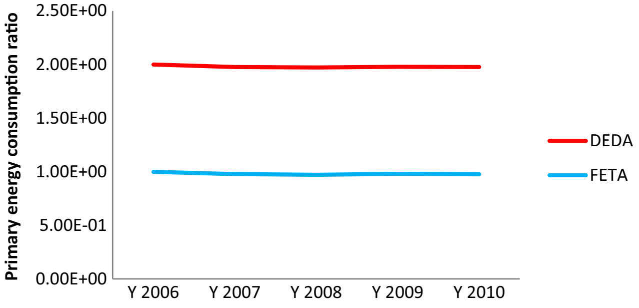

Fig. 4 Comparative analysis on the PECR of DEDA and FETA from 2006 to 2010

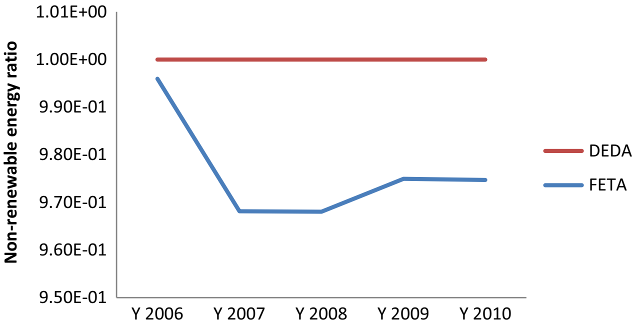

Fig. 5 The ratio of nonrenewable energy to PEE between DEDA and FETA

industrial parks were obtained through field survey, informal interviews, and reference reviews. After data collection and classification, we transformed these data to solar emergy by corresponding transformities (see Tables 1 and 2). In this paper, we refer to the new biosphere baseline, which means that emergy values calculated prior to that year are multiplied by 1.68 (the ratio of 15.83/9.44). Values of transformities are available in the scientific literature on emergy. By applying emergy analysis methods, the emergy diagrams of DEDA and FETA have been drawn (see Figs. 2 and 3) and then making calculation (see Tables 3, 4, and 5). At last, the values of the emergy indicators were determined (see Figs. 4, 5, and 6) by Eqs. 1–4.

From Tables 3 and 4 and Fig. 4, it can be seen that energy consumption of DEDA increased substantially and was much higher than that of FETA. The reason can be concluded as the two aspects: one is the economic scale and the other is the industrial structure. The economic scale of DEDA was much bigger than that of FETA. By the end of 2010, the GDP of DEDA was about 1.94E+11 $ while FETA was only 4.19E+10, nearly three times, which resulted in PEC and U of DEDA much higher than those in FETA. However, due to the industrial structure of DEDA, its energy consumption was even much higher than that of FETA. DEDA as an important port of northeast area of China was set as the heavy industrial base by the national strategy. Its main heavy industries like petrochemical industry, heavy manufacturing, and metallurgical industry played a dominant role in the area. Compared to other national industrial parks with similar economic scale like Beijing industrial park, Tianjin industrial park, the energy consumption intensity of DEDA was even much higher. For instance, in 2011, energy consumption intensity of DEDA was 0.69 t coal/GDP while Beijing industrial park and Tianjin industrial park were 0.157 and 0.154, respectively. The emergy indicator PECR also validated that DEDA was an industrial park with intensity energy consumption because the ratio of energy consumption accounted for higher ratio in the total emergy consumption during the process of industrial production. From Fig. 5, it can be seen that nonrenewable energy consumption took the dominant role in energy consumption in DEDA while FETA was in a better situation. The reason is that FETA was formed by the main industrial clusters like electronic and communication industrial cluster, food production industrial cluster, and even feedstock production industrial cluster light industrial layout, most of which are relatively low energy consumption industries.

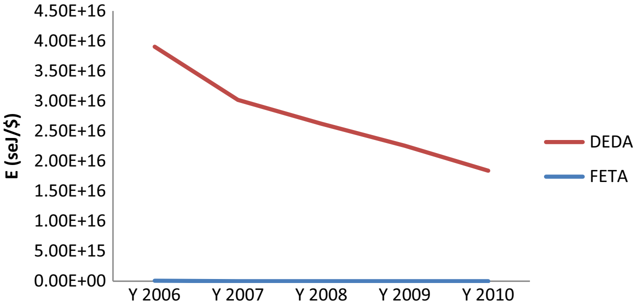

Fig. 6 Comparative analysis on the energy intensity between DEDA and FETA from year 2006 to 2010

From the Fig. 6, the results show that energy consumption intensity in the both two industrial parks had a decline trend. However, the energy consumption intensity in DEDA declined much bigger than that of FETA, which indicated that DEDA made a greater progress than FETA did in promoting energy efficiency during 2006 to 2010. Although DEDA consumed much more primary energy emergy than that in FETA, it made much achievement in saving primary energy consumption due to much effort done by DEDA to take the path of environmental-friendly way to develop economic development. During the period from year 2006 to 2010, DEDA government implemented local policies regarding ecological and environmental protection to save energy consumption and promoted the circulation level of waste resource such as “circular economic promotion regulation in Dalian city” and “ecological management in Dalian city”. Also, DEDA amended several local polices to improve the situation of energy consumption like namely “environmentally saving energy,” “promotion of scientific enterprises,” and “industrial development preferential treatment”. In order to save energy, DEDA planned the transition and promotion of industrial layout. The enterprises inside DEDA carried out the projects of technological energy-saving like dismantling of the boiler that is low efficient, developed energy-saving construction, implemented renewable energy vehicles, and input liquefied natural gas projects. Through measures taken mentioned above, DEDA had made much progress in saving energy consumption, while realized fast economic development. This is the reason that DEDA achieved high GDP growth at the same time promoting energy utilization efficiency.

Conclusion s and policy implications

This study firstly applied emergy indicator to demonstrate energy consumption intensity other than the traditional way.

Compared to traditional coal-equivalent indicator for performing energy consumption intensity, emergy analysis more concerned on the value of ecological contribution in the process of forming materials in the ecological system. Oppositely, traditional coal-equivalent indicator more demonstrates its utilization value. In other words, it reflects the utilization effect. The two different indicators have their own perspective and advantages. This paper shows an optional way to express energy consumption intensity from the perspective of ecological contribution embodying in the materials. Furthermore, case study was also investigated to verify the validity of this method. In this study, industrial park scale systems were selected as our cases study. The reason is that industrial park had a tremendous contribution for the national economic development. The production efficiency of industrial parks may also serve as an example for other types of industrial organizations. Hence, effective demonstration for industrial park may be a leading way for other industrial organizations in China.

Nevertheless, coal-equivalent indicator for performing energy consumption intensity has been applied for a long-time in statistical analysis and has its advantages. Energy is an important source for a country especially like China, which is a country consuming a large amount of energy for supporting its economic development. In recent years, China facilitated its pace to take a pathway of developing high efficient energy utilization so that it could keep the promise to realize its carbon emission target. Thus, an effective method for demonstrating energy consumption intensity or energy utilization efficiency is needed to validate its progress in the field of saving energy.

In China, there is much potential to develop the industries oriented to renewable primary energy, which could be a breakpoint for future development. In the field of renewable energy utilization, China is much less behind the developed countries. For instance, the nuclear power in France takes around 80 % power generation, while the figure is only less than 4 % in China. In west region of China, there is amount of wind resource that could be utilized (Geng et al. 2013b) as well as geothermal energy and nuclear energy.

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