Study on the construction of ecological network of a heavy chemical industry park based on industrial metabolism analysis: A case study of an energy heavy chemical industry

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Study on the construction of ecological network of a heavy chemical industry park based on industrial metabolism analysis: A case study of an energy heavy chemical industry

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Abstract. The industry characteristics of high pollution and high emission of energy heavy chemical industry pose a potential threat to the regional environmental safety. Therefore, it is very important to develop circular economy and carry out ecological transformation to achieve the pollution reduction and control. Based on the industrial metabolic theory and method, taking Energy Heavy Chemical Industry Park in Jinjie of Yulin City as the research object, this paper establishes the development mode of circular economy by constructing ecological chain network and conducted a comparative evaluation in lateral and vertical latitude using the method of energy analysis. The results showed that the energy yield in the cycle development phase (2015 ~) increases by 51.4% and 26.4% respectively in comparison with the first phase (2008-2015) and the initial development phase (2002-2008). The energy investment rate decreased by 4% and 1.3% respectively; the environmental load rate decreased by 9% and 3.7% respectively and the sustainable energy index increased by 64.6% and 29.2% respectively. It demonstrated that the production efficiency, ecological efficiency, competitiveness and capacity for sustainable development have been significantly improved. In terms of horizontal comparison, the energy investment rate in the cycle of development (2015 ~) was lower than the average of five provinces in northwestern China by 22%; the environmental load rate was higher than the average of five provinces in northwest China by 0.01%. This indicates that the performance of the system is higher; but the environmental load rate is somewhat high within the acceptable range. It indicates that the environmental pressure in industrial parks is larger and the system ecological efficiency needs to be further improved.

1. Introduction
Industrial Metabolism Analysis [1] (IM) is an effective analysis method in ecological industry to know the Element Metabolism and material flow based on law of conservation of mass. Through material balance sheet, the number of material flow and storage is estimated to describe the moving route and dynamic mechanism, and also indicates the physical and chemical state to reflect the industrial activity of the material [2].

IM, a very important outcome of Industrial Ecology, is a systematic analysis based on simulating the metabolism of natural beings. Similar to the natural ecological system, Industrial Ecology System also includes four basic parts, namely producers, consumers, recycler and external environment. Metabolic mechanism and Cybernetics Methodology of Industrial Ecology System is studied through analyzing the change of system structure, function simulation and analysis of industrial flow [3].

In the mid 1980s, Ayres et al [4] made a pioneering research on the effects of material and energy
flow on the environment in the economic operation, and put forward the concept of industrial metabolism according to the metabolism in the biological field. As an important part of Industrial Metabolism, analysis of material and energy metabolism develops together with the advancement of Industrial Metabolism.

At present, studies on metabolism of energy and materials mainly focuses on two aspects: one is the independent application of Industrial Metabolism Analysis method to the research, the other is industrial metabolic methods are used as part of the systematic research framework.

Early studies are devoted to study the construction of metabolic system: Zhe et al [1] made the metabolic analysis of China coal utilization process; Haberl [5] conducted a study on the energy metabolism of the global economic system.

While recent studies have focused on metabolic analysis methods, such as Chen et al [6] using the energy analysis method and energy metabolism of the Yellow River basin; Krausmann et al [7] have studied the modernization process of Austria's social and economic system from the perspective of energy metabolism; Huang et al [8] comprehensively have studied the social and economic system by using the methods of substance metabolism and energy metabolism analysis; Duan et al [9] and Xie [10] have studied the application of product metabolism in the circular economy; Wang et al [10] have studied the metabolism of energy of industrial park. Duan et al have studied cases of ecological industrial model of Chinese sugar industry (sugar cane); Xia et al [11] have made industrial metabolism analysis of Inner Mongolia Baotou aluminum ecological industrial park; Guo et al [12] have conducted metabolism analysis of carbon element in natural gas, but lack methods of ecologicalized transformation based on industrial metabolism analysis, particularly the energy heavy chemical industry. In 1980s, the US ecologist H T Odum proposed energy theory and method, which has taken solar energy (Solar Energy) as a unified unit of measurement to overcome the difficulties of incomparability and incalculability among different energies, and has involved the natural environment resources, economic resources, ecosystem services into the scope of the evaluation, to gain scientific and comprehensive analysis [13-15]. Energy analysis has now been widely used in agricultural ecosystem.

These studies show that industrial metabolic analysis can quantify the use of various resources or energy sources, the intensity of pollution emissions and the process of resource depletion or energy conversion in the industrial system, which can provide a basic method of support for quantitative research on how a region or park can build a circular economy or ecological transformation. However, the research on the method of ecological transformation of Energy Heavy Chemical Industry with high pollution and emission on large scale is still inadequate.

2. Material metabolism system of energy and heavy chemical industrial park
Currently the Energy and Heavy Chemical Industry Park has more than 100 enterprises with its main energy and heavy chemical products.

The Energy and Heavy Chemical Industry Eco-industrial Cluster is the typical mode of heavy chemical industry ecological manufacturing system in China's richly coaled area, which has important theoretical and practical significance to systematically analyze and study. For the industrial park location mainly relies on local abundant coal, calcium carbide, limestone, quartz sand resources, and surrounding areas rich in salt with “coal power, coal chemical industry, salt chemical industry,” as the leading industry, the cluster network of ecological industry chain is being planned to set up. The material and energy metabolism system of the Energy Heavy Chemical Industry Park is shown in figure 1.
Figure 1. Material flow analysis diagram of an industrial park.

Figure 2. Coal chemical industry-salt chemical industry-glass building materials eco industrial chain network.

3. Construction of eco-industrial network

3.1. Coal chemical industry - salt chemical industry - glass building materials industry chain network

The coal chemical industry and the salt industry's eco-industrial chain mainly include six enterprises: methanol plant, formaldehyde plant, 1.4 butanediol plant, acetic acid plant, polyvinyl chloride plant, and glass factory. The chain relationships formed by the six firms are shown in figure 2 (In addition to the special description unit, Units are: 10000t/year). Among them, Methanol and PVC plant are basic ones in developing coal chemical industry and salt chemical industry. Promising downstream products will be the priorities according to its market performance. Acetate plant can not only use methanol of the methanol plant through the underground pipeline directly transported to the plant. The carbon dioxide required for the project is entirely supplied by the methanol plant. The H2 required for the production of 1.4 butanediol is derived from the hydrogen gas
that must be discharged when the hydrochloric acid is produced by the polyvinyl chloride plant. Part of the raw materials for the production of methane chlorides also comes from the by-product liquid chlorine in the production of hydrochloric acid. The two are very good to reflect the symbiotic between salinization industry and coal chemical industry. Specific performance is to reduce the production costs and the wasting of resources. Silicone products are based on methane chloride and silicon powder as the main raw material. It is the link between the salt industry and the quartz sand bridge.

3.2. Mining industry - energy industry chain network

As shown in figure 3: Mining industry - ecological chain diagram of energy industry (Unit usually is: 10000t/year if there is no other specification). Jinjie Mine works with Guohua Power Plant, and plans an annual output of 10 million tons/year of coal, and recoverable reserves of 11.9 tons. The coal storage is stable with sound mining conditions, and the service life is approximately 117 years. The coal yard is less than 500 meters away from the power plant. After the completion of the 2nd phase of the large power plant, 9 million tons of raw coal goes will go out of the wellhead every year, and will be transferred directly to the original coal area through the conveyor. Every year 158 thousand and 800 tons of coal will be transferred to Yahua Power through the underground thermoelectric transmission channel. At the same time, Jinjie mine associated water emission is about 593 cubic meters/hour, a maximum of 720 cubic meters/hour, and two 300 tons of storage tanks have been built, 1/3 of which is for coal mining, and the rest of which will be transferred to large power plant through pipeline by 380 cubic meters/hour or 228,000 tons per year. According to the demand of Guohua, the thermal power plant supplies steam for it. About 10% of the power generated by Guohua Power Plant is supplied by coal mines and the factory itself, and the remaining 90% directly go to the North China Power Grid.

3.3. Chain network of chemical industry------building materials industry ----- energy industry

Figure 4 shows eco-industrial chain network of chemical industry and building materials industry and energy industry (Unit usually is 10000 t/year if there is no other specification). The cement plant utilizes the calcium carbide discharged from the polyvinyl chloride plant and the 14-butandiol plant to produce high quality cement; the largest solid waste emissions in the cluster are fly ash, and the development of fly ash brick factory and concrete sheet plant carry out the comprehensive application
of fly ash. Emissions of slag produced by large power plants and thermal plant can also be used as road construction; Gypsum board plant can fully use desulfurization produced by-product gypsum in the Guohua Large Power Plant to produce gypsum products or gypsum board; Gasifier slag from methanol plant with 40-45% of carbon can be sent to the thermal power plant boiler as fuel reuse, and the coarse gasifier slag can be used as hollow brick which is the raw materials for hollow brick factory.

**Figure 4.** Chemical industry, building materials industry and energy industry eco industrial chain network.

3.4. *Eco-industrial network of an energy heavy chemical industry park*

The four eco-industrial chain design is based on the construction of an Energy and Heavy Chemical Industrial park. Eco-industrial network is shown in figure 5. The figure shows that the core enterprise, the affiliated enterprise and the remote virtual enterprise establish a system based on material recycling, energy cascade utilization, water recycling and information sharing through material, energy, water and information integration. The resources in the whole production process is effectively used, and has changed the traditional linear model of resources - products - waste single, to maximize the establishment of recycling model of resources - products - Waste - resources - Sustainable.
4. Energy assessment of ecological network operation for an energy resource and heavy chemical industry park

Energy is a new scientific concept and measure tool proposed by American ecologist H T Odum. Energy is defined by H T Odum (1978) as the amount of energy contained in another type of energy flow or stored energy. The essence of energy is the energy contained. Any forms of energy come from the solar energy. Therefore, energy of any type of energy can be measured in terms of the solar energy [16].

4.1. Net energy yield ratio (EYR)

EYR is the ratio of the system output energy to economic feedback (input) energy. Feedback energy comes from the human society and economy and includes fuels, means of production and human labor. EYR is a measure of the economic contribution made by system output. Similar to the output-input ratio in economic analysis, EYR measures the production efficiency of a system. The higher the EYR, the higher the output energy under a certain economic energy input, that is, the higher the production efficiency of a system. EYR is very important for estimating the import and export value of energy. It can reflect the efficiency of energy production and utilization and represent the competitiveness of economic activities.

4.2. Energy investment ratio (EIR)

Energy investment ratio of an eco-economic system (environmental-economic system) is the feedback energy of an economy divided by the free energy input from the environment. The former includes fuels, electricity, materials and labor, all of which are purchased at a price. Therefore, it is the purchased energy. The latter includes land and mineral deposits the non-renewable energy, as well as solar energy, wind and rain the renewable energy. It is the free energy. Energy investment ratio is also known as the economy energy/environmental energy ratio.

Energy investment ratio is a measure of the economic development level and environmental load. The higher the energy investment ratio, the higher the level of economic development; on the contrary, the lower the energy investment ratio, the lower the level of economic development and the stronger
the environmental dependence of an economy. Energy investment ratio can be used to determine the benefits of the economic activities under certain conditions and hence to estimate the environmental loading ratio (ELR) for economic activities.

4.3. ELR
ELR is the ratio of the total input energy of non-renewable energy of a system to the total input energy of renewable energy. Input ratio of renewable energy is the ratio of total input energy of renewable energy to total input energy of a system. According to its definition and calculation formula, ELR is inversely proportional to the input ratio of renewable energy. The roles of the two indicators are similar in the assessment of a system and one of them should be eliminated. Here ELR is reserved due to its intuitiveness and definiteness in assessing the pressure bearing of the environment.

4.4. Energy index of sustainable development (EISD)
Social and economic benefits of a system are directly proportional to the development goal of the system. ELR is inversely proportional to sustainability requirement. EISD is defined as follows: The social and economic benefits of a system, i.e., the product of the energy output ratio and energy exchange ratio of a system, is taken as the numerator; ELR is taken as the denominator; the comprehensive evaluation indicator which is directly proportional to the sustainable development ability of the system is thus established as EISD. The higher the EISD, the higher the social and economic benefits under the unit environmental pressure and the higher the sustainable development ability of a system. EISD is expressed as

$$EISD = \frac{EYR \times EER}{ELR}$$

4.5. Energy conversion ratio
Energy conversion ratio is an important concept originating from the theory of food chain in ecosystem and the law of thermodynamics. It is a measure of energy quality of different types of energy and closely related to the energy grade of a system.

4.6. Calculation of energy indicators of Jinjie energy resource and heavy chemical industry park
Energy analysis table was compiled based on table 1, and calculation of the energy indicators was performed using this table. The indicator values calculated for different development stages of Jinjie energy resource and heavy chemical industry park are given in table 2. The overall performance of the industry park was compared horizontally, as shown in table 3.

Energy analysis table is formulated based on table 1 in this section to lay a foundation of the calculation of energy values. Using the energy analysis method, we can calculate the energy index of the ecological industry cluster in the different development stages. Table 2 shows the overall performance of the Eco-industrial Cluster at the present stage.

**Table 1.** Solar energy conversion ratio for different types of energy.

| Type of energy                                      | Solar energy conversion ratio (sej/J) |
|----------------------------------------------------|-------------------------------------|
| Solar energy                                       | 1                                   |
| Wind-driven                                        | 623                                 |
| Organic matters                                    | 4420                                |
| Potential energy of rain                           | 8888                                |
| Chemical energy of rain                            | 15423                               |
| Potential energy of river                          | 23564                               |
| Chemical energy of river                           | 41 000                              |
| Mechanical energy of waves and tides               | 17000-29 000                        |
| Fuels                                              | 18 000-58 000                       |
| Food, fruits & vegetables, grains, native products | 24 000-200 000                      |
Table 2. Vertical comparative energy index of ecoinTEGRATED manufacturing system of Kam energy heavy chemical industry cluster.

|                      | EYR  | EIR   | ELR  | ESID |
|----------------------|------|-------|------|------|
| Independent operation of enterprises | 3.64 | 0.403 | 0.56 | 6.5  |
| Phase I of ecological industry | 4.36 | 0.392 | 0.526| 8.28 |
| Cycle of development   | 5.51 | 0.387 | 0.515| 10.7 |

(Source: Odum, 1988, 1996) Unit: (sej/J)

Table 3. Lateral comparative energy index of eco-integrated manufacturing system of Kam energy heavy chemical industry cluster.

|                      | EHCIC-G Jin-jie | Industrial cluster of Shuozhou thermal power plant | Average level of five northwestern provinces in 2015 | Lu-bei ammonium phosphate cement production process |
|----------------------|-----------------|---------------------------------------------------|---------------------------------------------------|--------------------------------------------------|
| EYR                  | 5.51            | 3.14                                              |                                                   | 5.83                                             |
| EIR                  | 0.387           | 0.47                                              | 0.495                                             |                                                  |
| ELR                  | 0.515           | 0.508                                             |                                                   |                                                  |

From the longitudinal evaluation results, EYR of the initial stage 1st phase and the 2nd phase of development has increased to 4.36 from 3.64, by 19.8%, and then from 4.36 to 5.51 by 26.4%; EIR has decreased from 0.403 to 0.392, a reduction of 4%, and then from 0.392 to 0.387 by 1.3%; ELR has decreased from 0.56 to 0.53 by 0.05%, and then from 0.53 to 0.51, down by 0.04%; ESI has increased from 6.5 to 8.28 by 27.4%, and then from 8.28 to 10.7 by 29.2%.

From horizontal evaluation results, EIR is 0.387, 28% lower than the average level of the five northwestern provinces 0.495; ELR of Industrial Park is 0.515, 0.01% higher than the average level of the five northwestern provinces 0.508. The high investment rate of energy value shows the good system performance; but the environment load rate is also higher, indicating the environment pressure in the industrial park, and further improvement of eco-efficiency of the system is still needed. Comparing with the built Shuozhou Thermal Power Eco-industrial Cluster, Jinjie Industrial Park is very advantageous in resource utilization and the overall profit, but still needs to be improved in future compared with Shandong cement production process of ammonium phosphate.

5. Discussion

From the system energy evaluation, the future of the industrial park should focus on the following two aspects:

- Continue to strengthen the technology integration, product line extension and the integrated surface broadening. In the direction of development, it must go on with the fine chemical industry and the production of high value-added products, increase the degree of coupling between the industrial chain, upgrade the production technology to increase the technology dense of products. The park should expand the industrial chain, the stability of the industrial network, and the structure of the system. Compared with the Northwest five provinces, the average level of the industrial park's investment rate of energy value is obviously
advantageous which indicates the good performance of the system; but the environment load rate is also higher, indicating the pressure of the industrial park environment, and the need of further improvement of eco-efficiency.

- Continue to do a good job of system integration, evolution, upgradation. 1st. upgrade the structure and the system by introducing the supply chain enterprises to reform and upgrade the manufacturing process of the existing enterprises; 2nd. to strictly formulate and implement the enterprise access threshold, maintain and improve the system structure, increase the flexibility of the system; 3rd. to strengthen the construction of regional public facilities investment, such as sewage treatment, waste recycling market to enhance the system's self-purificability; 4th. to make full use of local advantages to develop the solar wind and generation of solar power by use of wind power and other renewable resources to reduce environmental load in the area.

6. Conclusion

Study on ecological chain network of the energy and heavy chemical industrial park helps to establish a bridge between these two important theories of sustainable development of ecological manufacturing and regional circular economy on the one hand, and make them complement each other, to build regional ecological manufacturing system of circular economy and provide technical support and guidelines for the smooth application and promotion of the idea of ecological circular economy for the integrated manufacturing system; on the other the integration of multi-subject knowledge will perfect the theoretical system of circular economy; last but not least. The research object of energy-heavy industry can carry out the implementation of theory of circular economy on a middle and micro level and provide theoretical guideline and practical method for the sustainability of energy and heavy industry development.

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