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Emergy Synthesis of the Sustainability of Chinese Cement Industry with Waste Heat Power Generation Technology

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ABSTRACT

Cement production consumes a considerable quantity of resources and energy and emits massive pollutants, which restricts the sustainable development of the cement industry. Therefore, a systematic method is needed to diagnose the sustainable development level of the cement production system and provide decision support for managers to implement the technology of energy-saving, consumption-reducing and pollution mitigation in the cement industry. This study revises the traditional emergy indicators, establishes a set of indicators system for cement production sustainability evaluation, compares and analyses the systems with and without waste heat power generation technology based on emergy synthesis. The study indicates that, the application of the waste heat power generation technology reduces the emergy flow with negative environmental consequences such as the electricity consumption emergy flow, and increases the sustainable development level of cement production system. The cement enterprises should change the emergy flow structure by the means of increasing the adoption rate of waste heat power generation technology and the proportion of industrial solid wastes in raw materials, adding more efficient desulfurization and denitrification treatment facilities, and adopting energy-saving equipment to improve the sustainable development level of cement industry.

INTRODUCTION

Cement is a basic raw material in national economy, and the cement industry plays an important role not only in China but also in the global economy. Since 1985, China has become the largest cement producer in the world, with a cement yield reaching 2.41 billion tons in 2013, accounting for about 60% of the world's total cement yield (Wei et al. 2015). The massive infrastructure construction in China will continue until 2035, therefore, Chinese cement yield will remain at a high level for a long period in the future.

Cement production includes raw material preparation, pulverized coal preparation, clinker calcination, cement grinding and other related processes. Cement manufacturing is an industry typically with high resource and energy consumption and heavy pollution, and the rapid development of this industry also brings many problems. The relative research indicates that, producing a ton of cement in China consumes approximately 1.1 tons of limestone, 0.18 tons of clay, 0.1 tons of standard coal and 110 kWh of electricity (Wang 2006, Jiang et al. 2010). The high raw materials and energy consumption, along with the emissions of SO_2, NO_X and other gas pollutants during the production, seriously affect the environment with ecological depletion and ecological retention and restrict the sustainable development of the cement industry. In order to solve the problems above, a systematic method is needed to diagnose the sustainable development level of the cement production system and provide decision support for managers to implement the technology of energy saving, consumption and pollution reduction in the cement industry.

Currently, various methods are used to evaluate the resource, energy and environment performance of an industrial system. These methods include exergy analysis (Sui et al. 2014), life cycle assessment (Li et al. 2015), emergy synthesis (Zhang et al. 2009) and other methods. Among them, emergy synthesis is a system analysis method based on energy analysis, using solar emergy as the unit of measurement. The system considers the contributions of environment and economic society, comprehensively measures the

Table 1: Traditional emergy indicators.

Item	Expression
Emergy Investment Ratio(EIR)	The feedback emergy of the economic system/The input emergy of the environment system
Emergy Yield Ratio(EYR)	The output emergy of the system/The feedback emergy of the economic system
Environment Load Ratio(ELR)	The nonrenewable emergy input of the system/The renewable emergy input of the system
Emergy Sustainable Indices(ESI)	Emergy Yield Ratio(EYR)/Environment Load Ratio(ELR)

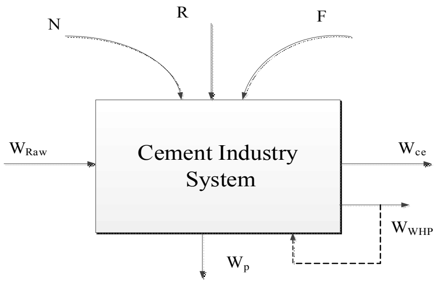


Fig. 1: Emergy input and output diagram of cement industry system.

impact of natural environment resources and human social activities. Emergy synthesis provides common scales for measuring and comparing different kinds of materials, energy, environmental impact and economic indicators. Therefore, the method of emergy synthesis is an effective way to evaluate the sustainable development level of an industrial system.

This study evaluates the sustainable development level of the cement production process based on the actual production data through emergy synthesis with the total natural resources, energy and economic input on the same scale. Furthermore, two systems with and without a waste heat power generation system are compared and analysed. The usage degree of resource and energy, the impact of waste heat power generation technology on the sustainable development level of the system are determined.

METHODOLOGY

Emergy synthesis: The concepts of emergy theory and emergy synthesis method were proposed by American ecologist H.T. Odum in the 1980s. He defined the emergy as the total available energy which was directly or indirectly put into the forming process of a product or service (Odum 1998). Since all the energy on earth is directly or indirectly derived from the solar energy, the amount of solar energy that any flowing energy or stored energy contains is the solar emergy of the energy, and its unit is solar emjoules (sej). Emergy is an important object function used to study the self-organization process of the ecological system and it plays an important role in the study and application of quantifying the ecosystem's function, depicting and simulating the ecosystem's behaviour, predicting the ecosystem's evolution trend, evaluating and analyzing the ecosystem's sustainability.

Based on the emergy theory, emergy synthesis introduces the solar transformity in the calculation. In order to assess the function and status of any energy in the system, it quantitatively analyses the system through converting different types and different levels of energy into the same standard emergy - the solar emergy. Its basic expression (Lan et al. 2002) is $M=T\times B$, where M represents the solar emjoules (the unit is sej), T is the solar transformity and B refers to the amount of the available energy. Emergy synthesis evaluates the sustainable development level and ecological economic benefits of the ecological economic system through thoroughly analyzing different ecological flows (energy flow, capital flow, substance flow and information flow, etc.) in the system and calculating a series of emergy evaluation indicators.

Emergy indicators system: The emergy indicators concluded through the emergy synthesis of the system can unify different kinds of ecological flows (energy flow, substance flow, currency flow, information flow and population flow, etc.) of the compound ecosystem on the emergy scale, quantitatively analyse the structure and function of the system, and reveal the relationship between the value of the natural environment production and the human economy, thus correctly handling the relationships among human beings, natural environment and economy and ensuring the sustainable development trend. Emergy indicators are important basis of evaluating the sustainability of the system.

Traditional emergy indicators system: Traditional emergy indicators (Lan et al. 2002) are as shown in Table 1.

Among them, emergy investment ratio is an indicator measuring the economic development level and environmental load degree of the system; emergy yield ration evaluates the emergy yield's contribution to the economy of the system; environment load ration denotes the pressure of the economic activities on the environment; while the emergy sustainable indices are equal to the ratio of EYR and ELR, reflecting the sustainable development degree of the system.

Improved emergy indicators system for cement production system: Traditional emergy indicators system is appli-

Table 2: The impact category and transformity of the pollutants (Zhang et al. 2009).

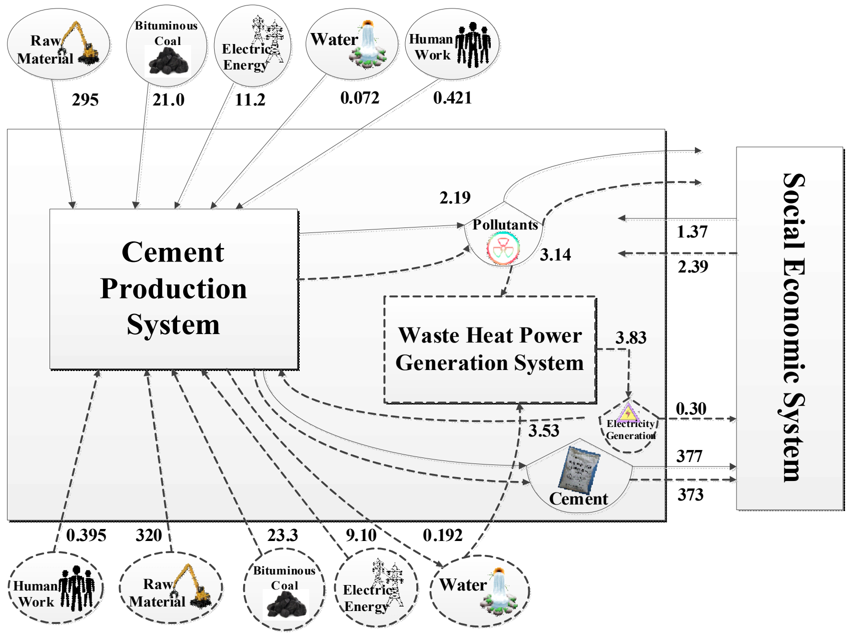
Pollutant	Impact Category	DALY/Mt	ECEC/Mt (sej/Mt)
Dust	Respiratory disorders	3.75E+05	1.28E+22
NO_2	Respiratory disorders	8.87E+04	3.03E+21
SO_2	Respiratory disorders	5.46E+04	1.86E+21
CO_2	Climate change	2.10E+02	7.17E+18

Table 3: The emergy inventory of Case 1.

Item	Basic Data	Unit	Transformity (sej/unit)	Emergy (sej)	Ratio
Input					
Raw Materials					
Limestone	2.08E+12	g	1.00E+09	2.08E+21	
Sandstone	1.34E+11	g	1.00E+09	1.34E+20	
Shale	1.00E+11	g	2.46E+09	2.47E+20	
Flyash	1.96E+11	g	1.00E+09	1.96E+20	
Iron Powder	3.47E+10	g	4.13E+09	1.43E+20	
Gypsum	8.70E+10	g	1.00E+09	8.70E+19	
Slag	7.06E+10	g	1.00E+09	7.06E+19	
Total				**2.95E+21**	**89.68%**
Nonrenewable Energy					
Bituminous Coal	5.24E+15	J	4.00E+04	2.10E+20	
Electric Energy	6.42E+14	J	1.74E+05	1.12E+20	
Total				**3.21E+20**	**9.75%**
Renewable Resource					
Water	6.73E+11	g	1.07E+06	7.20E+17	
Human Work	3.40E+11	J	1.24E+07	4.21E+18	
Total				**4.93E+18**	**0.15%**
Investment	1.14E+07	$	1.20E+12	**1.37E+19**	**0.42%**
Total Inputs				**3.29E+21**	
Output					
Pollutant					
Dust	5.38E+08	g	1.28E+10	6.88E+18	
NO_2	2.85E+09	g	3.03E+09	8.63E+18	
SO_2	5.61E+08	g	1.86E+09	1.04E+18	
CO_2	7.45E+11	g	7.17E+06	5.34E+18	
Total				**2.19E+19**	**0.58%**
Cement	1.82E+12	g	2.07E+09	**3.77E+21**	**99.42%**

cable to evaluate ecological systems. Since, there is no so-called waste in natural ecological systems, traditional emergy indicators do not take the environmental impact of the waste into consideration, and are not suitable for evaluating and analyzing the cement production system. The cement production process requires a large amount of nonrenewable energy, renewable resources and economic input. In aspect of input, cement production consumes plenty of natural resources as raw materials such as limestone, clay, gypsum and other auxiliary materials, and expends vast amounts of coal and electricity, while the production operation process needs site operation, technical and management personnel. In aspect of output, in addition to the yield of cement products, cement production process discharges large amounts of CO_2, NO_X, dust and other pollutants, causing a certain impact on the natural environment. In particular, the output side further comprises the waste heat and exhaust gas emissions from the AQC and SP of the cement kiln, resulting in a waste of energy.

Fig. 1 shows the emergy input and output diagram of cement industry system. The W_{Raw} represents the emergy input of limestone, clay, fly ash and other raw materials; the N denotes the emergy input of nonrenewable energy, including electric energy and coal; the R refers to the emergy input of renewable resources, consisting of water and human work and the F is the economic emergy input, while the W_{ce}, W_p and W_{WHP} represent the emergy output of cement products, pollutants and waste heat power generation, respectively.



Note: The dotted lines represent the waste heat power generation system and emergy flows of Case 2 (Unit: 10^{19} sej).
Fig. 2: Emergy system diagram of cement production.

Therefore, this study proposes the improved emergy indicators which are suitable for the cement industry system based on the traditional emergy indicators.

Improved emergy investment ratio: It represents the ratio of the economic feedback emergy (including the nonrenewable emergy and the economic investment emergy) to the sum of the raw material emergy and the renewable resource emergy in the cement production system, and the expression is as follows:

$$IEIR = (N + F) / (W_{Raw} + R) \quad \ldots(1)$$

IEIR represents the feedback emergy of the economic system brought by per unit emergy input of the environment system during the cement production process. The larger the value is, the higher the degree of the economic development and the lower the dependence on the environment in the cement production system; on the other hand, the smaller value indicates lower economic development level and the more dependence on the environment.

Improved emergy yield ratio: It denotes the ratio of the output emergy having positive influence on the environment (including the cement products emergy and the waste heat power generation emergy) and the economic feedback emergy (the sum of the nonrenewable emergy and the economic investment emergy) in the cement production system. When the positive emergy output of the cement system is larger and the total economic feedback emergy is smaller, the improved emergy yield ratio is greater. The calculation formula is as follows:

$$IEYR = (W_{ce} + W_{WHP}) / (N + F) \quad \ldots(2)$$

Where, the W_{WHP} refers to the power generation emergy of the cement plants with waste heat power generation technology. It should be pointed out that, for the system without waste heat power generation technology, the W_{WHP} is 0.

IEYR can reflect the relationship between the production efficiency and market competitiveness among different systems. The larger the value, the more emergy yield can be obtained by investing per unit economic feedback emergy and the competitiveness of the system is greater; on the other hand, the smaller value indicates lower emergy yield efficiency of the system and relatively lack of competitiveness.

Improved environment load ratio: It is equal to the ratio of the sum of the raw material emergy, nonrenewable emergy, the economic investment emergy and the emissions emergy of pollutants to the renewable resource emergy due to the pollutants output from the cement production system increasing the load on the environment. It describes the effect on the local environmental ecosystem during the cement production process:

$$IELR = (W_{Raw} + N + F + W_p) / R \quad \ldots(3)$$

IELR represents the negative impact on the environment by nonrenewable resource consumption and waste emissions. The larger the value is, the greater pressure the system has on the surrounding environment; on the other hand, the smaller value indicates less pressure on the surrounding environment when the system has a more eco-friendly production mode and the local has relatively adequate time and space to dilute the environmental impact.

Improved emergy sustainable indices: It denotes the ratio of the improved emergy yield ratio and the improved environment load ratio. It is a composite indicator reflecting the emergy yield efficiency under a certain environmental load and comprehensively evaluating two aspects of sustainable development of the cement production system. IESI can be applied to assess the sustainable development property of the system and its expression is as follows:

$$IESI = IEYR / IELR \quad \ldots(4)$$

The value of the IESI reflects the sustainable development degree of the system. The system with larger IESI has higher sustainable development ability than the system with smaller IESI.

Environmental impact emergy of the pollutants: In emergy calculation, the solar emergy of a certain type of energy is the arithmetic product of the amount of such energy and its corresponding transformity. However, there is no direct pollutants transformity for directly calculating the solar emergy of pollutants in the current researches on emergy analysis both domestically and abroad.

Disability adjusted life years (DALY) (Bakshi 2002) is an approach developed by the World Health Organization in order to measure the impact of polluted emissions on human well-being and ecological environment. The approach of DALY contains the impact of several common pollutants (including dust, CO_2, NO_2 and SO_2) on human health. Table 2 lists several air pollutants from the cement production system considered in this work, the impact categories they belong to and corresponding DALY values per Mt of emission.

Ukidwe and Bakshi discussed the approach for converting DALYs to ecological cumulative exergy consumption (ECEC) (Ukidwe et al. 2004). The relationship between DALY and ECEC is linear and 1 DALY/day of human health impact corresponds to 9.35E13sej/day of impact in ECEC terms. The exergy becomes equivalent to emergy if the analysis boundary, allocation approach and method for combining global energy inputs are identical (Hau et al. 2004), thus it can be seen that the unit of ECEC values is presented in the form of solar emjoules. Therefore, the emergy value of emissions' impact of cement industry system on environment can be expressed as ECEC values of emissions. The ECEC transformity values of different kinds of air pollutants are shown in Table 2.

CASE STUDY

Two running cement plants are selected in this study as the study cases. For the convenience of description, they are called Case 1 and Case 2.

The common features of Case 1 and Case 2: A new dry process of 5000 t/d cement clinker production line with advanced RSP (Reinforced Suspension Pre-heater) five-cyclone-stage pre-calciner technology for cement production, a rotary kiln, vertical raw material grinder, large ball mill equipped with roller press and other advanced cement manufacturing equipment.

The features of Case 2 only: With a waste heat power generation project implementation, a heating PH boiler heated by kiln exhaust from the five-cyclone-stage preheater, an AQC boiler heated by cooler exhaust from grate cooler. The heat in the exhaust is transformed into steam through high-efficiency boiler to run the generator to produce electricity. The waste heat power generation project operates steadily and brings certain economic and environmental benefits.

This study performs emergy synthesis evaluation based on the economic indicators, pollutants emissions indices and other indicators of the two cases through their actual production data.

Emergy inventory: Table 3 and Table 4 list the main resource and energy input and output of each cement production system. Different units of ecological flows are converted to a common emergy unit (solar emergy) based on the corresponding transformities of different kinds of resource and energy. The emergy inventory of each cement production system is shown in Table 3 and Table 4.

It can be seen from the Table 3 and Table 4, the total emergy input of Case 2 (3.55E+21sej/a) is larger than that of Case 1 (3.29E+21sej/a). For the components of the total emergy input, the raw material emergy is in the premier place in both cement plants, where the value is 3.20E+21sej/a in Case 2 and 2.95E+21sej/a in Case 1; followed by the nonrenewable emergy input, where the values are 3.24E+20sej/a and 3.21E+20sej/a, respectively; and the third-ranked constituent is the economic investment emergy input with the values of 2.39E+19sej/a and 1.37E+19sej/a respectively. However, the renewable emergy input occupies the smallest share in both cement plants, with the values of 5.87E+18sej/a and 4.93E+18sej/a respectively. As we can see, the value of Case 2 is higher than that of Case 1 for each type of emergy input.

In terms of emergy output, the output emergy of Case 1

Table 4: The emergy inventory of Case 2.

Item	Basic Data	Unit	Transformity (sej/unit)	Emergy (sej)	Ratio
Input					
Raw Materials					
Limestone	2.07E+12	g	1.00E+09	2.07E+21	
Clay	3.44E+11	g	1.68E+09	5.77E+20	
Flyash	2.22E+11	g	1.00E+09	2.22E+20	
Copper Slag	5.51E+10	g	1.80E+09	9.92E+19	
Gypsum	1.26E+11	g	1.00E+09	1.26E+20	
Slag	1.06E+11	g	1.00E+09	1.06E+20	
Total				**3.20E+21**	**90.03%**
Nonrenewable Energy					
Bituminous Coal	5.83E+15	J	4.00E+04	2.33E+20	
Electric Energy	5.23E+14	J	1.74E+05	9.10E+19	
Total				**3.24E+20**	**9.13%**
Renewable Resource					
Water	1.79E+12	g	1.07E+06	1.92E+18	
Human Work	3.19E+11	J	1.24E+07	3.95E+18	
Total				5.87E+18	0.17%
Investment	1.99E+07	$	1.20E+12	**2.39E+19**	**0.67%**
Total Inputs				**3.55E+21**	
Output					
Pollutant					
Dust	8.03E+08	g	1.28E+10	1.03E+19	
NO_2	4.47E+09	g	3.03E+09	1.36E+19	
SO_2	1.19E+09	g	1.86E+09	2.21E+18	
CO_2	7.45E+11	g	7.17E+06	5.34E+18	
Total				**3.14E+19**	**0.83%**
Electricity Generation	2.20E+14	J	1.74E+05	**3.83E+19**	**1.01%**
Cement	1.80E+12	g	2.07E+09	**3.73E+21**	**98.16%**

Note:
(1) For Case 1:
Coal consumption= (2.439E+8) kg × (2.1477E+7) J/kg (average low calorific value) = (5.24E+15) J
Electricity consumption= (1.7836E+8) kWh × (3.60E+6) J/kWh = (6.42E+14) J
Human work (Pulselli et al. 2008) =1740h × 373 (number of employees) × 125kcal/h × 4186 J/kcal = (3.40E+11) J
(2) For Case 2:
Coal consumption = (2.713E+8) kg× (2.1502E+7) J/kg = (5.83E+15) J
Electricity consumption = (1.453E+8) kWh × (3.60E+6) J/kWh = (5.23E+14) J
Human work= 1740h × 350 × 125 kcal/h × 4186 J/kcal = (3.19E+11) J
Electricity generation= (6.12E+7) kWh × (3.60E+6) J/kWh = (2.20E+14) J
(3) Transformities in this study are from the research achievements of H.T. Odum and other emergy research scholars (Lan et al. 2002, Pulselli et al. 2008, Cao et al. 2013), and the transformities of the substance whose transformities are undiscovered are determined by using the transforminty values of the substance with similar properties.

consists of cement products emergy (3.77E+21sej/a) and pollutants impact emergy (2.19E+19sej/a), while the output emergy of Case 2 is composed of the cement products emergy, waste heat power generation emergy, pollutants impact emergy and the values are 3.73E+21sej/a, 3.83E+19sej/a, 3.14E+19sej/a, respectively.

Emergy system diagram: The emergy system diagram of the cement production system is shown in Fig. 2. It is drawn based on the emergy input and output diagram above and the emergy inventories of the two cement plants.

Emergy indicators analysis: Emergy synthesis and evaluation on the two cement production systems are conducted based on the data in Table 3 and Table 4 and the improved emergy indicators system (1) - (4). The results are shown in Table 5.

It can be seen from Table 5, in terms of the emergy flow of the cement systems, the percentages of raw material emergy of Case 1 and Case 2 account for 89.68% and 90.03%, respectively; while the renewable emergy flow input of the two cement plants both have the smallest proportion, with the percentages of 0.15% and 0.17% respectively. In the aspect of nonrenewable emergy flow input, the proportion of Case 2 (9.13%) is lower than that of Case 1 (9.75%); on the contrary, the percentage of the investment

Table 5: The emergy flow and emergy indicators of the two cases.

Item	Case1	Case2
Raw material emergy flow %	89.68%	90.03%
Nonrenewable emergy flow %	9.75%	9.13%
Renewable emergy flow %	0.15%	0.17%
Investment emergy flow %	0.42%	0.67%
Cement emergy flow %	99.42%	98.16%
Pollutants emergy flow %	0.58%	0.83%
Waste Heat Power Generation emergy flow %	-	1.01%
IEIR	0.113	0.109
IEYR	11.2	10.8
IELR	672	610
IESI	1.67×10^{-2}	1.77×10^{-2}

emergy flow of Case 2 (0.67%) is relatively higher compared with Case 1 (0.42%). As for the emergy flow output, the ratio of the pollutants impact emergy of Case 2 (0.83%) is larger than that of Case 1 (0.58%); meanwhile, the waste heat power generation emergy flow of Case 2 occupies the proportion of 1.01% because of the waste heat power generation system.

In the aspect of emergy indicators, the IEIR and IEYR of Case 1 are both slightly higher than the ones of Case 2, the values are 0.113, 11.2 and 0.109, 10.8, respectively; however, the IELR of Case 2 (610) is obviously lower than that of Case 1 (672) and the IESI of Case 2 (1.77×10^{-2}) is higher compared with Case 1 (1.67×10^{-2}). It shows that the sustainable development level of Case 2 is relatively higher.

From a general view, the two cement plants both have the features of large environment load ratio and relatively small emergy sustainable indices, meaning that the cement production industry is an industry with great environmental load and relatively weak sustainable development level.

DISCUSSION AND CONCLUSION

A sustainable industrial system is technologically, environmentally and economically feasible. As for cement plants, technical feasibility and environmental feasibility requires the products to meet the quality standard and the emissions of NO_X, SO_2 and other pollutants during the production process to meet the national emission standard at the same time. It must be noted that a technologically feasible and environmentally feasible but not economically feasible industrial system must be non-competitive and unsustainable. The integrated evaluation of the sustainability in this study is carried out with the cement production system's energy flow, substance flow, currency flow and population flow on the same scale.

The manufacturing process adopted by both cement plants in this study is NSP precalcining cement production craft. The only difference in the cases is that Case 2 uses 9MW low-temperature waste heat power generation technology but Case 1 does not. The electricity generation in Case 2 is 61.20 million kWh per annum, saving 56.30 million kWh of electricity every year, while its annual average investment has greatly increased at the same time. Emergy synthesis method is a good way to solve the problem of how to evaluate the impact of different scales of input and output on the sustainable development level of the system.

The appropriate emergy evaluation indicators of the cement industrial system are established and are used to evaluate the two cement plants, one of which contains waste heat power generation technology and the other does not, through emergy synthesis. The results show that the difference between the two cement plants is not obvious in terms of the IEIR and IEYR; in the aspect of IELR, the value of Case 2 is obviously smaller than that of Case 1, meaning that the pressure of Case 2 on the environment is less than the pressure of Case 1, because of the application of waste heat power generation technology in Case 2 in its investment and output emergy flow, which reduces the emergy flow with a negative impact on the environment, such as the electricity consumption emergy etc. As a result, the IESI of Case 2 is higher than that of Case 1, showing that the waste heat power generation technology plays an important role in promoting the sustainable development level of cement production system.

The comprehensive emergy indicators of the two cement plants show that their IEIR, IELR and IESI are all in the magnitudes of 10^{-1}, 10^{2} and 10^{-2}, respectively. It can be seen that the cement production industry is an industry with weak economic development degree, serious environmental impact and relatively weak sustainable development level, relying on the nonrenewable resources. Therefore, the cement production system needs to change the structure of emergy flow through increasing renewable emergy flow input and reducing the share of the nonrenewable emergy flow, i.e. the cement enterprises should improve the sustainable development level of the cement industry by the means of increasing the adoption rate of waste heat power generation technology and the proportion of industrial solid wastes in the raw materials, adding more efficient desulfurization and denitrification treatment facilities, and adopting energy-saving equipment.

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