Journal of Cleaner Production 290 (2021) 125901

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Performance comparison of cement production before and after implementing heat recovery power generation based on emergy analysis and economic evaluation: A case from China

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ARTICLE INFO

*Article history:*
Received 17 August 2020
Received in revised form
22 October 2020
Accepted 6 January 2021
Available online 8 January 2021

Handling editor: Yutao Wang

*Keywords:*
Cement industry
Heat recovery power generation
Emergy
Pollutant emissions
Sustainability

ABSTRACT

HRPG (Heat recovery power generation) is widely adopted in the cement industry. However, the measure's impacts on the environmental and economic performance of this industry are not completely clear due to the extra resources inputs. To this end, this research implemented an emergy evaluation through considering emissions' impacts, to investigate impacts of HRPG on environmental performance of this industry. Meanwhile, a supplementary economic evaluation was done to explore changes of its economic performance before and after implementing HRPG. One cement enterprise with the two scenarios (Scenario 1 with HRPG vs. Scenario 2 without HRPG), as a case study, was investigated using the presented approach. It is found that (1) HRPG reduces total resources consumption by 1.13%, and raises share of renewable resources by 2.28%; (2) HRPG reduces dependence degree of this enterprise on imported resources and its wealth loss by 1.93% and 1.13% respectively; (3) HRPG enhances wastes recycling rate and energy efficiency by 329.44 times and 6.91% respectively; (4) HRPG enhances emergy yield rate by 0.89%, cuts environmental load rate by 1.77%, and improves environmental sustainability by 2.71%; (5) pollutant emissions' impacts reduce emergy yield rate by 9.48–9.56%, raise environmental rate by 0.02%, and weaken environmental sustainability by 9.50–9.59% (6) HRPG improves economic benefit of this enterprise by 22.24%, which roots in reduced electricity expense. Generally implementation of HRPG achieves energy-saving, emissions reduction and improvement of economic benefit, which well explains why this measure is widely adopted in cement industry. However, this measure is limited to improve environmental performance of this enterprise due to high dependence on nonrenewable resources, and it still has relatively lower energy efficiency than the updated one. Finally this study proposes some targeted suggestions to deal with these issues in the future.

## 1. Introduction

The fast development of infrastructure construction, real estate and new rural construction requires large quantities of cement in China. Data from the National Bureau of Statistics of China (2020) showed that China's cement output has climbed by 3.94 times from 5.97E08 tons in 2000 to 2.35E09 tons in 2019. Cement industry consumes quantities of ore resources and fossil energy sources and then leads to lots of air emissions (Shen et al., 2015). Kajaste and Hurme (2016) found that approximately 5–8% of global carbon dioxide ($CO_2$) emissions come from China's cement production. And air pollutant emissions from this industry have also aggravated the regional air pollution (Richards and Agranovski, 2015; Zhao et al., 2014). Meanwhile, the increasing consumption of ore resources and fossil energy sources accelerates the exhaustion of those nonrenewable resources (Bontempi, 2017). These issues not only weaken the comprehensive performance of China's cement industry, but also hinder the sustainable development of this country's social economy to some degree. As one of energy-

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https://doi.org/10.1016/j.jclepro.2021.125901
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saving measures, many pure low temperature HRPG systems have been constructed for cement kilns in China to recycle waste heat (Tang, 2007). However, the impacts of HRPG on environmental and economic performance of cement production are not completely clear due to extra resources input.

To meet the abovementioned challenges, investigating the comprehensive performance of cement industry is necessary for policy-making. Song et al. (2016) adopted LCA (life cycle assessment) to investigate environmental impacts of cement production, Huang et al. (2016) applied EA (energy analysis) to energy efficiency assessment of cement production, Wang et al. (2016) explored resources intensity of cement production using MFA (material flow analysis), and Cagiao et al. (2011) researched carbon emission intensity of cement production using CF (carbon footprint). These works can provide related resources and environment information for policy-making from different angles; however, generally they just provided part of policy-making information due to their limited concerns and analysis boundaries. As for effect of HRPG systems on the performance of cement industry, Jiang et al. (2008) compared the environmental load of a coal fired power plant, a HRPG system by supplementary fuel and a pure low temperature HRPG system in a cement plant using LCA, and found that the pure low temperature HRPG system had the smallest environmental burden among the three systems. The research of Piao et al. (2012) showed that HRPG saved 173 Kwh per ton cement and reduced the environmental impacts by 50% through comparing LCA results of a Chinese cement plant before and after implementing HRPG scheme. Song et al. (2016) implemented a life-cycle environmental impact analysis of a typical cement production chain, and found that corn straw as coal substitution and heat recovery and cogeneration could achieve a notable environmental benefit for cement production. But the research of Jiang et al. (2008), Piao et al. (2012) and Song et al. (2016) did not considered environmental contribution to these production systems, quality differences of diverse categories of resources and energy sources and related economic performance. Wang et al. (2015) investigated ORC (organic Rankine cycles) integrated with a typical China cement production line using economic evaluation and LCA, and they thought ORCs had good economic performance and reduced the air pollutant emissions. Likewise, they ignored environmental contribution and quality differences of diverse categories of resources and energy sources. Sui et al. (2014) compared environmental performance of cement production processes with and without HRPG, and they found that the energy efficiency and exergy efficiency of each subsystem can be improved to different degree after implementing HRPG compared with those before. But energy analysis ignores quality differences of different energy sources, and exergy analysis does not consider environmental contribution. Song et al. (2019) carried out an extended exergy accounting for a typical cement industry in China, and they found that although waste heat recovery recycles the waste, the cumulative exergy consumption conversion efficiency almost keeps no changes due to the extra capital investments on kilns and power generation units, which is not recommended for upgrade of cement production from the exergoeconomic perspective. However, they did not consider environmental contribution and related economic performance. Generally all abovementioned studies investigated performance of cement industry and impacts of HRPG on this system from different angles, and provided some helpful information for decision-making. However, these adopted methods have the following drawbacks. Therein, the weights' decision depending on the expert scoring could incur somewhat subjectivity in LCA; ignoring the quality differences among different energy sources in EA makes diverse formation processes and energy sources incomparable; MFA neglects the quality differences between diverse types of materials; CF just provides limited information for policy-making due to its narrow boundary and limited concerns, and exergy analysis has not considered environmental role in industrial production due to its narrow boundary (Shen et al., 2019). Common flaw of these methods roots in ignorance of the environmental contribution to cement production, and thus they could leave out part of information of environmental value, which could lead to somewhat deviation of final decision-making.

Comparatively speaking, the EmA (emergy analysis) has some advantage over the abovementioned methods in investigating the environmental performance of cement industry, including (a) common measure unit for quantifying all kinds of flows (Odum, 1988), and (b) consideration of the environmental contribution to this industry through extending the analysis boundary. And these advantages have attracted some scholars to apply this approach to performance evaluation of cement production. Therein, Pulselli et al. (2008) calculated the specific emergy values of cement and concrete, and they revealed its high dependence degree on nonrenewable natural resources. Zhang et al. (2017) evaluated the resources efficiency and environmental load and comprehensive performance of Chinese cement industry in 2010 by classic EmA. Song and Chen (2016) assessed resources efficiency of a cement production chain in mainland China using EmA. All these works gave relatively comprehensive environmental information for decision-making of cement industry. However, these researchers did not consider environmental emissions' adverse effect on social economy and the environmental ingredients, and thus they cannot provide full information for policy-making (Chen et al., 2018). Mikulcic et al. (2016) evaluated several cement manufacturing technologies using EmA and ecological footprint analysis, but other performances (emergy yield rate, sustainability index, etc.) and other environmental emissions (such as $SO_2$, dust, NOx, COD, etc.) have not been considered. In addition, how to integrate the results from the two methods is worth exploring. Chen et al. (2016) evaluated performance of Chinese cement industry using EmA from a life cycle angle, but the environmental cost from pollutant emissions has been overlooked; meanwhile, the ecological service ($F_1$) should not be integrated into the emergy yield rate because it just enhances the environmental load rate. Liu et al. (2016) compared performance of four sewage sludge treatment scenarios in cement production based on emergy. Although they considered environmental emissions' impacts, these impacts were not merged into the relevant indictors to show emissions' influence degree on these performance indicators. In recent years, some scholars have rebuilt the theory of EmA from a thermodynamic point of view and proposed the ECE (embodied cosmic exergy) analysis to investigate performance of some ecological economic systems. For example, Fan et al. (2020) evaluated environmental sustainability of a solar concentrating plant using ECE analysis, and found that this system is ecologically unfriendly due to heavy dependence on nonrenewable input and a limited life cycle. Wu et al. (2014) applied ECE analysis to evaluation of environmental performance of an integrated “pig—biogas—fish” system, and found this system has its advantage in ecological economy over the conventional agricultural system so long as its life cycle reaches or exceeds eight years. Although this is a promising approach to innovate emergy evaluation according to its extended boundary (from solar energy to cosmic exergy) and more rigorous theory (from a thermodynamic point of view), comparatively it still has relatively lower approval degree than EmA according to number of related public published papers, mainly derived from its immature operational method and incomplete database as well as rising uncertainty due to extended analysis boundary. And these flaws need further improvement to promote its application in the future.

Meanwhile, classic EmA still could not provide related information on economic performance, which is necessary for practical policy-making. To this end, some scholars have adopted a jointed approach composed of EmA and economic evaluation to explore performance of eco-economic systems for providing more complete information. For example, Chen et al. (2020) investigated performance of a compound fertilizer production system in China using modified EmA and economic analysis, and they discovered that the sulfur-based fertilizer subsystem has the highest economic benefit but the least environmental sustainability among the four subsystems. Yang et al. (2019) implemented environmental and economic analysis of cropping systems from fragmented to concentrated farmland in the North China Plain using EmA and economic analysis and LCA, and their results indicated that the environmental and economic performance of the cropping system were improved simultaneously when the farmland was managed in a concentrated model instead of a fragmented one.

HRPG is widely adopted in the cement industry, but its impacts on the comprehensive performance of this industry have not been fully investigated. Especially few studies have been found to investigate HRPG's influence on comprehensive performance of cement production using EmA and economic analysis. And this is not helpful for improving HRPG application in cement industry due to lacking full decision-making information. This paper aims to exploring impacts of HRPG on environmental performance of one typical cement enterprise in China by one adjusted EmA based on our previous work (Zhang et al., 2018). In addition, a complementary economic evaluation is also done to compare economic performance of this enterprise before and after implementation of HRPG. This work contributed to the related research fields through (1) improving performance evaluation of cement production through a joint approach composed of adjusted EmA and economic evaluation. Therein, the adjusted EmA integrated emissions' impacts (ecological service and emergy loss derived from environmental emissions), wastes reuse and recycling into several classic emergy based indicators; meanwhile, a new indicator ECI (Energy consumption intensity) was founded to reflect the energy efficiency of cement production in terms of emergy, and (2) enriching the existing emergy database using the updated unit emergy values of cement products with and without HRPG. The adopted approach and related indicator system were applied to (1) exploration of pollutant emissions' impacts on environmental performance of cement production, and (2) assessment of influence of HRPG on comprehensive performance of this industry. By doing so, the proposed approach and the related indicator system can well adapt to the industrial system's characteristics, and then its performances can be investigated more fully for targeted decision-making.

## 2. Introduction of the study case

The study case is situated in one county in Xinjiang Uygur Autonomous Region of China (longitudes 88°30′E ~ 89°30′E and latitudes 43°30′N ~ 45°30′N), and this enterprise covers an area of 35.76 ha. This county lies in the medium temperate continental arid climate zone, where on average, there are an annual average temperature of 7 °C, an annual average wind speed of 2.0 m/s, and an annual average rainfall of 227.5 mm. According to the local environmental quality report, main air pollutants cannot satisfy the related standard values of GradeIIin Ambient air quality standards of China (GB 3095—2012) in most days of one year. So there is no extra air environmental capacity in this region. Meanwhile, there is not sufficient water environmental capacity in this region due to low precipitation. The enterprise adopts the mainstream technology of cement production in China - the new suspension preheater dry production technology, while it still adopts a pure low temperature HRPG measure. Its raw materials include limestone, silica, iron ore, sandstone, shale, sulfuric-acid residue, gypsum, coal, etc., which can well stand for the kind of enterprises which implement wastes reuse and/or waste heat recycling. Generally the cement production is divided into three stages, including raw material grinding, clinker sintering and cement grinding. As shown in Fig. 1, at the first stage, the raw materials (limestone, sandstone, shale, and sulfuric-acid residue) are firstly crushed, then they are fed into the pre-homogenization field, next these raw materials are milled and dried in the raw mill. And coal is also prepared in the coal mill system at this stage. At the secondary stage, the prepared raw materials with a suitable proportion are calcined in a kiln system with coal as fuel to produce clinker. At the final stage, clinker is firstly blended with desulfurization gypsum, fly ash and furnace slag, and then the mixture is sent into the grinding system to attain the final product-cement. Therein, the waste heat from the kiln system is used to generate electricity using the HRPG system, which can provide part of electric power for this enterprise. The HRPG system was mainly composed of two kiln head waste heat boilers, two Kiln tail waste heat boilers, two steam turbines and two power generators. Its main thermal and technical parameters were given in Tables 1 and 2. It is worth mentioning that the specific HRPG technologies mainly include HRPG systems by supplementary fuel and pure low-temperature HRPG ones in Chinese cement industry. Therein, the former has been forbidden by Chinese government mainly due to high coal consumption and heavy environmental pollution (Wang and Wang, 2010). Meanwhile, Karellas et al. (2013) compared efficiency of steam cycle and ORC for HRPG of cement plants, and their study showed that the former had higher efficiency than the latter when exhaust gas temperature exceeded 310 °C. So the HRPG system in the case study has good representativeness in the country.

In order to compare impacts of HRPG on performance of the study case, here two scenarios were considered, including Scenario 1 (the real system, shown in Fig. 1): cement production with HRPG; Scenario 2 (a theoretical system, illustrated in Fig. 2): cement production without HRPG.

## 3. Methodology

### 3.1. EmA

Odum (1988; 1996) defined emergy as the sum of a kind of available energy consumed in the formation of one kind of output, expressed as solar emergy joule (sej). EmA evaluates and compares the role of various types of natural resources in the social economic system based on the secondary law of thermodynamics and the

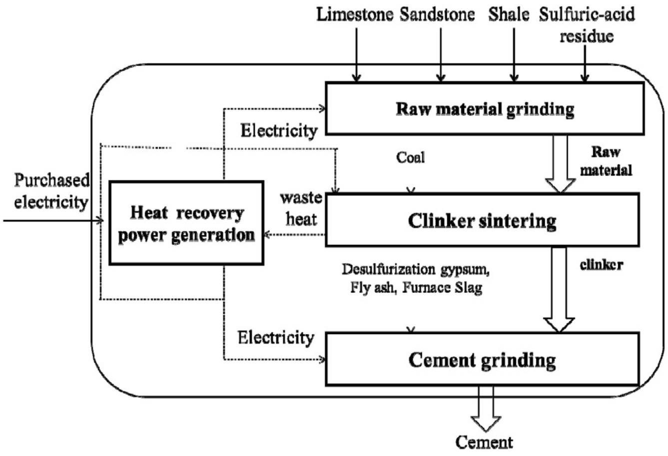

**Fig. 1.** The technological diagram of Scenario 1.

**Table 1**
Thermal parameters for the heat recovery power generation technology.

| Parameters' name | Clinker output of 2 × 3000 t/d | |
|---|---|---|
| | Parameters' values for kiln head waste heat boiler | Parameters' values for kiln tail waste heat boiler |
| Flue gas flow ($Nm^3/h$) | $2 \times 1.35 \times 10^5$ | $2 \times 2.10 \times 10^5$ |
| Temperature of inlet flue gas (°C) | 360 | 330 |
| Temperature of exit flue gas (°C) | 100 | 210 |
| Superheated steam temperature (°C) | 330 | 300 |
| Superheated steam flow (t/h) | 2 × 12.5 | 2 × 16.5 |
| Superheated steam pressure (MPa) | 1.27 | 1.27 |
| Inlet steam flow of turbine (t/h) | 2 × 29.0 | 2 × 29.0 |
| Inlet steam temperature of turbine (°C) | 310 | 310 |
| Inlet steam pressure of turbine (MPa) | 1.2 | 1.2 |
| Output power of turbine (kW) | 2 × 5300 | 2 × 5300 |

**Table 2**
Technical parameters for the heat recovery power generation technology.

| Serial number | Parameters' name | Unit | Parameters' values |
|---|---|---|---|
| 1 | Rated capacity | MW | 2 × 6 |
| 2 | Average output power | kW | 2 × 5300 |
| 3 | Annual operation time | Hour | 7200 |
| 4 | Annual quantity of power generation | $\times 10^4$ kW•h | 2 × 3816 |
| 5 | Annual electricity supply | $\times 10^4$ kW•h | 2 × 3511 |
| 6 | Electricity use rate for HRPG | % | 8 |

maximum power principle (Rydberg and Jansén, 2002). All types of inputs in one system can be quantified and contrasted in terms of emergy (Liu et al., 2015a). Brown and Ulgiati (2004) pointed out EmA is a comprehensive method for investigating diverse systems with different categories or sizes.

The emergy value of different products or service is obtained by multiplying its amount by the related unit emergy value (Brown et al., 2012). There could be different UEVs for one kind of input based on diverse emergy baselines. Here 12.00E24 seJ/yr (Brown et al., 2016), as the latest updated emergy baseline, is adopted for keeping consistency of the final results. The operational procedure of EmA has been given in detail by Odum (1996).

#### 3.1.1. System description of the two scenarios and their emergy flows

According to Figs. 3 and 4, the inputs' categories for scenarios 1 and 2 include local renewable resources $R_1$ (sunlight, wind, rain, geothermal energy, waves and tides), local nonrenewable resources N (limestone), purchased renewable resources $F_{1R}$ (fresh water, sulfuric-acid residue, desulfurization gypsum, fly ash, and furnace). Here these wastes (sulfuric-acid residue, desulfurization gypsum, fly ash, and furnace slag) are regarded as the purchased renewable sources because generally the generation speed of the wastes is faster than that of its consumption (Winfrey and Tilley 2016). The outputs include product Y (cement) and wastes discharges. It should be noted that those wastes discharges from the two systems could cause the two kinds of negative impacts due to lacking sufficient environmental capacity in this region as abovementioned in Section 2, including (1) local extra ecological service ($R_2$) to dilute them to ensure related environmental functions, and (2) potential ecological loss ($R_3$) and human health damage ($F_2$) caused by environmental emissions before they attain related environmental quality standards, and the relevant calculation methods were introduced in Section 3.1.2.

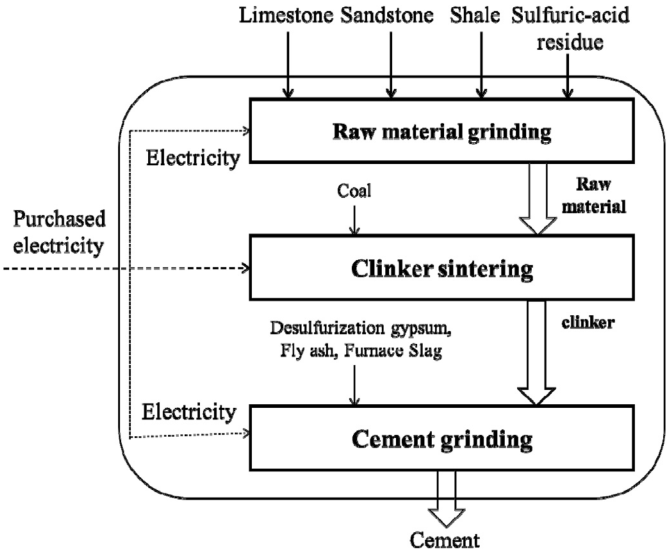

**Fig. 2.** The technological diagram of Scenario 2.

#### 3.1.2. Calculating emissions' impacts

(1) Local extra ecological services: Ulgiati and Brown (2002) firstly put forward one brief method to compute local extra ecological services for diluting air pollutants, and then Zhang et al. (2009a) popularized this method to calculate local extra ecological services for diluting air and water pollutants. Firstly, the required mass of dilution air/water could be computed, as follows.

$$M = d \times \frac{W}{c} \tag{1}$$

where, M refers to the required quantity of dilution air/water (kg/yr); d stands for the density of air or water (1.29 $kg/m^3$ and 1.00E03 $kg/m^3$ for air and water respectively); W means the annual emitted amount of one pollutant from the cement enterprise (kg/yr, the fourth and fifth columns for scenarios 1 and 2 respectively in Table 5); c is the concentration limits of pollutants from legal regulations ($kg/m^3$, the second column in Table 5).

Next, according to work of Pan et al. (2016), kinetic energy of dilution air can be converted into emergy using formula (2), and chemical energy of dilution water can be converted into emergy by formula (3), as follows.

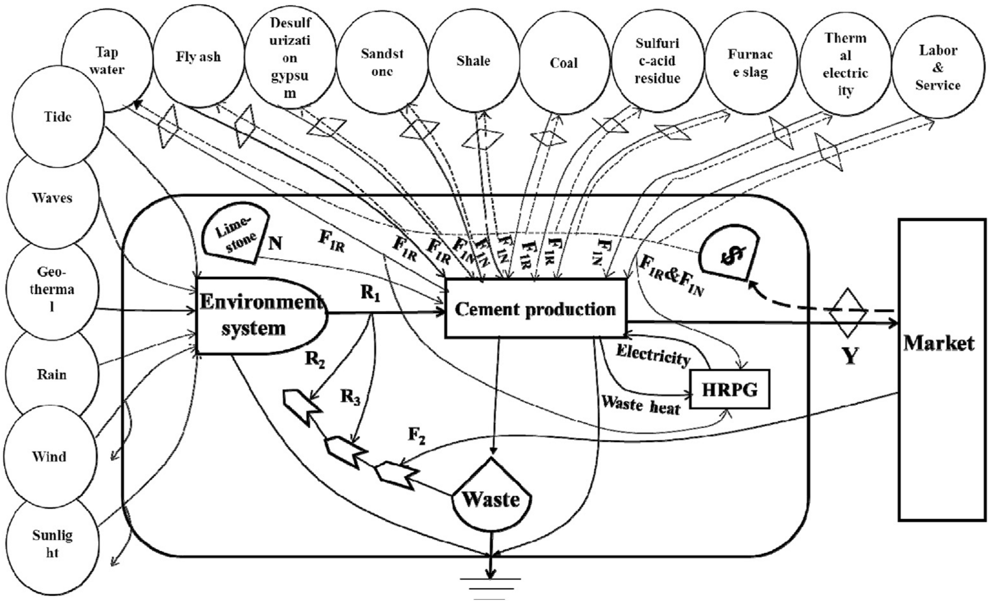

**Fig. 3.** The energy flow system diagram of Scenario 1. HRPG: heat recovery power generation; $R_1$: the local renewable resources inputs; N: the local nonrenewable resources inputs; $F_{1R}$: the purchased renewable resources inputs; $F_{1N}$: the purchased nonrenewable resources inputs; Y: emergy of cement products; $R_2$: emergy of ecological services needed to dilute the emissions; $R_3$: emergy of the ecological losses caused by the emissions; $F_2$: emergy of the economic losses caused by the emissions.

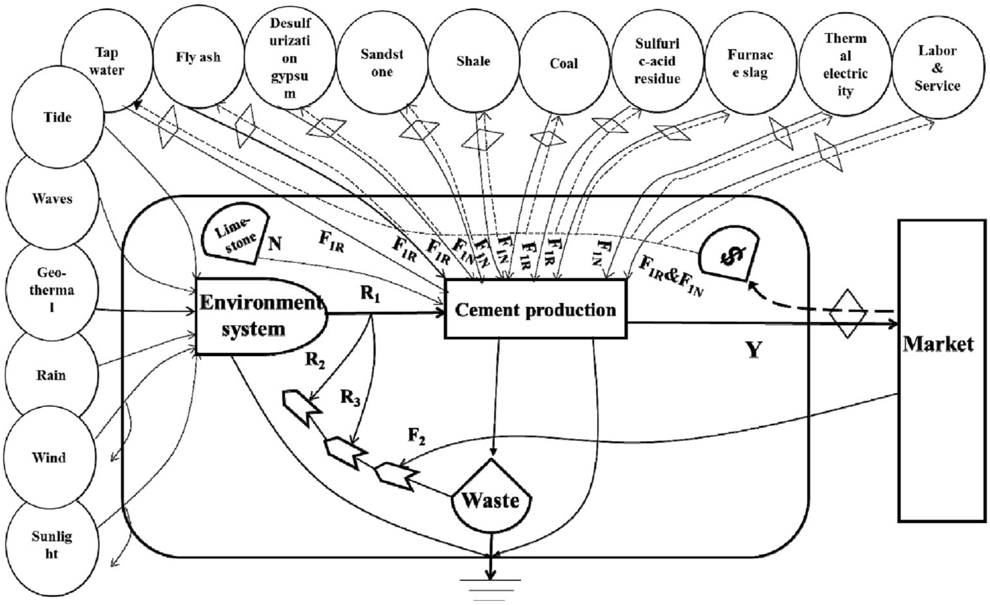

**Fig. 4.** The energy flow system diagram of Scenario 2. $R_1$: the local renewable resources inputs; N: the local nonrenewable resources inputs; $F_{1R}$: the purchased renewable resources inputs; $F_{1N}$: the purchased nonrenewable resources inputs; Y: emergy of cement products; $R_2$: emergy of ecological services needed to dilute the emissions; $R_3$: emergy of the ecological losses caused by the emissions; $F_2$: emergy of the economic losses caused by the emissions.

$$\mathrm{R}_{2,\mathrm{air}} = \frac{1}{2} \times \mathrm{M} \times \mathrm{V}^2 \times \mathrm{Tr}_{wind} \tag{2}$$

$$R_{2,water} = M \times Tr_{runoff} \tag{3}$$

$$R_2 = \max(R_{2,air}) + \max(R_{2,water}) \tag{4}$$

where, $\mathrm{R}_{2,\ \mathrm{air}}$ is local extra ecological services for diluting air emissions (sej/yr); v means annual average wind speed (2.0 m/s for this study case); $\mathrm{Tr}_{\mathrm{wind}}$ is unit emergy value of wind energy, here it is 8.00E02 sej/J, corrected to the emergy baseline 12.00E24 seJ/yr (Brown and Ulgiati, 2016); $\mathrm{R}_{2,\ \mathrm{water}}$ is local extra ecological services to dilute water pollutants (sej/yr), and $\mathrm{Tr}_{\mathrm{runoff}}$ is the unit emergy value of surface runoff in China, i.e. 1.00E08 sej/kg, based on the emergy baseline 12.00E24 seJ/yr (Brown and Ulgiati, 2016). Since atmosphere or water body can dilute different air or water contaminants simultaneously, final value of ecological services equals to the sum of largest ones of $\mathrm{R}_{2,\ \mathrm{air}}$ and $\mathrm{R}_{2,\ \mathrm{water}}$, as shown in formula (4).

(2) Emergy loss resulting from environmental emissions: This study did not take into account ecological loss ($\mathrm{R}_3$) due to the

**Table 3**
Emergy evaluation table of Scenario 1 (Based on the baseline 12.0E+24 seJ/yr).

| Item | Basic data | Units | Unit emergy value (sej/unit) | Solar emergy (sej/yr) | Percent (%) |
|---|---|---|---|---|---|
| **Input** | | | | 7.00E+21 | 100.00% |
| **R₁**(Largest of secondary and tertiary sources) | | | | 5.98E+15 | 0.00% |
| 1.Sunlight | 1.31E+15 | J | 1 | 1.31E+15 | – |
| 2. Earth cycle, heat flow | 6.80E+10 | J | 4.90E+03 | 3.33E+14 | – |
| 3. Tide, kinetic energy | 3.32E+10 | J | 3.09E+04 | 1.03E+15 | – |
| Sum of global tripartite (1–3) | | | | 2.67E+15 | 0.00% |
| 4. Wind, kinetic energy | 7.47E+12 | J | 8.00E+02 | 5.98E+15 | – |
| 5. Waves, kinetic energy | 9.59E+10 | J | 4.20E + 03 | 4.03E+14 | – |
| 6. Rain, chemical potential | 4.46E+11 | J | 7.00E + 03 | 3.12E+15 | – |
| 7. Runoff, geopotential | 3.94E+10 | J | 1.28E+04 | 5.04E+14 | – |
| 8. Runoff, chemical potential | 8.70E+10 | J | 2.13E+04 | 1.85E+15 | – |
| Largest of secondary and tertiary sources (4–8) | | | | 5.98E+15 | 0.00% |
| **N** (Sum of 9) | | | | 2.93E+21 | 41.87% |
| 9.Limestone | 2.31E+06 | t | 1.27E+15 | 2.93E+21 | 41.87% |
| **F₁R** (Sum of 10–16) | | | | 2.57E+21 | 36.67% |
| 10.Tap water | 2.01E+06 | t | 1.26E+12 | 2.53E+18 | 0.04% |
| 11.Sulfuric-acid residue | 6.05E+04 | t | 3.38E+15 | 2.04E+20 | 2.92% |
| 12.Desulfurization gypsum | 1.38E+05 | t | 1.27E+15 | 1.75E+20 | 2.50% |
| 13.Fly ash | 1.76E+05 | t | 3.53E+14 | 6.21E+19 | 0.89% |
| 14.Furnace Slag | 2.73E+05 | t | 7.75E+15 | 2.12E+21 | 30.29% |
| 15.Service (renewable part) | 1.46E+07 | $ | 1.53E+11[a] | 2.23E+18 | 0.03% |
| 16.Labor | 2.09E+06 | $ | 1.53E+11[a] | 3.20E+17 | 0.00% |
| **F₁N**(Sum of 17–22) | | | | 1.50E+21 | 21.46% |
| 17.Thermal electricity | 5.08E+14 | J | 2.03E+05 | 1.03E+20 | 1.47% |
| 18.Sandstone | 1.03E+05 | t | 1.42E+15 | 1.46E+20 | 2.09% |
| 19.Shale | 4.28E+05 | t | 1.27E+15 | 5.44E+20 | 7.77% |
| 20.Soft coal | 6.66E+15 | J | 8.77E+04 | 5.84E+20 | 8.34% |
| 21.Service (nonrenewable part) | 1.46E+07 | $ | 7.49E+12[b] | 1.09E+20 | 1.56% |
| 22. Labor | 2.09E+06 | $ | 7.49E+12[b] | 1.57E+19 | 0.22% |
| **Recycling** (Sum of 23–24) | | | | 5.26E+19 | 0.75% |
| 23.Electricity | 2.53E+14 | J | 2.03E+05 | 5.14E+19 | 0.73% |
| 24.Recycling water | 4.14E+10 | kg | 2.85E+07 | 1.18E+18 | 0.02% |
| **Outputs** | | | | | |
| **Y** | | | | | |
| 25.Cement | 2.40E+06 | t | 2.92E+15[c] | | |
| 26. Economic output | 1.22E+08 | US$ | | | |
| **W** | | | | | |
| 27.COD | 2.88E+02 | kg | | | |
| 28.Dust | 6.80E+05 | kg | | | |
| 29.SO₂ | 1.84E+05 | kg | | | |
| 30.NOx | 2.95E+06 | kg | | | |
| 31.Fluoride | 4.74E+03 | kg | | | |
| 32.CO₂ | 1.02E+09 | kg | | | |

Note.
*The calculation of renewable fraction ($R_1$) is according to Brown and Ulgiati (2016).
**The related footnotes for items 1–32 and a-c were given in SM (Supplementary Materials)-2.

related basic data unavailability. The emergy loss ($F_2$), derived from pollutants' harm to human health (Liu et al., 2013), can be computed using formula (5):

$$F_2 = \sum_{i=1}^{n} M_{\mathrm{i}} \times_{\mathrm{DALYi}} \times \tau_{\mathrm{H}} \tag{5}$$

where, $M_i$ stands for the released amount of pollutant i (kg/yr, the fourth and fifth columns for scenarios 1 and 2, as shown in Table 6), $DALY_i$ means the impact coefficient of the i-th pollutant on human health (person·yr/kg of emissions, given in the third column in Table 6); $\tau_h$ is the per capita emergy use per year, here it is 4.14E16 sej/(person·yr) for this study case (For this case: $\tau_h$ = ($REM_{2011}$ × GDP in the year 2011)/total population in the year 2011). According to the work of Campbell et al. (2014), here the parameter $REM_i$ in the year i was calculated as follows.

$$REM_i = REM_{2008} \times \left[\frac{IGDP_i}{IGDP_{2008}} \div \frac{GDP_{v,i}}{GDP_{v,2008}}\right] \tag{6}$$

where, $REM_i$ and $REM_{2008}$ stand for ratios of emergy to money in the years i and 2008. Therein, $REM_{2008}$ = 8.68E12 sej/$, corrected to the emergy baseline 12.0E24 sej/yr (National Environmental Accounting Database, 2008); $IGDP_i$ and $IGDP_{2008}$ refer to the indices of gross domestic product in years i and 2008, corrected to the year 1978, and the related data in the year 2011 were cited from National Bureau of Statistics of the People's Republic of China (2013); $GDP_{V,\ i}$ and $GDP_{V,\ 2008}$ are the gross domestic product in the years i and 2008 (CNY/yr), and the basic data in the two years came from National Bureau of Statistics of the People's Republic of China (2013).

### 3.1.3. The corresponding emergy - based indicators

(1) EIR (Emergy investment ratio): According to the work of Odum (1996), this indicator can be calculated using formula (7). It reflects dependence degree of an industrial system on external resources and its attraction to exterior investment during the course of exploiting the local resources (Cao and Feng, 2007).

**Table 4**
Emergy evaluation table of Scenario 2 (Based on the baseline 12.0E+24 seJ/yr).

| Item | Basic data | Units | Unit emergy value (sej/unit) | Solar emergy (sej/yr) | Percent (%) |
|---|---|---|---|---|---|
| **Input** | | | | 7.08E+21 | 100.00% |
| **$R_1$**(Largest of secondary and tertiary sources) | | | | 5.98E+15 | 0.00% |
| 1.Sunlight | 1.31E+15 | J | 1 | 1.31E+15 | – |
| 2. Earth cycle, heat flow | 6.80E+10 | J | 4.90E+03 | 3.33E+14 | – |
| 3. Tide, kinetic energy | 3.32E+10 | J | 3.09E+04 | 1.03E+15 | – |
| Sum of global tripartite (1–3) | | | | 2.67E+15 | 0.00% |
| 4. Wind, kinetic energy | 7.47E+12 | J | 8.00E+02 | 5.98E+15 | – |
| 5. Waves, kinetic energy | 9.59E+10 | J | 4.20E + 03 | 4.03E+14 | – |
| 6. Rain, chemical potential | 4.46E+11 | J | 7.00E + 03 | 3.12E+15 | – |
| 7. Runoff, geopotential | 3.94E+10 | J | 1.28E+04 | 5.04E+14 | – |
| 8. Runoff, chemical potential | 8.70E+10 | J | 2.13E+04 | 1.85E+15 | – |
| Largest of secondary and tertiary sources (4–8) | | | | 5.98E+15 | 0.00% |
| **N (4)** | | | | 2.93E+21 | 41.40% |
| 9.Limestone | 2.31E+06 | t | 1.27E+15 | 2.93E+21 | 41.40% |
| **$F_{1R}$ (Sum of 5–10)** | | | | 2.57E+21 | 36.25% |
| 10.Tap water | 1.09E+06 | t | 1.26E+12 | 1.37E+18 | 0.02% |
| 11.Sulfuric-acid residue | 6.05E+04 | t | 3.38E+15 | 2.04E+20 | 2.88% |
| 12.Desulfurization gypsum | 1.38E+05 | t | 1.27E+15 | 1.75E+20 | 2.47% |
| 13.Fly ash | 1.76E+05 | t | 3.53E+14 | 6.21E+19 | 0.88% |
| 14.Furnace slag | 2.73E+05 | t | 7.75E+15 | 2.12E+21 | 29.96% |
| 15.Service (renewable part) | 1.85E+07 | $ | 1.53E+11[a] | 2.83E+18 | 0.04% |
| 16.Labor | 1.92E+06 | $ | 1.53E+11[a] | 2.94E+17 | 0.00% |
| **$F_{1N}$(Sum of 11–15)** | | | | 1.58E+21 | 22.35% |
| 17.Thermal electricity | 7.61E+14 | J | 2.03E+05 | 1.54E+20 | 2.18% |
| 18.Sandstone | 1.03E+05 | t | 1.42E+15 | 1.46E+20 | 2.06% |
| 19.Shale | 4.28E+05 | t | 1.27E+15 | 5.44E+20 | 7.69% |
| 20.Soft coal | 6.66E+15 | J | 8.77E+04 | 5.84E+20 | 8.25% |
| 21.Service (nonrenewable part) | 1.85E+07 | $ | 7.49E+12[b] | 1.39E+20 | 1.96% |
| 22. Labor | 1.92E+06 | $ | 7.49E+12[b] | 1.44E+19 | 0.20% |
| **Recycling** | | | | 1.61E+17 | |
| 23.Recycling water | 5.65E+09 | kg | 2.85E+07 | 1.61E+17 | |
| **Outputs** | | | | | |
| **Y** | | | | | |
| 24.Cement | 2.40E+06 | t | 2.95E+15[c] | | |
| 25. Economic output | 1.22E+08 | US$ | | | |
| **W** | | | | | |
| 26.COD | 2.88E+02 | kg | | | |
| 27.Dust | 8.46E+05 | kg | | | |
| 28.$SO_2$ | 1.84E+05 | kg | | | |
| 29.NOx | 2.95E+06 | kg | | | |
| 30.Fluoride | 4.74E+03 | kg | | | |
| 31.$CO_2$ | 1.02E+09 | kg | | | |

Note.
*The calculation of renewable fraction ($R_1$) is according to Brown and Ulgiati (2016).
**The related footnotes for items 1–31 and a-c were given in SM (Supplementary Materials)-3.

**Table 5**
Ecological services needed to dilute some air and water pollutants for the two scenarios[a].

| Pollutants' name | Acceptable concentration (c, kg/m$^3$) | References | Annual emissions (W, kg/yr) | | $R_2$ (sej/yr) | |
|---|---|---|---|---|---|---|
| | | | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| COD | 1.50E-02 | B | 2.88E+02 | 2.88E+02 | 2.29E+14 | 2.29E+14 |
| Dust | 8.00E-08 | C | 6.80E+05 | 8.46E+05 | 1.47E+17 | 1.83E+17 |
| $SO_2$ | 2.00E-08 | C | 1.84E+05 | 1.84E+05 | 1.59E+17 | 1.59E+17 |
| NOx | 5.00E-08 | C | 2.95E+06 | 2.95E+06 | 1.02E+18 | 1.02E+18 |
| Fluoride | 7.00E-09 | C | 4.74E+03 | 4.74E+03 | 1.17E+16 | 1.17E+16 |
| Total ecological services | – | – | – | – | 1.02E+18 | 1.02E+18 |

Note.
[a] The concentrations in the first grade levels in the corresponding environmental quality stands are regarded as the related pollutants' acceptable concentrations for the fact that they are the safest for human and the environment.
[b] Ministry of Ecology and Environment of the People's Republic China. Surface Water Quality Standard of China (GB3838-2002). Available online: http://kjs.mep.gov.cn/hjbhbz/bzwb/shjbh/shjzlbz/200206/W020061027509896672057.pdf (11 October, 2020; in Chinese).
[c] Ministry of Ecology and Environment of the People's Republic China. Air Quality Standard of China (GB3095-1996). Available online: http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjbh/dqhjzlbz/201203/W020120410330232398521.pdf (11 October, 2020; in Chinese).

$$EIR = \frac{F_{1R} + F_{1N}}{R_1 + N} \tag{7}$$

(2) EER (Emergy exchange ratio): To assess whether the enterprise earns or loses wealth during the course of market exchanges, Odum (1996) proposed the indicator EER to deal with this issue, and it can be described using formula (8).

**Table 6**
The emergy loss caused by the air emissions for the two scenarios.

| Pollutants' name | Damage category of human health | $DALY_i$ (person·yr/kg) | Amount of emission ($M_i$, kg/yr) | | $F_2$ (sej/yr) | |
|---|---|---|---|---|---|---|
| | | | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| Dust | Respiratory Disorders | 1.70E-03[a] | 6.80E+05 | 8.46E+05 | 4.79E+19 (7.90%) | 5.95E+19 (9.64%) |
| $SO_2$ | Respiratory Disorders | 2.70E-04[a] | 1.84E+05 | 1.84Ev05 | 2.06E+18 (0.34%) | 2.06E+18 (0.33%) |
| NOx | Respiratory Disorders | 2.30E-04[a] | 2.95E+06 | 2.95E+06 | 2.81E+19 (4.64%) | 2.81E+19 (4.55%) |
| $CO_2$ | Climate change | 1.25E-05[a] | 1.02E+09 | 1.02E+09 | 5.28E+20 (87.12%) | 5.28E+20 (85.48%) |
| TEL[b] | – | – | – | – | 6.06E+20 (100.00%) | 6.18E+20 (100.00%) |

[a] These parameters came from Ref. (Huijbregts et al., 2017).
[b] TEL: Total emergy loss.

$$EER = \frac{R_1 + N + F_{1R} + F_{1N}}{EO \times REM} \tag{8}$$

where, EO: the economic output (US$/yr); REM is ratio of emergy to money, here it was 7.64E12 sej/US$ in China in 2011, attained according to formula (6). EER>1 means this enterprise loses wealth, EER = 1 means it neither loses nor earns wealth, and EER<1 means it earns wealth during the course of market exchanges (Lan et al., 2002).

(3) WRR (Wastes recycling ratio): Since this enterprise has carried out wastes reuse and heat energy recovery, its wastes recycling degree should be concerned, which can be described using the indicator WRR, as follows.

$$WRR = \frac{Em_R}{R_1 + N + F_{1R} + F_{1N}} \tag{9}$$

where, $Em_R$ is the emergy of recycled wastes (sej/yr). Here the recycled water of the two scenarios substitutes the function of tap water, so the emergy of recycled water is considered as that of the tap water with equal quantity; the electricity from HRPG substitutes the function of thermal electricity, so the emergy of recycled electricity is regarded as that of thermal electricity with equal quantity. Larger indicator values mean higher recycling level or self-organization ability (Wu et al., 2014).

(4) ECI (Energy consumption intensity; sej/t): As a high energy consumption industry, its energy efficiency should be concerned. To consider energy quality, here the emergy based indicator ECI was adopted to describe energy efficiency, as follows.

$$ECI = \sum_{i=1}^{n} Em_i / Y_{output} \tag{10}$$

where, $Em_i$ stands for annual emergy use of the i-th energy source (sej/yr); $Y_{output}$ is annual output of cement product (t/yr). This indicator reflects the energy efficiency of cement production in terms of emergy. And larger indicator value means lower energy efficiency.

(5) IEYR (Improved emergy yield ratio): To integrate environmental emissions' adverse impacts, the classic indicator - emergy yield ratio was adjusted referring to Ref. (Zhang et al., 2018), as follows.

$$IEYR = \frac{R_1 + N + F_{1R} + F_{1N} - F_2}{F_{1R} + F_{1N}} \tag{11}$$

where, $F_2$: emergy loss caused by environmental emissions (sej/yr). Here emergy loss, as one kind of potential environmental cost, should be also merged into EYR (emergy yield ratio) to embody external diseconomies of industrial systems. The IEYR considers the adverse effects of emissions on the positive output of industrial processes. This indicator reflects the competition ability of one production system more properly (Ulgiati and Brown, 2002).

(6) IELR (Improved environmental load ratio): In order to consider extra environmental load derived from environmental emissions, Zhang et al. (2018) put forward the improved emergy based indicator – IELR, as follows.

$$IELR = \frac{N + F_{1N} + R_2}{R_1 + F_{1R}} \tag{12}$$

Compared with the classic environmental load rate, IELR distinguishes the renewable and non-renewable parts of purchased inputs and considers emissions' load on the local environment. It quantifies the environmental load of industrial production resulting from large share of local non-renewable resources and/or high external non-renewable investment as well as environmental emissions. The larger indicator value means the higher environmental press.

(7) IESI (Improved emergy sustainable index): After considering environmental emissions' impacts, the previous emergy sustainability index was also modified (Zhang et al., 2018), as follows.

$$IESI = \frac{IEYR}{IELR} \tag{13}$$

This index indicates the comprehensive environmental performance of the process, i.e. positive output per unit environmental load. And larger index value embodies relatively higher environmental sustainable level.

### 3.2. Economic evaluation

EmA mainly concentrates on environmental performance of an eco-economic system, and it cannot point out practical competition ability of products or service of a system being concerned in the market when value of environmental contribution has not been fully embodied during the course of exchange of commodities. In order to compare impacts of HRPG on real competition ability of cement production, economic evaluation needs to be carried out to supplement lacking information of EmA. Here the two indicators, i.e. cost per unit cement output (CUCO, US$/t) and ratio of economic output and economic input (REOI), were adopted. Therein, CUCO is defined as sum of annual investment and annual operation expense divided by the cement output, and it can be calculated as follows.

$$CUCO = \frac{AI + AOE}{Y_{output}} \tag{14}$$

where, AI: annual investment (US$/yr); AOE: annual operation expense (US$/yr). REOI refers to ratio of annual sales revenue to sum of annual investment and annual operation expense, and it is expressed using formula (15).

$$REOI = \frac{ASR}{AI + AOE} \tag{15}$$

where, ASR: annual sales revenue (US$/yr). Cement production systems with lower values of CUCO and higher values of REOI have relatively stronger economic competition ability.

### 3.3. Data sources

The regional meteorological data were cited from the local meteorological department, and the basic data of the study case were attained through our investigation and consultation. The corresponding UEVs were derived from the published literature and related database, as shown in SM (Supplementary Materials)-1.

## 4. Results and discussion

### 4.1. Comparison of emergy flows of the two scenarios

Emergy flows of scenarios 1 and 2 were given in Tables 3 and 4 respectively. As for the local renewable resources input, it mainly comes from wind energy, its share approximately equals to zero in total emergy input and its share almost keeps no changes before and after implementing HRPG. For the local nonrenewable resources input, it is derived from limestone, and HRPG just enhances its share by 1.14% (41.40% before vs. 41.87% after). Regarding purchased renewable resources input, it mainly comes from furnace slag, followed by sulfuric-acid residue and desulfurization gypsum, and implementation of HRPG only raises its share by 1.16% (36.25% before vs. 36.67% after). As far as the purchased nonrenewable resources input is concerned, implementation of HRPG reduces its share by 3.98% (22.35% before vs. 21.46% after), mainly rooting in the decreased share of thermal electricity (decrease by 32.57%). And it mainly come from soft coal, followed by shale and thermal electricity before implementing HRPG, while it is mainly from soft coal, followed by shale and sandstone after implementing HRPG.

Generally total resources consumption decreased by 1.13% (arriving at 8.00E19 sej/yr), share of renewable resources increased by 2.28%, and share of nonrenewable resources descended by 2.84% after implementation of HRPG. Therefore, HRPG both saves resources and improves structure of resources input to different degree.

### 4.2. Emissions' impacts

Emissions' impacts from the two scenarios were provided in Tables 5 and 6 Although dust emissions from scenario 2 consume the more ecological service than scenario 1, generally NOx emissions from the two scenarios need the largest ecological service among the several pollutants. And the total value of ecological services needed is same for the two scenarios, i.e. 1.02E18 sej/yr; therein, air emissions have share of 99.81%, to which NOx has the absolute contribution. It is found that implementation of HRPG reduces extra environmental load by 19.67%, derived from dust emissions reduction.

The emergy loss is reduced by 1.94% from 6.18E19 sej/yr to 6.06E19 sej/yr after implementing HRPG. Before and after implementing HRPG, $CO_2$ contributes the largest to the emergy loss, followed by dust, NOx and $SO_2$. However, after implementing HRPG, shares of $CO_2$, NOx and $SO_2$ are all raised by 1.93%, respectively, and share of dust decreases by 18.07% compared to that before implementing HRPG. Therefore, reduced emergy loss by implementation of HRPG is derived from dust emissions reduction.

In summary, emissions' impact mainly comes from potential human health harm, rooting in extra environmental emissions exceeding environmental capacity. Implementation of HRPG can slightly mitigate this adverse effect. Although the effectiveness of this measure is limited, the total environmental benefit will be huge if all cement enterprises adopt this measure in China. Of course, to further improve environmental quality in study region, local government has been implementing other emissions reduction measures, such as adjusting industrial structure, improving energy mix, strengthening environmental supervision, etc. Of course, the detailed exploration on all these issues is not within this study scope.

### 4.3. Emergy-based indicators

Table 7 gave the indicator values for the two scenarios. As for EIR, the indicator value of scenario 1 is 1.93% lower than that of scenario 2, which means that HRPG slightly reduces dependence degree of this enterprise on imported resources. For EER, The indicator values of the two scenarios are both much bigger than 1. Moreover, the indicator value of scenario 1 is 1.13% smaller than that of scenario 2. This suggests that other purchasers benefit greatly from the enterprise through buying its cement products while HRPG slightly reduces wealth loss of this enterprise. For WRR, the indicator value of scenario 1 is 329.44 times larger than that of scenario 2, reflecting that HRPG obviously enhances wastes recycling degree of this enterprise, which strengthens its self-organization ability (Wu et al., 2014). For ECI, this indicator value decreases by 6.91% when adopting HRPG, meaning HRPG moderately improves the energy efficiency of this enterprise. Regarding IEYR, the indicator value of scenario 1 is 0.89% larger than that of scenario 2, which shows HRPG slightly enhances production efficiency of this enterprise. If emissions' impacts are ignored, the values of EYR for scenarios 1 and 2 will increase by 9.48% and 9.56%, respectively. For IELR, generally the two scenarios have low load on the local environment, and the environmental load rate of scenario 1 is 1.77% lower than that of scenario 2, reflecting that HRPG slightly mitigates the environmental load of this enterprise. The environmental load rate of the two scenarios will descend by 0.02% respectively when ignoring the emissions' impacts. The index values of IESI show that the two scenarios are unsustainable in the long term according to Ref (Cao and Feng, 2007). While HRPG enhances the sustainability level of this enterprise by 2.71%, mainly due to decreased emergy loss caused by HRPG. When neglecting emissions' impacts, the IESI values of scenarios 1 and 2 will increase by 9.50% and 9.59%, respectively.

Generally HRPG moderately improves the environmental sustainability of this enterprise, mainly derived from improvement of production efficiency caused by increased energy efficiency and emissions reduction; therein, implementation of HRPG significantly raised waste recycling rate, followed by improvement of energy efficiency. In addition, environmental emissions have much larger impact on production efficiency and environmental sustainability than environmental load of this enterprise.

In order to assess main input parameters' influence on emergy based indicator results, the sensitivity analysis is carried out, as shown in SM-4.1–4.4. When the four main input parameters (>5%, including limestone, furnace slag, shale and soft coal) range

**Table 7**
The emergy based indicator values for the two scenarios.

| Name | EIR | EER | WRR | ECI (sej/t) | IEYR | IELR | IESI | EYR | ELR | ESI | IEYR%[a] | IELR%[b] | IESI%[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenario 1 | 1.39 | 7.51 | 0.751% | 2.86E+11 | 1.57 | 1.72 | 0.91 | 1.72 | 1.72 | 1.00 | 9.48% | −0.02% | 9.50% |
| Scenario 2 | 1.42 | 7.60 | 0.002% | 3.08E+11 | 1.56 | 1.76 | 0.89 | 1.71 | 1.75 | 0.97 | 9.56% | −0.02% | 9.59% |
| Changes rate[d] | −1.93% | −1.13% | 32944.19% | −6.91% | 0.89% | −1.77% | 2.71% | 0.81% | −1.77% | 2.63% | – | – | – |

Note.
[a] IEYR% = (EYR-IEYR)*100%/IEYR.
[b] IELR% = (ELR-IELR)*100%/IELR.
[c] IESI% = (ESI-IESI)*100%/IESI.
[d] Changes rate of indicator value = (indicator value of Scenario 1-indicator value of Scenario 2)/indicator value of Scenario 2.

between −10%−10% based on their original input values, there are no clear changes in the selected indicator values for the two scenarios; furthermore, the original emergy evaluation results still keep no changes under different simulation scenarios. Therefore, the research results can act as references for decision-making. In addition, it is found that limestone has the largest impacts on indicator values of EIR, followed by IELR of the two scenarios; furnace slag has the biggest impacts on indicator values of IELR, followed by IESI and EIR of the two scenarios, and soft coal has the largest effects on indicator values of ECI of the two scenarios among the four main input parameters. Therefore, the data quality of the three input parameters should be emphasized in the future.

### 4.4. Economic evaluation

As shown in Table 8, the indicator values of CUCO are 6.96 and 8.50 $/t for scenarios 1 and 2 respectively, and indicator values of REOI are 7.31 and 5.98 for the two scenarios accordingly. These results reflect that implementation of HRPG reduces the cost of this enterprise by 18.12% and raises its economic benefit by 22.24%, which roots in reduced electricity expense.

Therefore, implementation of HRPG can obviously enhance competition ability of this enterprise in the market, which is very appreciated by all enterprises. And the obvious benefit of this measure is helpful to eliminate the possible obstacles confronted in the process of its application in cement industry. In view of its environmental benefit, as above-mentioned, this measure can also acquire support of governments at all levels. And the two advantages of this measure explain why it can be widely used in cement industry.

### 4.5. Discussions and policy suggestions

As for specific emergy of cement products, although HRPG improves resources efficiency of this cement enterprise (2.92E15 sej/t for scenario 1 (Table 3) vs. 2.95E15 sej/t for scenario 2 (Table 4), the improvement rate is very limited (1.02%). Compared with other cement production systems, its resources efficiency is 26.41% lower than the cement enterprise in Guizhou province (2.31E15 sej/t, corrected to 12.0E24 sej/yr; Song and Chen, 2016), and 5.80% lower than the average level of Chinese cement industry (2.76E15 sej/t, reference to the emergy baseline 12.0E24 sej/yr; Zhang et al., 2017). Hashimoto et al. (2010) pointed out that wastes substitution of part raw materials could achieve energy saving and potential environmental benefit, which is consistent with this study. Large share of wastes reuse in the two scenarios alleviates environmental pressure compared to those enterprises which have not implemented wastes reuse (Song and Chen 2016). However, here wastes substitutions of raw materials and HRPG have no clear contribution to improvement of resources efficiency of cement production due to extra resources input. So other measures should be deeply explored to further improve the resources efficiency of this enterprise in the future. The existing study results show that wastes reused as alternative raw materials could significantly reduce mineral resources consumption and environmental emissions (Usón et al., 2013). Several alternative technologies in cement industry have been developed in recent years, such as replacing about 50% of the raw materials with red mud and coal gangue together (Zhang et al., 2009b), replacement of fossil fuels with waste biomass (Gao et al., 2015), the technique of co-processing through introducing alternative fuels (Lamas et al., 2013), substitution of limestone-based clinker by wastes (Hashimoto et al., 2010), etc. To this end, this enterprise has potential ability to substitute part of limestone and fuels using the coal gangue and biomass resources because there are plentiful source of the two wastes in the study region. However, this could require adjustment of part of original technical parameters. With help of China's industrial policies on energy-saving and emissions reduction, this enterprise could solve these technical issues through cooperation with building materials related research institutes.

**Table 8**
The economic indicator values for the two scenarios.

| Item | Scenario 1 | Scenario 2 | Changes rate (%)[d] |
|---|---|---|---|
| Total cost ($/yr)[a] | 1.67E+07 | 2.04E+07 | −18.14% |
| Cement output (t/yr) | 2.40E+06 | 2.40E+06 | 0.00% |
| Sales revenue ($/yr) | 1.22E+08 | 1.22E+08 | 0.00% |
| CUCO ($/t)[b] | 6.96 | 8.50 | −18.12% |
| REOI[c] | 7.31 | 5.98 | 22.24% |

Note.
[a] Total cost = sum of annual investment and annual operation expense.
[b] CUCO: cost per unit cement output.
[c] REOI: ratio of economic output and economic input.
[d] Changes rate = (Indicator values of Scenario 1- Indicator values of Scenario 2)* 100%/Indicator values of Scenario 2.

Meanwhile, the existing HRPG technology in this enterprise has relatively lower efficiency of power generation compared to the third generation technology, and the latter can generate electricity 48−52 kWh per ton clinker (Liu et al., 2015b), which is 16.99−26.74% higher than this study case (41.03 kWh per ton clinker). To enhance performance of the existing HRPG system, on one hand, this enterprise could strengthen management through introducing artificial intelligence to optimize the operational parameters. On the other hand, the technical upgrade of the existing HRPG system could be considered, such as adopting the third generation technology of HRPG, adding two HRPG systems using ORC to further recycle waste heat from low temperature exhaust gas with temperature of 100−200 °C, etc. Of course, the specific schemes should be carefully assessed using the presented approach besides their technical feasibility. Since Chinese government is striving to push forward energy-saving and emissions reduction, some preferential policies on HRPG have been promulgated. Therefore, this enterprise should fully utilize these existing policies to promote technical progress of its HRPG system in the future.

As far as the comparability of the results of emissions' impacts are concerned, as given in the footnote of Table 5, here the parameter “c” is chosen as the concentration limits in the first grade levels in the corresponding environmental quality stands considering the fact that they are the safest for human health and the environment. Specifically, this work adopted the two national environmental quality stands, i.e. Surface Water Quality Standard of China and Air Quality Standard of China, and they are all mandatory standards of Chinese government. So the comparability of the results can be ensured in other nations and regions if the same concentration limits are adopted.

Finally, it should be pointed out that the results of emissions' impacts could be influenced to some degree, resulting from ignoring the ecological loss caused by environmental emissions. And the factor can be integrated in the corresponding results in the future when these data availability.

## 5. Conclusion

This study investigated comprehensive performance of the enterprise before and after implementation of HRPG by the proposed approach. The presented methods and indicators improve emergy assessment of cement industry through considering emissions' impacts and distinguishing the related categories, and separating the purchased renewable inputs from the purchased nonrenewable ones. Research results that HRPG has moderate contribution to improvement of environmental sustainability of this enterprise, and also clearly improves its economic benefit. And the two advantages of HRPG root in energy-saving and emissions reduction, which promotes wide application of this measure in cement industry. Further endeavors should concentrate on improvement of resources input's mix of this enterprise and update of the existing HRPG technology considering it high dependence degree on nonrenewable inputs and limited contribution of HRPG to improvement of its environmental performance. The prosed methods can not only act as one of policy-making tools for the cement industry, but also provide useful references for other resource-dependent industries.

## Credit author statement

**Xiaohong Zhang**: Conceptualization, emergy analysis, the indicator system construction, Data curation, manuscript revision, Resources, Funding acquisition. **Ni Xiang:** Raw data collection, Writing- Original draft preparation. **Hengyu Pan:** improvement of emergy analysis, manuscript revision. **Xiangdong Yang**: Writing – review & editing. **Jun Wu**: Data curation. **Yanzong Zhang**: Supervision. **Hongbing Luo**: Visualization. **Changlian Xu**: Formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This study was supported by the National Key R&D Program of China (2017YFD0200703), National Natural Science Foundation of China (Grant No. 31572204, 31872177), the Dual Support Plan of Sichuan Agricultural University (03570312, 03571248, 03571906, and 03572533).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.125901.

## References

Bontempi, E., 2017. A new approach for evaluating the sustainability of raw materials substitution based on embodied energy and the $CO_2$ footprint. J. Clean. Prod. 162, 162–169.

Brown, M.T., Ulgiati, S., 2004. Emergy analysis and environmental accounting. In: Cleveland, C. (Ed.), Encyclopedia of Energy. Academic Press, Elsevier, Oxford, UK, pp. 329–354.

Brown, M.T., Raugei, M., Ulgiati, S., 2012. On boundaries and ‘investments’ in Emergy Synthesis and LCA: a case study on thermal vs. photovoltaic electricity. Ecol. Indicat. 15 (1), 227–235.

Brown, M.T., Ulgiati, S., 2016. Emergy assessment of global renewable sources. Ecol. Model. 339, 148–156.

Brown, M.T., Campbell, D.E., Vilbiss, C.D., Ulgiati, S., 2016. The geobiosphere emergy baseline: a synthesis. Ecol. Model. 339, 92–95.

Cagiao, J., Gómez, B., Doménech, J.L., Mainar, S.G., Lanza, H.G., 2011. Calculation of the corporate carbon footprint of the cement industry by the application of MC3 methodology. Ecol. Indicat. 11 (6), 1526–1540.

Cao, K., Feng, X., 2007. Distribution of emergy indices and its application. Energy Fuels 21 (3), 1717–1723.

Campbell, D.E., Lu, H., AllenWalker, H., 2014. Relationships among the energy, emergy, and money flows of the United States from 1900 to 2011. Front. Energy Res. 2, 1–31. https://doi.org/10.3389/fenrg.2014.00041.

Chen, W., Liu, W.J., Geng, Y., Ohnishi, S., Sun, L., Han, W.Y., Tian, X., Zhong, S.Z., 2016. Life cycle based emergy analysis on China's cement production. J. Clean. Prod. 131, 272–279.

Chen, D., Bi, B., Luo, Z., Cao, X., Wang, W., Chen, J., 2018. Communicating about the environmental sustainability assessment of China's cement industry based on emergy. Ecol. Indicat. 86, 96–97.

Chen, Y., Zhang, X., Yang, X., Lv, Y., Wu, J., Lin, L., Zhang, Y., Wang, G., Xiao, Y., Zhu, X., Yu, X., Peng, H., 2020. Emergy evaluation and economic analysis of compound fertilizer production: a case study from China. J. Clean. Prod. 260, 121095.

Fan, Y., Wu, X., Wu, X., Li, C., Yang, Q., Hayat, T., Alsaedi, A., Wang, P., Chen, G., 2020. A unified ecological assessment of a solar concentrating plant based on an integrated approach joining cosmic exergy analysis with ecological indicators. Renew. Sustain. Energy Rev. 129, 109934.

Gao, T., Shen, L., Shen, M., Chen, F.N., Liu, L.T., Gao, L., 2015. Analysis on differences of carbon dioxide emission from cement production and their major determinants. J. Clean. Prod. 103 (103), 160–170.

Huang, Y.H., Chang, Y.L., Fleiter, T., 2016. A critical analysis of energy efficiency improvement potentials in Taiwan's cement industry. Energy Pol. 96, 14–26.

Hashimoto, S., Fujita, T., Geng, Y., Nagasawa, E., 2010. Realizing $CO_2$ emission reduction through industrial symbiosis: a cement production case study for Kawasaki. Resour. Conserv. Recycl. 54 (10), 704–710.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., Zelm, R.v., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147.

Jiang, D.Y., Cang, D.Q., Guan, S.L., Wu, H., Wang, Z.H., Cui, S.P., 2008. Environment loading analysis and evaluation of waste heat power generation on cement kiln. Chinese Cement (4), 76–78 (in Chinese).

Kajaste, R., Hurme, M., 2016. Cement industry greenhouse gas emissions – management options and abatement cost. J. Clean. Prod. 112, 4041–4052.

Karellas, S., Leontaritis, A.D., Panousis, G., Bellos, E., Kakaras, E., 2013. Energetic and exergetic analysis of waste heat recovery systems in the cement industry. Energy 58 (9), 147–156.

Liu, G.Y., Yang, Z.F., Chen, B., Zhang, Y., Su, M., Zhang, L.X., 2013. Emergy evaluation of the urban solid waste handling in liaoning province, China. Energies 6 (10), 5486–5506.

Liu, G., Yang, Z., Chen, B., Zhang, J., Liu, X., Zhang, Y., Su, M., Ulgiati, S., 2016. Scenarios for sewage sludge reduction and reuse in clinker production towards regional eco-industrial development: a comparative emergy based assessment. J. Clean. Prod. 103, 371–383.

Liu, Z., Geng, Y., Wang, H., Sun, L., Ma, Z., Tian, X., Yu, X.M., 2015a. Emergy-based comparative analysis of energy intensity in different industrial systems. Environ. Sci. Pollut. Res. 22 (23), 18687–18698.

Liu, Y., Wang, H.M., Zhang, F., Tian, G., Deng, S., Wang, X.F., 2015b. Review of waste gas volume reduction technologies to decrease emission of pollutants [J]. J. Environ. Eng. Technol. 5 (3), 220–226 (in Chinese).

Lan, S.F., Qin, P., Lu, H.F., 2002. Emergy Synthesis of Ecological Economic Systems. Chemical Industry Press, Beijing, China (in Chinese).

Lamas, W.D.Q., Palau, J.C.F., Camargo, J.R.D., 2013. Waste materials co-processing in cement industry: ecological efficiency of waste reuse. Renew. Sustain. Energy Rev. 19 (1), 200–207.

Mikulčić, H., Cabezas, H., Vujanović, M., Duić, N., 2016. Environmental assessment of different cement manufacturing processes based on Emergy and Ecological Footprint analysis. J. Clean. Prod. 130, 213–221.

National Bureau of, 2020. Statistics of the People's Republic of China. National data (in Chinese). http://data.stats.gov.cn/search.htm?s=cement. (Accessed 4 October 2020).

National Environmental Accounting Database, 2008. NEAD Data by Country (in Chinese). https://cep.ees.ufl.edu/nead/data.php?country=31&year=368. (Accessed 20 November 2017).

National Bureau of, 2013. Statistics of the People's Republic of China. China Statistical Yearbook (in Chinese). http://www.stats.gov.cn/tjsj/ndsj/2013/indexch.htm. (Accessed 20 November 2017).

Odum, H.T., 1988. Self-organization, transformity and information. Science 242 (4882), 1132–1139.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons, New York.

Pan, H.Y., Zhang, X.H., Wang, Y.Q., Qi, Y., Wu, J., Lin, L.L., Peng, H., Qi, H., Yu, X.Y., Zhang, Y.Z., 2016. Emergy evaluation of an industrial park in Sichuan Province, China: a modified emergy approach and its application. J. Clean. Prod. 135, 105–118.

Piao, W.H., Chen, Y., Zhang, S.S., Xu, X.L., 2012. Cleaner production audit for a cement enterprise based on LCA. Acta Sci. Circumstantiae 32 (7), 1785–1792 (in Chinese).

Pulselli, R.M., Simoncini, E., Ridolfi, R., Bastianoni, S., 2008. Specific emergy of cement and concrete: an energy-based appraisal of building materials and their transport. Ecol. Indicat. 8 (5), 647–656.

Richards, G., Agranovski, I.E., 2015. Air emission from the co-combustion of alternative derived fuels within cement plants: gaseous pollutants. J. Air Waste Manag. Assoc. 65 (2), 186–196.

Rydberg, T., Jansén, J., 2002. Comparison of horse and tractor traction using emergy analysis. Ecol. Eng. 19 (1), 13–28.

Shen, J., Zhang, X., Lv, Y., Yang, X., Wu, J., Lin, L., Zhang, Y., 2019. An improved emergy evaluation of the environmental sustainability of China's steel production from 2005 to 2015. Ecol. Indicat. 103, 55–69.

Shen, W.G., Cao, L., Li, Q., Zhang, W.S., Wang, G.M., Li, C.C., 2015. Quantifying $CO_2$ emissions from China's cement industry. Renew. Sustain. Energy Rev. 50, 1004–1012.

Song, D., Yang, J., Chen, B., Hayat, T., Alsaedi, A., 2016. Life-cycle environmental impact analysis of a typical cement production chain. Appl. Energy 164, 916–923.

Song, D., Chen, B., 2016. Sustainability evaluation of a typical cement production chain in China – an emergy perspective. Energy Procedia 104, 98–103.

Song, D., Lin, L., Wu, Y., 2019. Extended exergy accounting for a typical cement industry in China. Energy 174, 678–686.

Sui, X., Zhang, Y., Shao, S., Zhang, S., 2014. Exergetic life cycle assessment of cement production process with waste heat power generation. Energy Convers. Manag. 88, 684–692.

Tang, J., 2007. Exploration on assessment methods of pure low temperature waste heat power generation technologies in cement production. Chinese Cement (5), 58–62 (in Chinese).

Ulgiati, S., Brown, M.T., 2002. Quantifying the environmental support for dilution and abatement of process emissions: the case of electricity production. J. Clean. Prod. 10 (4), 335–348.

Usón, A.A., López-Sabirón, A.M., Ferreira, G., Sastresa, E.L., 2013. Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options. Renew. Sustain. Energy Rev. 23 (4), 242–260.

Wang, H., Wang, H.T., 2010. Low Temperature Waste Heat Power Generation Organic Rankine Cycle Technology. Science Press, Beijing, China (in Chinese).

Wang, H., Xu, J., Yang, X., Miao, Z., Yu, C., 2015. Organic Rankine cycle saves energy and reduces gas emissions for cement production. Energy 86, 59–73.

Wang, w., Jiang, D., Chen, D.J., Chen, Z.B., Zhou, W.J., Zhu, B., 2016. A Material Flow Analysis (MFA)-based potential analysis of eco-efficiency indicators of China's cement and cement-based materials industry. J. Clean. Prod. 112, 787–796.

Winfrey, B.K., Tilley, D.R., 2016. An emergy-based treatment sustainability index for evaluating waste treatment systems. J. Clean. Prod. 112, 4485–4496.

Wu, X.F., Wu, X.D., Li, J.S., Xia, X.H., Mi, T., Yang, Q., Chen, G.Q., Chen, B., Hayat, T., Alsaedi, A., 2014. Ecological accounting for an integrated "pig-biogas-f ish" system based on emergetic indicators. Ecol. Indicat. 47, 189–197.

Yang, X., Suia, P., Zhanga, X., Dai, H., Yan, P., Li, C., Wang, X., Chen, Y., 2019. Environmental and economic consequences analysis of cropping systems from fragmented to concentrated farmland in the North China Plain based on a joint use of life cycle assessment, emergy and economic analysis. J. Environ. Manag. 251, 10958.

Zhao, Y., Zhang, J., Nielsen, C.P., 2014. The effects of energy paths and emission controls and standards on future trends in China's emissions of primary air pollutants. Atmos. Chem. Phys. 14 (6), 335–338.

Zhang, X.H., Jiang, W.J., Deng, S.H., Peng, K., 2009a. Emergy evaluation of the sustainability of Chinese steel production during 1998–2004. J. Clean. Prod. 17 (11), 1030–1038.

Zhang, X.H., Shen, J.M., Wang, Y.Q., Qi, Y., Liao, W.J., Shui, W., Li, L., Qi, H., Yu, X.Y., 2017. An environmental sustainability assessment of China's cement industry based on emergy. Ecol. Indicat. 72, 452–458.

Zhang, N., Sun, H.H., Liu, X.M., Zhang, J.X., 2009b. Early-age characteristics of red mud–coal gangue cementitious material. J. Hazard Mater. 167 (1–3), 927–932.

Zhang, X., Xiang, N., Wang, W., Liao, W., Yang, X., Shui, W., Wu, J., Deng, S., 2018. An emergy evaluation of the sewage sludge treatment system with earthworm compositing technology in Chengdu, China. Ecol. Eng. 110, 8–17.