Comparative environmental sustainability study of an improved sewage sludge treatment and sludge reuse system based on emergy analysis in China

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Abstract

As the significant residuals in the sewage treatment system, sludge treatment and reuse play a pivotal impact on the environmental sustainability study in China. In this paper, two sewage sludge treatment systems have been investigated, calculated, and analyzed, including the conventional treatment system (Scenario A) and improved reuse system (Scenario B), respectively. The results demonstrate that (1) Compared to Scenario A, Scenario B is a comprehensive system, which integrates a sewage sludge treatment system and a brick production system for sludge recycling. (2) After considering the brick system (scenario B), on the one hand, the sludge treatment capacity has been enhanced and raised sludge utilization; on the other hand, negative influences have also generated due to the non-renewable resources input and several outputs. (3) In Scenario A and Scenario B, the input resources part reflects the main impact (about 59.6% in the entire emergy value). (4) In this new paper, the UEVs are $2.73\text{E} + 11\text{sej/kg}$ and $6.29\text{E} + 11\text{sej/kg}$ in Scenario A and Scenario B, respectively. (5) The emergy sustainability indexes (ESI) are 0.012292 and 0.00848, which express the weak comprehensive effects in Scenario A and Scenario B. (6) Scenario B has a more extensive range of change than Scenario A because of the more resource input for the sensitivity analysis. Given the all discussions, there are two effective approaches to be used for perfecting environmental sustainability in the Scenario A system and Scenario B system.

Keywords Sewage sludge treatment and reuse · Emergy analysis · Indicators · Sustainability

Introduction

A mass of sewage discharge was performed in order to satisfy economic development demand in China. In 2015, a great deal of wastewater was produced (73.53 billion tons), including chemical oxygen demand (22.235 million tons) and $\text{NH}_3\text{-N}$ (2.299 million tons) (China Environmental Statistics Annual Report 2015). Therefore, lots of sewage sludge will generate after sewage discharge. On the one hand, vast quantities of mud are buried in landfills resulting in severe

environmental load for sustainable development in China (Kui and Boqiang 2019; Wenjun et al. 2019). On the other hand, a lot of resources were wasted, such as sewage sludge, but the sewage sludge can be reused as a recycling resources to reduce waste. Under such a circumstance, it is necessary to develop the improved sludge treatment and reuse system to enhance environmental sustainability in China.

Until now, several related sludge studies were executed by some researchers on the basis on disparate views. Plenty of scholars have investigated sewage sludge reuse directions, such as material angles (Yuchi et al. 2020; Zhi-Xiang et al. 2019), agricultural perspective (Mirko et al. 2019; Cassio et al. 2019; Bo et al. 2019), health effects (Choudri and Yassine 2019), the biological perspective (Patrick et al. 2019; Agata et al. 2019), land application (Liping et al. 2019), chemical angles (Xueya et al. 2019; Jialin et al. 2020), Urban field (Nozela et al. 2018), life cycle assessment (LCA) perspective (Raphael et al. 2018; Domagoj Nakic 2018), and systematic assessment framework (Ferrans et al. 2020).

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In addition, several shortcomings can be found in these studies, containing (1) The single views. There is only one or insufficient views to explain the sludge reuse process and results, which have inaccurate results. (2) Lack of consideration for natural resources. The negative effect will be generated for the sustainability of evaluated system. (3) Disparate sludge reuse subsystem proportion. The undifferentiated contribution degree will lead to a certain amount of error. (4) Be short of a unified platform, consisting of resources, energy, labor, and reuse subsystem. (5) Without pollutant emissions consideration simultaneously, such as waste gas. Based on the above five drawbacks, the results of the environmental sustainability evaluation are subject to mistakes for some extent.

Compared to these studies, the emergy approach can perfect the defects and it was brought up by Odum (Odum 1996). Emergy method considers all inputs, including renewable energy, non-renewable resource, synthetic fuels labor, and pollutants, in order to complete environmental sustainability assessment on a comprehensive platform. Hence, it can be applied to different systems of natural, artificial, and complex models and realize the assessment by a series of indices. On the basis of emergy method, lots of studies have been conducted, involving sewage system evaluation (Junxue and Lin 2020), agricultural studies (XiaoHong et al. 2010, 2018), city assessments (Gengyuan et al. 2015; Brandon and Winfrey 2016), green building field (Shuai et al. 2017; Marc et al. 2016), production systems (Natalia et al. 2018; Johanna et al. 2001), national research (Sam et al. 2019), pollutant treatment (Ling et al. 2014), traffic range (Sadegh et al. 2020).

Specifically speaking, XiaoHong et al. (2010) have carried out relationship research between sustainability and sludge reuse in China. Based on the emergy method, XiaoHong et al. (2018) investigated sustainability through

earthworm composting technology in sewage sludge treatment (Xiaohong et al. 2018). In view of four different Scenarios in sewage sludge treatment systems, sustainability has been assessed using improved emergy indicators by Gengyuan et al. (2015) (Gengyuan et al. 2015). Taking wastewater treatment as an example, Brandon et al. (2016) assessed sustainability several on the basis of emergy approach in China (Brandon and Winfrey 2016). Shuai et al. (2017) implemented emergy analysis in the sewage treatment factory, which involved a sludge treatment process (Shuai et al. 2017). The LCA-emergy method has been used in the wastewater treatment system, and the sludge waste products can be utilized in land application (Marc et al. 2016). Natalia et al. (2018) performed an emergy analysis for sustainability by using biosolids generated in a municipal wastewater treatment plant (Natalia et al. 2018). Emergy analysis of municipal wastewater treatment has been executed, and the electricity was generated by digestion of sewage sludge (Johanna et al. 2001). Via the in urban water systems, a holistic emergy analysis was carried out by Sam et al. (2019) (Sam et al. 2019). Ling et al. (2014) conducted some introductions about the method, indicator, and application in the wastewater treatment system on the basis of emergy method, including the sludge treatment process (Ling et al. 2014). According to the study of Sadegh et al. (2020), a sustainability evaluation of wastewater treatment plants has been surveyed based on Emergy-LCA method (Sadegh et al. 2020).

Three disadvantages can be displayed in Table 1, including (1) Lack of comprehensive sewage sludge treatment and reuse assessment system. By the statistics of research articles, the comprehensive sewage sludge reuse system emergy has not been considered in the system (shown in Table 1). (2) Old emergy baseline. Most of the articles applied the old emergy baselines. (3) Partial emergy indexes. There are only the basic emergy indicators and lack of indicators of

Table 1 Comparisons of published papers using emergy in sludge reuse systems

No	References	Emergy baseline	Sludge and emergy analysis			Country
			Sludge treatment	Single reuse	Second reuse	
1	Johanna et al. (2001)	Old	✓	×	×	Sweden
2	XiaoHong et al. (2010)	Old	✓	✓	×	China
3	Ling et al. (2014)	Old	✓	×	×	China
4	Gengyuan et al. (2015)	Old	✓	✓	×	China
5	Brandon et al. (2016)	Old	✓	×	×	USA
6	Marc et al. (2016)	Old	✓	✓	×	USA
7	Shuai et al. (2017)	Old	✓	×	×	China
8	XiaoHong et al. (2018)	New	✓	✓	×	China
9	Natalia et al. (2018)	Old	✓	✓	×	Colombia
10	Sam et al. (2019)	New	✓	×	×	USA
11	Sadegh et al. (2020)	None	✓	×	×	Iran
~	This paper Now	New	✓	✓	✓	China

improvement. The above three disadvantages should be solved in sewage sludge treatment, and reuse system and these weaknesses support the completion of this article.

In this paper, two sewage sludge treatment systems are designed to assess sustainability, which have four contributions: (1) Taking entire views into account so as to evaluate sludge reuse process; (2) Building an improved and integral energy indicators; (3) Computing two unit energy values of different sludge reuse systems; (4) Raising the resolution strategies to improve negative results.

In the end, the structure of this paper is shown as follows. Part 1 is introduction. Part 2 demonstrates the data and method. Part 3 shows the major result and discussion, including Scenario A and Scenario B systems analysis. Part 4 gives the active strategy, and the last part is the conclusions.

Methodology

The basic situation

The original data

The basic data source of this article is from a sewage sludge treatment factory and there are 500 employees, which belongs to Shanghai city in China. An yearly wind speed of 3.25 m/s can be found from related data in Shanghai (Shanghai Meteorological Bureau 2019). As the largest city in China, its has 474.6 billion US dollars of GDP in 2018 and 6340.5 square kilometers of land area. The sludge comes from municipal sewage in Shanghai, which must satisfy the mandatory national standards (GB 18918-2002).

Sewage sludge treatment and reuse process

Based on the statistics in the factory, vital data are given as follows: 12,100 tons/year of sludge volume, truck transport distance of 10 km, and 18.76 \$/ton of mud treatment service fee. All calculations are based on US dollars, and the exchange rate is 6.87RMB:1US\$.

Figure 1 illustrates the sludge reuse system craft process. In Fig. 2, as the subsystem in the Scenario B system, the brick production process is made up of bottom ash storage procedure, pretreatment process, screening process, stirring process, and molding process. Bottom ash is the residue product after the sludge treatment process. Besides, some other materials are needed to support the brick production process, including cement, tap water, steel slag, gravel, and limestone.

Energy approach

Energy analysis (EmA)

The energy concept is defined as the effective energy and the unit is solar energy (sej). It was put forward by Odum (1996) firstly. Energy is an all-around view and contains the direct input, indirect part, energy part, and labor and service section. The energy approach can integrate some sections into the unified platform to evaluate the environmental level (Luís et al. 2016; Brown et al. 2012). Specifically speaking, the environmental sustainability of sludge reuse can be assessed by transforming all kinds of physical units, involving energy (J), mass (kg), and financial (\$) (Wei et al. 2016). Through multiplied by unit energy values (UEVs), various types of energy can be calculated (Zhou et al. 2009), containing energy/energy (sej/j), specific energy (sej/g), and energy/money (sej/\$), respectively (Yan et al. 2018).

Energy baseline is another pivotal issue that will impact on accuracy in sludge reuse system sustainability, and it illustrates energy of biosphere, including solar, tidal, and geothermal energy. Until now, there are currently five baselines, which are $9.44\text{E}+24\text{sej/year}$ (Odum 1996), $9.26\text{E}+24\text{sej/year}$ (Campbell, 1998), $15.83\text{E}+24\text{sej/year}$ (Odum 2000), $15.2\text{E}+24\text{sej/year}$ (Brown and Ulgiati 2010), $12\text{E}+24\text{sej/year}$ (Brown and Ulgiati 2016a), respectively. In this article, the latest energy baseline of $12\text{E}+24\text{sej/year}$ was used to calculate energy in sludge reuse system.

Energy diagrams of the sewage sludge treatment systems (Scenario A and Scenario B)

There are two Scenarios for the sewage sludge treatment system, as shown in Figs. 3 and 4. The most significant difference between them is the sludge reuse system consideration. Compared to Scenario A, sludge treatment and reuse system are integrated into the process (Green part in Scenario B). In Fig. 4, non-renewable resources are needed for the brick production system, involving cement, tap water, steel slag, gravel, and limestone. The renewable energy is composed of sunlight energy, rain energy, wind energy, and heat energy.

Ecological sustainable indexes

Several indexes will be utilized in two sludge reuse system assessments (Scenario A and Scenario B) in Table 2.

1. Renewability rate (R_r): the rate that entire energy divided by renewable part. The bigger the number, the better the sustainability.
2. Non-renewability rate (N_r) shows the ratio of non-renewable resources to total energy. Lower N_r illustrates better sustainable level.

Fig. 1 Sewage sludge reuse system craft

Fig. 2 Small brick production subsystem in Scenario B

Fig. 3 Scenario A: the original energy flow of sewage sludge treatment system

Fig. 4 Scenario B: the improved energy flow of sewage sludge treatment system

3. Non-renewability rate of purchased resource (N_p) is the rate between purchased input and emergy sum. The smaller the number, the better the sustainability.
4. Emergy personal density (E_d) is the emergy of one person. It means a high amount reveals good environmental state.
5. Emergy intensity (E_i) means the emergy amount of unit area that shows emergy efficiency.
6. Pollutant environmental impact rate (PEIR) is pollutants emergy ratio. Larger value demonstrates poor environmental sustainability.
7. Emergy yield ratio (EYR): EYR represents the ability of generating emergy. The lower the EYR is, the worse the result of sludge reuse system is (Ulgiati and Brown 2002).
8. Environmental loading ratio (ELR): It can be utilized to display the environmental load in the system. Generally speaking, there are three standards for the ELR, which are acceptable standard (Less than 2), basic qualifications ($3 < ELR < 10$), and unqualified result (more than 10) (Cao and Feng 2007).
9. Emergy sustainability index (ESI): It is a proportion between EYR and ELR, which represents the sustainability in the system. In general, three standards have been adopted (Cao and Feng 2007), including $ESI < 1$ (poor), $1 < ESI < 5$ (qualified), and $ESI > 5$ (good).
10. Unit emergy values (UEVs) demonstrate emergy amount based on a unit of substance, energy, labor service, and money, which shows the effect in the process (Brown et al. 2012).

Table 2 Total indexes in two sludge reuse systems

Types	Meaning
Renewable energy emergy (R)	Fundamental view
Non-renewable resource emergy (F)	Fundamental view
Purchased emergy (P)	Fundamental view
Wastewater treatment chemicals emergy (C)	Fundamental view
Labor and service emergy (L)	Fundamental view
Energy emergy (E)	Fundamental view
Transportation emergy (S)	Fundamental view
Pollutant emergy (P_e)	Fundamental view
Entire emergy (T)	Entire emergy
Renewability rate (R_r)	Renewable ratio
Non-renewability rate of local resource (N_r)	Local resource ratio
Non-renewability rate of purchased resource (N_p)	Outside economic impact
Emergy personal density (E_d)	Emergy per person
Emergy intensity (E_i)	Emergy per area
Pollutant environmental impact rate (PEIR)	Pollutant level
Environmental loading ratio (ELR)	Environmental stress
Emergy yield rate (EYR)	Financial effect
Emergy Sustainability Index (ESI)	Sustainable state

Sensitivity analysis

As a test of effectiveness, sensitivity analysis must be checked after the emergy evaluation in the system. So as to enhance the efficiency, it can be computed on account of emergy element error variation and the formula can be utilized as (1):

$$E_m(i) = [(E + \varepsilon_e) \times i] \times [(T + \varepsilon_t) \times i] \quad (1)$$

where E_m shows emergy value; E displays energy (J), mess (kg), and economical (\$), respectively; T is emergy conversion rate, ε_e represents the error, and ε_t signifies the failure (Hwang and William 2015).

Waste gas emergy calculations of sludge reuse systems

Basic emission situation

In Figs. 3 and 4, exhaust gas has been shown in sludge treatment system a and sludge treatment system B. On the basis of the national standard (GB 13223-2011), dust, sulfur dioxide, nitrogen oxides, carbon dioxide, and nitrous oxide will be produced in sludge treatment A system and sludge treatment B system. Respiratory disease and bad ecological balance will be generated because of exhaust gases so as to harm ecosystem sustainability of sludge reuse (Zhang et al. 2009). To achieve the overall assessment, there are two aspects that need to compute, involving ecological service emergy and economic loss emergy. After waste gas

treatment process, the basic data become $35 \mu\text{g}/\text{m}^3$ (dust), $50 \mu\text{g}/\text{m}^3$ (SO_2), $80 \mu\text{g}/\text{m}^3$ (NO_x), $200 \mu\text{g}/\text{m}^3$ (CO_2), $80 \mu\text{g}/\text{m}^3$ (N_2O) based on ambient air quality standard (National mandatory standard in China) (GB3095-2012).

Economic loss accounting

As part of the emergy calculation, the economic losses of exhaust gas must be considered and calculated in the two systems. In light of the DALY in Table 3, human health impact can be calculated using formula 2. Relevant literature can be referred to Bakshi (2002) and Liu et al. (2013).

$$L = \sum W_i \times \text{DALY}_i \times \alpha \quad (2)$$

L represents emergy loss because of the human health effect (sej/a); I shows the gas item. W_i is the waste gas amount. DALY is the impact item (a/kg). α is emergy to humans per

Table 3 DALY data of exhaust gas emission emissions in this article (Yan et al. 2018)

Name of gas	Amount/y	Damage impact on human health	DALY (a/Kg of discharge)
Dust	1.44E04 kg	Respiratory	5.46E−05
SO_2	2.97E03 kg	Respiratory	8.87E−05
NO_x	1.75E03 kg	Respiratory	3.75E−04
CO_2	7.83E05 kg	Climate change	2.10E−07
N_2O	6.92E02 kg	Respiratory	6.90E−05

year and is 1.68E16sej/(a·person) on the basis of the baseline 12.0E24sej/a (Yan et al. 2018) (Table 4).

Ecological services calculation

Another part of exhaust gas emergy calculation is ecological services, which have also a passive environmental impact. Therefore, emergy assessment of five waste gases should be computed, including two steps.

Firstly, the exhaust gas amount can be calculated by using formula (3).

$$M_i = c \times \left(\frac{U_i \times 10^6}{s_i} \right) \quad (3)$$

Therein, M_i is the dilution air mass (Kg/a). c shows gas item. c represents air density (1.23 kg/m³). U_i means the annual air pollutants mass (Kg/a). s_i represents the acceptable concentration (mg/m³). The acceptable concentrations include dust (0.08 mg/m³) SO₂ (0.02 mg/m³), NO_x (0.05 mg/m³), 0.2 μg/m³ (CO₂), and 0.08 μg/m³ (N₂O), respectively (GB3095-2012). Secondly, the emergy of ecological service needs to be calculate by using formula (4).

$$R_{\text{air},i} = 0.5 \times M_i \times v^2 \times T_w \quad (4)$$

where $R_{\text{air},i}$ represents environmental service emergy, sej/a. v is the average wind speed (3.25 m/s). T_w is wind emergy conversion rate (1.86E03sej/J) based on baseline of 12.0E24sej/a[39].

Results and discussion

Emergy calculated table of the sewage treatment sludge plant in China

Emergy analysis (EmA)

There are two Scenarios (A and B) that are calculated in Table 5 and Table 6. In Scenario A, the sludge reuse process has been executed, but the sludge reuse measures have not been performed (shown in Table 5).

There are seven parts in Scenario A, containing renewable section, input resource, economic investment, labor and service, energy, transportation, and all the outputs (Mainly exhaust gas). In view of the emergy proportions, input resources, economic investment, and energy are the critical elements for the whole emergy in Scenario A system (at least 96.4% of the entire emergy). Therein, input resources part is the key contributor, accounting for 59.6% of emergy sum, followed by energy (22.3%), economic investment (14.5%), labor and services (2.35%), renewable energy (0.72%), transportation (0.47%), all the outputs (Mainly exhaust gas) (0.01%). In particular, as the cruxes, untreated sludge is the main influencing factors (about 53%); meanwhile, electricity (Plant usage) and operating costs are the pivotal element for the energy part and economic investment part, which are 22.1% and 9.73%. Renewable energy (0.72%), transportation (0.47%), all the outputs (Mainly exhaust gas) (0.01%) have a small effect on the entire evaluated system in Scenario A.

Table 4 Unit emergy values (UEVs) correction based on 12.00E24 sej/year (Mark et al. 2016)

Item	Raw UEVs	Emergy base-line (sej/a)	References	Corrected UEVs
Sunlight	1	12.00E24	Jae and William (2017)	1 sej/j
Rain (chemical)	2.35E04	12.00E24	Jae and William (2017)	2.35E04 sej/j
Rain (geopotential)	1.31E04	12.00E24	Jae and William (2017)	1.31E04 sej/j
Wind (kinetic energy)	1.90E03	12.00E24	Jae and William (2017)	1.90E03 sej/j
Geothermal heat	4.37E04	12.00E24	Wei et al. (2016)	4.37E04 sej/j
Gravel	1.42E12	12.00E24	Wei et al. (2016)	1.42E12 sej/kg
Limestone	1.27E12	12.00E24	Wei et al. (2016)	1.27E12 sej/kg
Cement	1.93E12	12.00E24	Wei et al. (2016)	1.93E12 sej/kg
Steel slag	2.75E12	9.44E24	Hengyu et al. (2016)	3.49E12 sej/kg
Tap water	9.03E11	12.00E24	Yan et al. (2018)	9.03E11 sej/m ³
Bottom ash	7.58E14	12.00E24	Yanqing et al. (2018)	7.58E14 sej/kg
Labor and services	1.51E10	15.83E24	Bo and Sergio (2013)	1.14E10 sej/\$
Investment	1.89E11	15.2E24	Shao and Chen (2016)	1.49E11 sej/\$
Operating cost	2.05E12	15.2E24	Shao and Chen (2016)	1.62E12 sej/\$
Landfill cost	2.05E12	15.2E24	Shao and Chen (2016)	1.62E12 sej/\$
Electricity	4.50E05	12.00E24	Wei et al. (2016)	4.50E05 sej/j

Table 5 Emergy calculated details of original sludge treatment process (Scenario A)

Name	Basic data	UEVs sej/unit	Ref. for UEVs	Emergy (sej/y)	%
1-Renewable Energy (See Appendix 1 for the specific calculation process)				2.39E16	0.72
Sunlight	1.32E08 J/yr	1	Jae and William (2017)	1.32E08	0.00
Rain (chemical potential)	6.41E11 J/yr	2.35E04	Jae and William (2017)	1.51E16	0.46
Rain (geo potential)	2.80E11 J/yr	2.79E04	Jae and William (2017)	7.81E15	0.24
Wind (kinetic energy)	4.43E11 J/yr	1.90E03	Jae and William (2017)	8.42E14	0.03
Geothermal heat	3.51E11 J/yr	3.44E04	Wei et al. (2016)	1.27E14	0.00
2-Input resources				1.97E18	59.6
Untreated sludge	1.21E07 kg	1.45E11	Gengyuan et al. (2015)	1.75E18	53.0
Flocculant	3.41E02 kg	6.38E14	Brown and Ulgiati (2010)	2.18E17	6.61
3- Economic investment				4.80E17	14.5
Investment	3.74E05\$	1.49E11	Shao and Chen (2016)	5.57E16	1.69
Operating cost	1.98E05\$	1.62E12	Shao and Chen (2016)	3.21E17	9.73
Landfill cost	6.36E04\$	1.62E12	Shao and Chen (2016)	1.03E17	3.12
4-Labor and services				7.74E16	2.35
Labor and services	3.02E05\$	1.14E10	Bo and Sergio (2013)	3.44E15	0.10
Governmental subsidies	4.57E04\$	1.62E12	Shao and Chen (2016)	7.40E16	2.24
5-Energy				7.35E17	22.3
Electricity (Plant usage)	1.62E12 J	4.50E05	Wei et al. (2016)	7.29E17	22.1
Coal (fuel in turbine)	5.43E10 J	1.11E05	Brown and Ulgiati (2010)	6.03E15	0.18
6-Transportation				1.55E16	0.47
Transportation	2.04E04 t-km	7.61E11	Wei et al. (2016)	1.55E16	0.47
7-All the outputs (Mainly exhaust gas)				4.70E14	0.01
Exhaust gas emissions	Dust	35 µg/m ³	GB3095-2012	2.49E13	0.00
	SO ₂	50 µg/m ³	GB3095-2012	4.46E13	0.00
	NO _x	80 µg/m ³	GB3095-2012	1.11E14	0.00
	CO ₂	200 µg/m ³	GB3095-2012	1.78E14	0.01
	N ₂ O	80 µg/m ³	GB3095-2012	1.11E14	0.00
Total	~			3.30E18	100
UEVs		UEVs = 2.73E + 11sej/kg for the sewage sludge treatment and reuse system (Scenario A)			

All calculated emergy baseline is 12.00E+24sej/yr and the related calculations can be found in Appendix 1

Compared to Scenario A, Scenario B is a comprehensive system, which integrates the sewage sludge treatment system and brick production system for sludge recycling.

Eight subsections contribute to the emergy proportions, containing renewable energy (0.31%), non-renewable resources (27.5%), input resource (37.2%), economic investment (6.30%), labor and service (1.02%), energy (9.65%), transportation (0.20%), and all the outputs (18% of exhaust gas emissions, electricity and products' economic benefit). As the main contributors, non-renewable resources, input resource, economic investment, energy, and outputs play the decisive impact on the sustainability evaluation, which account for 98.65% of the whole emergy in the Scenario B system. The input resource acts as a pivotal role, composing of untreated sludge (22.9%), flocculant (2.86%), and bottom ash (11.3%). Among them, untreated sludge is the crucial part and has 61.6% ratio for the entire input resource emergy. Non-renewable resource plays a second important

role, containing cement (13.8%), tap water (0.49%), steel slag (10.2%), gravel (2.99%), limestone (0.02%). Hence, in the non-resource input, cement, steel slag, and gravel occupy the dominant positions. All the outputs (exhaust gas emissions, electricity and products' economic benefit) hold a third influence (18%) for the complete result because of the joint brick production system in Scenario B. In the outputs, electricity (9.57%) and products' economic benefit (8.44%) is the main force compared to the exhaust gas emissions (near zero), which consists of dust, SO₂, NO_x, CO₂, and N₂O. In addition, the energy (9.65%) and economic investment (6.30%) have the function which cannot be ignored in the whole assessment of Scenario B.

Finally, labor and service (1.02%) are not significant factors in Scenario B, while renewable energy (0.31%) and transportation (0.20%) have almost no effect in Scenario B.

Compared with Scenario A and Scenario B, the most significant difference is the brick production system

Table 6 Emergy calculated details of improved sludge treatment process (Scenario B)

Name	Formula ratio	Basic data	UEVs sej/unit	Ref. for UEVs	Emergy (sej/y)	%
1-Renewable Energy (See Appendix 2 for the specific calculation process)					2.39E16	0.31
Sunlight		1.32E08 J/yr	1	Jae and William (2017)	1.32E08	0.00
Rain (chemical potential)		6.41E11 J/yr	2.35E04	Jae and William (2017)	1.51E16	0.20
Rain (geo potential)		2.80E11 J/yr	2.79E04	Jae and William (2017)	7.81E15	0.10
Wind (kinetic energy)		4.43E11 J/yr	1.90E03	Jae and William (2017)	8.42E14	0.01
Geothermal heat		3.51E11 J/yr	3.44E04	Wei et al. (2016)	1.27E14	0.00
2-Non-renewable resources (mainly for the brick production subsystem usages)					2.09E18	27.5
Cement		5.44E05 kg	1.93E12	Wei et al. (2016)	1.05E18	13.8
Tap water		1.45E04 m ³	9.03E11	Yan et al. (2018)	3.71E16	0.49
Steel slag		2.83E05 kg	2.75E12	Hengyu et al. (2016)	7.78E17	10.2
Gravel		2.03E05 kg	1.42E12	Wei et al. (2016)	2.28E17	2.99
Limestone		1.31E03 kg	1.27E12	Wei et al. (2016)	1.66E15	0.02
3-Input resources					2.83E18	37.2
Untreated sludge		1.21E07 kg	1.45E11	Gengyuan et al. (2015)	1.75E18	22.9
Flocculant		3.41E02 kg	6.38E14	Brown and Ulgiati (2010)	2.18E17	2.86
Bottom ash (Brick plant)		1.14E03 kg	7.58E14	Yanqing et al. (2018)	8.64E17	11.3
4-Economic investment					4.80E17	6.30
Investment		3.74E05\$	1.49E11	Shao and Chen (2016)	5.57E16	0.73
Operating cost		1.98E05\$	1.62E12	Shao and Chen (2016)	3.21E17	4.21
Landfill cost		6.36E04\$	1.62E12	Shao and Chen (2016)	1.03E17	1.35
5-Labor and services					7.74E16	1.02
Labor and services		3.02E05\$	1.14E10	Bo and Sergio (2013)	3.44E15	0.05
Governmental subsidies		4.57E04\$	1.62E12	Shao and Chen (2016)	7.40E16	0.97
6-Energy					7.35E17	9.65
Electricity (Plant usage)		1.62E12 J	4.50E05	Wei et al. (2016)	7.29E17	9.57
Coal (fuel in turbine)		5.43E10 J	1.11E05	Brown and Ulgiati (2010)	6.03E15	0.08
7-Transportation					1.55E16	0.20
Transportation (truck)		2.04E04 t·km	7.61E11	Wei et al. (2016)	1.55E16	0.20
8-All the outputs					1.37E18	18.0
Exhaust gas emissions	Dust	35 µg/m ³	Refer Appendix 2		2.49E13	0.00
	SO ₂	50 µg/m ³	Refer Appendix		4.46E13	0.00
	NO _x	80 µg/m ³	Refer Appendix 2		1.11E14	0.00
	CO ₂	200 µg/m ³	Refer Appendix 2		1.78E14	0.00
	N ₂ O	80 µg/m ³	Refer Appendix 2		1.11E14	0.00
Electricity (Power generation)			Refer Appendix 2		7.29E17	9.57
Products' economic benefit (brick plant)			Refer Appendix 2		6.43E17	8.44
Total	~				7.62E18	100
UEVs	UEVs = 6.29E+11sej/kg for the sewage sludge treatment and reuse system (Scenario B)					

All calculated emergy baseline is 12.00E+24sej/yr and the related calculations can be found in Appendix 2

consideration to improve the sludge treatment and reuse. After considering the brick system (Scenario B), on the one hand, the sludge treatment capacity has been enhanced and raised sludge utilization; on the other hand, negative influences have also generated due to the non-renewable resources input and several outputs.

Emergy indicators calculation

Ecological indexes of the sludge reuse systems (Scenario A and Scenario B) are displayed in Table 7.

1. The renewability rates (R_r) are 0.007242 and 0.003136. The weak sustainability was displayed for both Scenario A and Scenario B. Compared to Scenario A system, Scenario B has worse sustainability.

Table 7 Calculated results of ecological indicators

No	Index	Scenario A	Scenario B
1	R	2.39E+16sej	2.39E+16sej
2	F	~	2.09E+18sej
3	P	1.97E+18sej	2.83E+18sej
4	C	4.80E+17sej	4.80E+17sej
5	L	7.74E+16sej	7.74E+16sej
6	E	7.35E+17sej	7.35E+17sej
7	S	1.55E+16sej	1.55E+16sej
8	P_e	4.70E+14sej	1.37E+18sej
9	T	3.30E+18sej	7.62E+18sej
10	R_r	0.007242	0.003136
11	N_r	~	0.274903
12	N_p	0.596356	0.371654
13	E_d	6.60E+15sej/per	1.52E+16sej/per
14	E_i	5.2E+8sej/m ²	1.20E+9sej/m ²
15	PEIR	0.000142	0.000062
16	ELR	82.362742	263.283243
17	EYR	1.012383	2.232743
18	ESI	0.012292	0.00848

- Non-renewability rate of local resources (N_r) reveals the ratios (0 and 0.274903). Because the sludge reuse was integrated in Scenario B, resulting in a substantial non-renewable rate. It shows a mass of non-resource input and can give a negative environmental impact. In Scenario A system, the sludge reuse was ignored to execute, so N_r is zero.
- Non-renewability rates of input resources (N_p) are 0.596356 and 0.371654. Compared to Scenario A system, Scenario A system has less dependency on the input resource. There is an obvious fact and that is superfluous non-resource input resulting in unsustainable state.

- Emergy personal density (E_d) is 6.60E+15sej/per and 1.52E+16sej/per, demonstrating a higher personal emergy in Scenario A and Scenario B system.
- Emergy intensities (E_i) are 5.2E+8 sej/m² and 1.20E+9 sej/m², which reveal a good land use effect.
- Pollutant environmental impact rates (PEIRs) are 0.000142 and 0.000062. They decide the poor influences on total emergy evaluation. In this regard, Scenario B is better than Scenario A.
- The environmental loading ratios (ELR) are 82.362742 and 263.283243, which show the huge stress. Due to the mass of non-resources input in Scenario B, ELR of Scenario B is 3.2 times of Scenario A. Based on related standard, it is not qualified and need to find ways to optimize the result.
- Emergy yield ratios (EYR) are 1.012383 and 2.232743. According to the EYR values, they are unqualified; meanwhile, Scenario B has higher EYR based on several non-resources inputs.
- The emergy sustainability index (ESI) is 0.012292 and 0.00848. They express the weak comprehensive effects on the evaluated system. Therein, the lack of non-resources in Scenario B leads to higher ESI than Scenario A. Based on the literature, the ESI values of Scenario A and Scenario B have the unsustainable statuses (< 1) in the long term.

In Fig. 5, all indicator comparisons have been displayed. According to overall trend consideration in Scenario A and Scenario B, Scenario B has more severe environmental stress and less environmental sustainability than Scenario A. The reason for this phenomenon is the consideration of sewage sludge reuse system in Scenario B, especially for the non-resource input in the brick production system.

Fig. 5 Indicators comparison between Scenario A and Scenario B

Based on the entire analysis for all indicators, a fact should be demonstrated that the sludge reuse needs more non-resources and financial support, which can lead to several environmental pressures to some extent.

Unit emergy values (UEVs)

According to the literature review, there is the only article that has been investigated for the UEVs of sludge reuse system in China based on emergy approach[23]. Gengyuan et al. 2015 conducted the sewage sludge reduction and reuse in cement production and four UEVs of sewage sludge treatment and reuse system have been calculated, which are $1.59\text{E}+12$ sej/kg, $1.59\text{E}+12$ sej/kg, $1.59\text{E}+12$ sej/kg, $1.59\text{E}+12$ sej/kg, respectively[23]. In the published article, the sludge reuse system is the cement production system rather than the brick production system. Due to excess mass and economic investment in the cement production system, the integrated platform system based on sludge treatment system and reuse system (cement production) has a higher environmental load and lower ecological sustainability resulting in larger UEVs.

Compared with the cement production reuse system, the brick production reuse system has distinct advantages, including reduced inputs of non-renewable resources and energy consumption.

Therefore, in this new paper, the UEVs are $2.73\text{E}+11$ sej/kg and $6.29\text{E}+11$ sej/kg in Scenario A and Scenario B, respectively. On the basis of the integration platform between the sludge treatment system and reuse system (brick production), it provides the second reference for the new sludge treatment and reuse system in order to enhance the environmental sustainability.

Sensitivity analysis

In Scenario A system, input resources, economic investment, and energy play the dominant effects in Table 5; meanwhile, non-renewable resources, input resources, economic investment, energy, and outputs are the major contributors in Scenario B system. Sensitivity changes should be considered in Scenario A system and Scenario B system to verify the stability. The assumption is that the major terms vary by 10%, meanwhile, others remain unchanged.

The sensitivity analysis results of indexes are computed in Table 8 and shown in Fig. 6.

Within 10% changes in these sections, sensitivity change ratios can be concluded in Scenario A and Scenario B, which are R_r (9.71% and 8.06%), N_r (0 and 1.53%), N_p (0.36% and 1.68%), E_d (9.72% and 8.07%), E_i (9.72% and 8.07%), PEIR (9.39% and 8.75%), ELR (26.97% and 13.92%), EYR (19.33% and 30.01%), ESI (10.47% and 18.69%), respectively.

Table 8 The indicators changes between former and latter in Scenario A and Scenario B

No	Index	Scenario A		Scenario B	
		Former	Latter	Former	Latter
1	R_r	0.007242	0.006601	0.003136	0.002902
2	N_r	~	~	0.274903	0.279164
3	N_p	0.596356	0.598491	0.371654	0.378006
4	E_d	$6.60\text{E}+15$	$6.02\text{E}+15$	$1.52\text{E}+16$	$1.41\text{E}+16$
5	E_i	$5.2\text{E}+8$	$4.74\text{E}+08$	$1.20\text{E}+9$	$1.11\text{E}+09$
6	PEIR	0.000142	0.000129	0.000062	0.000057
7	ELR	82.3627	112.7811	263.2832	305.8577
8	EYR	1.012383	1.254901	2.232743	3.190039
9	ESI	0.012292	0.011127	0.00848	0.010429

According to Table 8 and Fig. 6, Scenario B has a broader range of change than Scenario A because of the more resource input. It is found that EYR (19.33% and 30.01%) has the most significant impact, followed by ELR (26.97% and 13.92%) and ESI (10.47% and 18.69%). The higher the emergy ratio, the greater the sensitivity impact results in Scenario A system. The same explanations can be for Scenario B system. To sum up, the staple emergy contributor exerts the first implications for sensitivity analysis.

Theoretical value of the parameters

Input resources part (non-renewable resources) is the key contributor in Scenario A and Scenario B. In order to calculate the theoretical value of the parameters, taking non-renewable resources as an example, its theoretical value has been counted as follows:

In general, three standards have been adopted (Cao and Feng 2007), including $\text{ESI} < 1$ (poor), $1 < \text{ESI} < 5$ (qualified), and $\text{ESI} > 5$ (good). In order to meet the most basic sustainable state, according to sustainability standard, assuming ESI is equal to 1, then ELR is equal to EYR. The new theoretical value of non-renewable resources in Scenario A and Scenario B can be obtained, which are 24.8% and 7.86% of the total emergy. Compared to changes in Scenario A and Scenario B, the non-renewable resources proportion changes from 59.6 to 24.8% in Scenario A, from 27.5 to 7.86% in Scenario B.

Strategies and suggestions

In order to ease the negative situation, a number of strategies are put forward for the better sustainability in the sludge reuse systems.

Fig. 6 Proportion variations between former and latter in Scenario A and Scenario B

Improving renewable energy input proportion

According to Tables 5 and 6, the lack of renewable energy results in the passive sustainable impact on the sludge reuse systems. Until now, three types of renewable energy were widely used in China, involving solar power, hydropower, and wind power, which can offer mature technical support. However, some weaknesses block their usages, for instance, high investment, professional barriers, and geographical limit.

Currently, plenty studies have been executed by using renewable energy, which contain solar power (Peronato et al. 2018; Taixiu et al. 2019), hydropower (Ludovic et al. 2014; Shengwen et al. 2019), wind power (Yimin et al. 2019; Sayed et al. 2019); meanwhile, fiscal care can be as beneficial strategies to enhance renewable energy utilization ratio.

Use renewable materials

Except for the adjustment of the proportion of renewable energy, non-renewable resources should be reduced or replaced by renewable materials. Taking cement as an example, it is a major input for Scenario B system (approximately 13.8%). In order to lower the non-renewable resources proportion, several industrial waste and by-products can be utilized, such as industrial waste and constructional residuums. So far, there are a great number of studies that have been conducted through renewable material substitution (Gonçalves et al. 2020; Xingyang et al. 2020). The recycled concrete aggregate has been reused to replace the cement input by Gonçalves et al. (2020), which have a better sustainable effect. On the basis of Xingyang et al. (2020)'s study, wet-milling slurry waste is good alternatives compared to new cement input.

Conclusion

Based on emergy evaluations in Scenario A and Scenario B, the sustainable assessment of two sewage sludge treatment and reuse systems has been selected and studied in the article. The major contents including:

1. Compared to Scenario A, Scenario B is a comprehensive system, which integrates a sewage sludge treatment system and brick production system for sludge recycling.
2. After considering the brick system (Scenario B), on the one hand, the sludge treatment capacity has been enhanced and raised sludge utilization; on the other hand, negative influences have also generated due to the non-renewable resources input and several outputs.
3. In Scenario A, input resources part plays a dominant role, accounting for 59.6% of sum of emergy, followed by energy (22.3%), economic investment (14.5%), labor and services (2.35%), renewable energy (0.72%), transportation (0.47%), all the outputs (Mainly exhaust gas) (0.01%)
4. As the main contributors, non-renewable resources, input resource, economic investment, energy, and outputs play the decisive impact on the sustainability evaluation, which account for 98.65% of the whole emergy in the Scenario B system.
5. Scenario B has more severe environmental stress and less environmental sustainability than Scenario A. The reason for this phenomenon is the consideration of sewage sludge reuse system in Scenario B, especially for the non-resource input in the brick production system.
6. In this new paper, the UEVs are $2.73\text{E}+11\text{sej/kg}$ and $6.29\text{E}+11\text{sej/kg}$ in Scenario A and Scenario B, respectively.

7. The emergy sustainability index (ESI) is 0.012292 and 0.00848, which express the weak comprehensive effects in Scenario A and Scenario B. Scenario B has a more massive range of change than Scenario A because of the more resource input.
8. Scenario B has a broader range of change than Scenario A because of the more resource input. It is found that EYR (19.33% and 30.01%) has the most significant impact, followed by ELR (26.97% and 13.92%) and ESI (10.47% and 18.69%).

In spite, the integrated reuse system (Scenario B) can improve the sludge reuse capacity than without an integrated reuse system (Scenario A), but it will cause a certain amount of environmental stress resulting in negative sustainability. Thence, two active suggestions are raised related to renewable energy and recycled materials.

Appendix 1 (Table 5)

1. Renewable Energy calculation:

$$\begin{aligned}
 &(1) \text{ Solar energy calculation: Area of Scenario A system} \\
 &= 3.18E + 05 \text{ m}^2; \text{ Insolation (Hubei Province, China)} \\
 &= 5.43 \times 109 \text{ J/m}^2/\text{yr}; \text{ Albedo} \\
 &= 0.30 \text{ (Lou and Ulgiati 2013). Energy} \\
 &= (\text{solation}) \times (1 - \text{albedo}) \times (\text{area}) \\
 &= (5.43 \times 109 \text{ J/m}^2/\text{yr}) \times (1 - 0.30) \times (3.18E + 05 \text{ m}^2) \\
 &= 1.32E + 08 \text{ J/yr. UEV} \\
 &= 1.00 \text{ sej/J by definition. Emergy} \\
 &= 1.32E08 \text{ J/yr} \times 1 \text{ yr} \times 1 \text{ sej/J} \\
 &= 1.32E08 \text{ sej}
 \end{aligned}$$

$$\begin{aligned}
 &(2) \text{ Rain (chemical potential energy) calculation: Area of Scenario A system} = 3.18E + 05 \text{ m}^2; \\
 &\text{Rainfall (annual average, } n = 5) = 0.68 \text{ m/year (Jiangsu Provincial Bureau of Statistics, China, 2012 – 2016.);} \\
 &\text{Water density} = 1.00 \text{ kg/m}^3; \text{ Evapotranspiration rate} = 60\% \text{ (Lou and Ulgiati 2013; Gao et al. 2007);} \\
 &\text{Gibbs free energy of water} = 4.94 \times 10^3 \text{ J/kg. Energy} = (\text{area}) \times (\text{rainfall}) \times (\text{evapotranspiration rate}) \times \\
 &(\text{water density}) \times (\text{Gibbs free energy of water}) = (3.18E05\text{m}^2) \times (0.68 \text{ m/yr}) \times (60\%) \times (1E03 \text{ kg/m}^3) \\
 &\times (4.94E03 \text{ J/kg}) = 6.41E11 \text{ J/year. UEV} = 2.35E + 04 \text{ sej/J (Jae and William 2017).} \\
 &\text{Emergy of one year} = 6.41E + 11 \text{ J/yr} \times 1 \text{ yr} \times 2.35E + 04 \text{ sej/J} = 1.51E + 16 \text{ sej.}
 \end{aligned}$$

$$\begin{aligned}
 &(3) \text{ Rain (geopotential energy) calculation: Area of Scenario A system} = 3.18E + 05 \text{ m}^2; \\
 &\text{Rainfall (annual average, } n = 5) = 0.68 \text{ m/year (Brown and Bardi 2001);} \\
 &\text{Average elevation} = 316 \text{ m (Wu et al. 2013); water density} = 1.00E + 03 \text{ kg/m}^3; \\
 &\text{Runoff rate} = 40.00\% \text{ (Lou and Ulgiati 2013). Energy} = (\text{area}) \times (\text{rainfall}) \\
 &\times (\text{runoff rate}) \times (\text{water density}) \times (\text{average elevation}) \times (\text{gravity}) \\
 &= (3.18E + 05\text{m}^2) \times (0.71 \text{ m/yr}) \times (40\%) \times (1E03 \text{ kg/m}^3) \times (316 \text{ m}) \times (9.8 \text{ kg/m}^2) \\
 &= 2.80E + 11 \text{ J/yr. UEV} = 2.79E + 04 \text{ sej/J (Brown and Bardi 2001).} \\
 &\text{Emergy of one year} = 2.80E + 11 \text{ J/yr} \times 1 \text{ yr} \times 2.79E + 04 \text{ sej/J} = 7.81E + 15 \text{ sej}
 \end{aligned}$$

$$\begin{aligned}
 &(4) \text{ Wind energy calculation : Area of Scenario A system} = 3.18E + 05 \text{ m}^2; \text{ Air density} = 1.29 \text{ kg/m}^3; \\
 &\text{Wind velocity (annual average, } n = 2) = 3.25\text{m/s (Wu et al. 2013); Velocity of geostrophic wind} \\
 &= 3.25 \text{ m/s (surface winds are considered as 0.6 of geostrophic wind (China Meteorological} \\
 &\text{Administration, 2015); Drag coefficient} = 1.00 \times 10^{-3} \text{ (Miller 1964). Energy} = (\text{area}) \\
 &\times (\text{air density}) \times (\text{drag coefficient}) \times (\text{velocity of geostrophic wind})^3 = (3.18E + 05 \text{ m}^2) \\
 &\times (1.29 \text{ kg/m}^3) \times (1.00 \times 10^{-3}) \times (3.25 \text{ m/s})^3 \times (3.15E + 07 \text{ s/year}) = 4.43E + 11 \text{ J/yr.} \\
 &\text{UEV} = 1.90E03 \text{ sej/J (Hwang and William 2015).} \\
 &\text{Emergy of one year} = 4.43E11 \text{ J/yr} \times 1 \text{ yr} \times 1.9E03 \text{ sej/J} = 8.42E14 \text{ sej}
 \end{aligned}$$

(5) Geothermal heat calculation : Area of Scenario A system = $3.18E + 05 \text{ m}^2$;

Heat flow(average) = $3.50 \times 10^{-2} \text{ J/m}^2/\text{s}$. Energy = (area) $\times$ (heat flow)

= $(3.18E + 05 \text{ m}^2) \times (3.50E - 02 \text{ J/m}^2/\text{s}) \times (3.15E + 07 \text{ s/year}) = 3.51E + 11 \text{ J/yr}$.

UEV = $3.44E + 04 \text{ sej/J}$ (Brown and Bardi 2001).

Emergy of one year = $3.51E + 11 \text{ J/yr} \times 1 \text{ yr} \times 3.44E + 04 \text{ sej/J} = 1.27E + 14 \text{ sej}$

2. Input resources

The amount emergy:

Untreated sludge = $1.21E07 \times 1.45E11 = 1.75E18 \text{ sej}$;

Flocculant = $3.41E02 \times 6.38E14 = 2.18E17 \text{ sej}$;

3. Economic investment

The emergy calculations: Investment = $3.74E05 \times 1.49E11 = 5.57E16 \text{ sej}$;

Operating cost = $1.98E05 \times 1.62E12 = 3.21E17 \text{ sej}$; Land-fill cost = $6.36E04 \times 1.62E12 = 1.03E17 \text{ sej}$;

4. Labor and services

The amount emergy of labor and services:

Labor and services = $3.02E05 \times 1.14E10 = 3.44E15 \text{ sej}$;
Governmental subsidies = $4.57E04 \times 1.62E12 = 7.40E16 \text{ sej}$.

5. Energy

The amount emergy of energy:

Electricity (Plant usage) = $1.62E12 \times 4.50E05 = 7.29E17 \text{ sej}$;
Coal (fuel in turbine) = $5.43E10 \times 1.11E05 = 6.03E15 \text{ sej}$.

6. Transportation

Transportation emergy of annual sludge treatment

= $(55.8 \text{ tons} \times 10 \text{ km} \times 365 \text{ d}) \times (7.61E + 11)$

= $1.55E + 16 \text{ sej}$

7. Exhaust gas emissions emergy of Scenario A

(1) The economic loss emergy:

$$L_{\text{Dust}} = \sum W_i \times \text{DALY}_i \times \alpha = (35E - 09) \times (3.75E - 04) \\ \times (1.68E + 16) \times 365 \times (2.5E + 05) = 2.01E + 13 \text{ sej}$$

$$L_{\text{SO}_2} = \sum W_i \times \text{DALY}_i \times \alpha \\ = (50E - 09) \times (5.46E - 05) \times (1.68E + 16) \\ \times 365 \times (2.5E + 05) = 4.18E + 13 \text{ sej}$$

$$L_{\text{NO}_x} = \sum W_i \times \text{DALY}_i \times \alpha = (80E - 09) \\ \times (8.87E - 04) \times (1.68E + 16) \\ \times 365 \times (2.5E + 05) = 1.09E + 14 \text{ sej}$$

$$L_{\text{CO}_2} = \sum W_i \times \text{DALY}_i \times \alpha = (200E - 09) \times (5.46E - 05) \\ \times (1.68E + 16) \times 365 \times (2.5E + 05) = 1.67E + 14 \text{ sej}$$

$$L_{\text{N}_2\text{O}} = \sum W_i \times \text{DALY}_i \times \alpha = (80E - 09) \times (8.87E - 04) \\ \times (1.68E + 16) \times 365 \times (2.5E + 05) = 1.09E + 14 \text{ sej}$$

(2) The ecological services emergy:

$$M_{\text{Dust}} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(35E - 09) \times (1.0E + 06)}{0.08} \right] \\ \times (2.5E + 05) \times 365 = 4.93E + 07 \text{ kg/a}$$

$$M_{\text{SO}_2} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(50E - 09) \times (1.0E + 06)}{0.02} \right] \\ \times (2.5E + 05) \times 365 = 2.81E + 08 \text{ kg/a}$$

$$M_{\text{NO}_x} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(80E - 09) \times (1.0E + 06)}{0.05} \right] \\ \times (2.5E + 05) \times 365 = 1.79E + 08 \text{ kg/a}$$

$$M_{\text{CO}_2} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(200E - 09) \times (1.0E + 06)}{0.02} \right] \\ \times (2.5E + 05) \times 365 = 1.12E + 09 \text{ kg/a}$$

$$M_{\text{N}_2\text{O}} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(80E - 09) \times (1.0E + 06)}{0.05} \right] \\ \times (2.5E + 05) \times 365 = 1.79E + 08 \text{ kg/a}$$

$$R_{\text{Dust}} = 0.5 \times M_{\text{Dust}} \times v^2 \times T_w = 0.5 \times (4.93E + 07) \\ \times 3.25^2 \times (1.86E + 03) = 4.84E + 12 \text{ sej}$$

$$R_{\text{SO}_2} = 0.5 \times M_{\text{SO}_2} \times v^2 \times T_w = 0.5 \times (2.81E + 08) \\ \times 3.25^2 \times (1.86E + 03) = 2.76E + 12 \text{ sej}$$

$$R_{\text{NO}_x} = 0.5 \times M_{\text{NO}_x} \times v^2 \times T_w = 0.5 \times (1.79E + 08) \\ \times 3.25^2 \times (1.86E + 03) = 1.76E + 12 \text{ sej}$$

$$R_{\text{CO}_2} = 0.5 \times M_{\text{CO}_2} \times v^2 \times T_w = 0.5 \times (1.12E + 09) \\ \times 3.25^2 \times (1.86E + 03) = 1.10E + 13 \text{ sej}$$

$$R_{N_2O} = 0.5 \times M_{N_2O} \times v^2 \times T_w = 0.5 \times (1.79E + 08) \\ \times 3.25^2 \times (1.86E + 03) = 1.76E + 12 \text{ sej}$$

(3) The sum:

$$\text{Emergy}_{\text{dust}} = (2.01E + 13) + (4.84E + 12) = 2.49E + 13 \text{ sej}$$

$$\text{Emergy}_{\text{SO}_2} = (4.18E + 13) + (2.76E + 12) = 4.46E + 13 \text{ sej}$$

$$\text{Emergy}_{\text{NO}_x} = (1.09E + 14) + (1.76E + 12) = 1.11E + 14 \text{ sej}$$

$$\text{Emergy}_{\text{CO}_2} = (1.67E + 14) + (1.10E + 13) = 1.78E + 14 \text{ sej}$$

$$\text{Emergy}_{\text{NO}_x} = (1.09E + 14) + (1.76E + 12) = 1.11E + 14 \text{ sej}$$

Appendix 2 (Table 6)

1. Renewable Energy calculation:

(1) Solar energy calculation : Area of Scenario A system = $3.18E + 05 \text{ m}^2$;

Insolation (Hubei Province, China) = $5.43 \times 109 \text{ J/m}^2/\text{yr}$; Albedo = 0.30 (Lou and Ulgiati 2013).

$$\text{Energy} = (\text{solation}) \times (1 - \text{albedo}) \times (\text{area}) = (5.43 \times 109 \text{ J/m}^2/\text{yr}) \times (1 - 0.30) \times (3.18E + 05 \text{ m}^2) \\ = 1.32E + 08 \text{ J/yr. UEV} = 1.00 \text{ sej/J by definition. Emergy} = 1.32E08 \text{ J/yr} \times 1 \text{ yr} \times 1 \text{ sej/J} = 1.32E08 \text{ sej}$$

(2) Rain(chemical potential energy) calculation : Area of Scenario A system = $3.18E + 05 \text{ m}^2$;

Rainfall (annual average, $n = 5$) = 0.68 m/year (Jiangsu Provincial Bureau of Statistics, China, 2012 – 2016.);

Water density = 1.00 kg/m^3 ; Evapotranspiration rate = 60%(Lou and Ulgiati 2013; Gao et al. 2007);

$$\text{Gibbs free energy of water} = 4.94 \times 10^3 \text{ J/kg. Energy} = (\text{area}) \times (\text{rainfall}) \times (\text{evapotranspiration rate}) \\ \times (\text{water density}) \times (\text{Gibbs free energy of water}) = (3.18E05 \text{ m}^2) \times (0.68 \text{ m/yr}) \times (60\%) \times (1E03 \text{ kg/m}^3) \\ \times (4.94E03 \text{ J/kg}) = 6.41E11 \text{ J/year. UEV} = 2.35E + 04 \text{ sej/J(Jae and William 2017).}$$

$$\text{Emergy of one year} = 6.41E + 11 \text{ J/yr} \times 1 \text{ yr} \times 2.35E + 04 \text{ sej/J} = 1.51E + 16 \text{ sej.}$$

(3) Rain (geopotential energy) calculation: Area of Scenario A system = $3.18E + 05 \text{ m}^2$;

Rainfall (annual average, $n = 5$) = 0.68 m/year (Brown and Bardi 2001);

Average elevation = 316 m (Wu et al. 2013); water density = $1.00E + 03 \text{ kg/m}^3$;

Runoff rate = 40.00% (Lou and Ulgiati 2013). Energy = (area) $\times$ (rainfall)

$$\times (\text{runoff rate}) \times (\text{water density}) \times (\text{average elevation}) \times (\text{gravity}) \\ = (3.18E + 05 \text{ m}^2) \times (0.71 \text{ m/yr}) \times (40\%) \times (1E03 \text{ kg/m}^3) \times (316 \text{ m}) \times (9.8 \text{ kg/m}^2) \\ = 2.80E + 11 \text{ J/yr. UEV} = 2.79E + 04 \text{ sej/J (Brown and Bardi 2001).}$$

$$\text{Emergy of one year} = 2.80E + 11 \text{ J/yr} \times 1 \text{ yr} \times 2.79E + 04 \text{ sej/J} = 7.81E + 15 \text{ sej}$$

(4) Wind energy calculation: Area of Scenario A system = $3.18E + 05 \text{ m}^2$; Air density = 1.29 kg/m^3 ;

Wind velocity (annual average, $n = 2$) = 3.25 m/s (Wu et al. 2013); Velocity of geostrophic wind

= 3.25 m/s (surface winds are considered as 0.6 of geostrophic wind (China Meteorological

Administration 2015); Drag coefficient = 1.00×10^{-3} (Miller 1964). Energy = (area) $\times$

$$(\text{air density}) \times (\text{drag coefficient}) \times (\text{velocity of geostrophic wind})^3 = (3.18E + 05 \text{ m}^2) \\ \times (1.29 \text{ kg/m}^3) \times (1.00 \times 10^{-3}) \times (3.25 \text{ m/s})^3 \times (3.15E + 07 \text{ s/year}) = 4.43E + 11 \text{ J/yr.}$$

$$\text{UEV} = 1.90E03 \text{ sej/J (Hwang and William 2015).}$$

$$\text{Emergy of one year} = 4.43E11 \text{ J/yr} \times 1 \text{ yr} \times 1.9E03 \text{ sej/J} = 8.42E14 \text{ sej}$$

(5) Geothermal heat calculation: Area of Scenario A system = $3.18E + 05 \text{ m}^2$;

Heat flow (average) = $3.50 \times 10^{-2} \text{ J/m}^2/\text{s}$. Energy = (area) $\times$ (heat flow)

= $(3.18E + 05 \text{ m}^2) \times (3.50E - 02 \text{ J/m}^2/\text{s}) \times (3.15E + 07 \text{ s/year}) = 3.51E + 11 \text{ J/yr}$.

UEV = $3.44E + 04 \text{ sej/J}$ (Brown and Bardi 2001).

Emergy of one year = $3.51E + 11 \text{ J/yr} \times 1 \text{ yr} \times 3.44E + 04 \text{ sej/J} = 1.27E + 14 \text{ sej}$

2. Non-renewable resources:

The amount emergy: Cement = $5.44E05 \times 1.93E12 = 1.05E18 \text{ sej}$;

Steel slag = $2.83E05 \times 2.75E12 = 7.78E17 \text{ sej}$;

Limestone = $1.31E03 \times 1.27E12 = 1.66E15 \text{ sej}$;

Gravel = $2.03E05 \times 1.42E12 = 2.28E17 \text{ sej}$; Tap water = $1.45E04 \times 2.56E12 = 3.71E16 \text{ sej}$.

3. Input resources

The amount emergy:

Untreated sludge = $1.21E07 \times 1.45E11 = 1.75E18 \text{ sej}$;

Flocculant = $3.41E02 \times 6.38E14 = 2.18E17 \text{ sej}$;

4. Economic investment

The emergy calculations: Investment = $3.74E05 \times 1.49E11 = 5.57E16 \text{ sej}$;

Operating cost = $1.98E05 \times 1.62E12 = 3.21E17 \text{ sej}$; Land-fill cost = $6.36E04 \times 1.62E12 = 1.03E17 \text{ sej}$;

5. Labor and services

The amount emergy of labor and services:

Labor and services = $3.02E05 \times 1.14E10 = 3.44E15 \text{ sej}$;

Governmental subsidies = $4.57E04 \times 1.62E12 = 7.40E16 \text{ sej}$.

6. Energy

The amount emergy of energy:

Electricity (Plant usage) = $1.62E12 \times 4.50E05 = 7.29E17 \text{ sej}$;

Coal (fuel in turbine) = $5.43E10 \times 1.11E05 = 6.03E15 \text{ sej}$.

7. Transportation

Transportation emergy of annual sludge treatment

= $(55.8 \text{ tons} \times 10 \text{ km} \times 365 \text{ d}) \times (7.61E + 11) = 1.55E + 16 \text{ sej}$

8. All inputs of Scenario B

(1) Exhaust gas emissions emergy of Scenario B.

1) The economic loss emergy:

$$L_{\text{Dust}} = \sum W_i \times \text{DALY}_i \times \alpha = (35E - 09) \times (3.75E - 04) \times (1.68E + 16) \times 365 \times (2.5E + 05) = 2.01E + 13 \text{ sej}$$

$$L_{\text{SO}_2} = \sum W_i \times \text{DALY}_i \times \alpha = (50E - 09) \times (5.46E - 05) \times (1.68E + 16) \times 365 \times (2.5E + 05) = 4.18E + 13 \text{ sej}$$

$$L_{\text{NO}_x} = \sum W_i \times \text{DALY}_i \times \alpha = (80E - 09) \times (8.87E - 04) \times (1.68E + 16) \times 365 \times (2.5E + 05) = 1.09E + 14 \text{ sej}$$

$$L_{\text{CO}_2} = \sum W_i \times \text{DALY}_i \times \alpha = (200E - 09) \times (5.46E - 05) \times (1.68E + 16) \times 365 \times (2.5E + 05) = 1.67E + 14 \text{ sej}$$

$$L_{\text{N}_2\text{O}} = \sum W_i \times \text{DALY}_i \times \alpha = (80E - 09) \times (8.87E - 04) \times (1.68E + 16) \times 365 \times (2.5E + 05) = 1.09E + 14 \text{ sej}$$

(2) The ecological services emergy:

$$M_{\text{Dust}} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(35E - 09) \times (1.0E + 06)}{0.08} \right] \times (2.5E + 05) \times 365 = 4.93E + 07 \text{ kg/a}$$

$$M_{\text{SO}_2} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(50E - 09) \times (1.0E + 06)}{0.02} \right] \times (2.5E + 05) \times 365 = 2.81E + 08 \text{ kg/a}$$

$$M_{\text{NO}_x} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(80E - 09) \times (1.0E + 06)}{0.05} \right] \times (2.5E + 05) \times 365 = 1.79E + 08 \text{ kg/a}$$

$$M_{\text{CO}_2} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(200E - 09) \times (1.0E + 06)}{0.02} \right] \times (2.5E + 05) \times 365 = 1.12E + 09 \text{ kg/a}$$

$$M_{\text{N}_2\text{O}} = c \times \left(\frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left[\frac{(80E - 09) \times (1.0E + 06)}{0.05} \right] \times (2.5E + 05) \times 365 = 1.79E + 08 \text{ kg/a}$$

$$R_{\text{Dust}} = 0.5 \times M_{\text{Dust}} \times v^2 \times T_w = 0.5 \times (4.93E + 07) \times 3.25^2 \times (1.86E + 03) = 4.84E + 12 \text{ sej}$$

$$R_{\text{SO}_2} = 0.5 \times M_{\text{SO}_2} \times v^2 \times T_w = 0.5 \times (2.81E + 08) \times 3.25^2 \times (1.86E + 03) = 2.76E + 12 \text{ sej}$$

$$R_{\text{NO}_x} = 0.5 \times M_{\text{NO}_x} \times v^2 \times T_w = 0.5 \times (1.79E + 08) \times 3.25^2 \times (1.86E + 03) = 1.76E + 12 \text{ sej}$$

$$R_{\text{CO}_2} = 0.5 \times M_{\text{CO}_2} \times v^2 \times T_w = 0.5 \times (1.12E + 09) \times 3.25^2 \times (1.86E + 03) = 1.10E + 13 \text{ sej}$$

$$R_{N_2O} = 0.5 \times M_{N_2O} \times v^2 \times T_w = 0.5 \times (1.79E + 08) \\ \times 3.25^2 \times (1.86E + 03) = 1.76E + 12 \text{ sej}$$

(3) The sum:

$$\text{Emergy}_{\text{dust}} = (2.01E + 13) + (4.84E + 12) = 2.49E + 13 \text{ sej}$$

$$\text{Emergy}_{\text{SO}_2} = (4.18E + 13) + (2.76E + 12) = 4.46E + 13 \text{ sej}$$

$$\text{Emergy}_{\text{NO}_x} = (1.09E + 14) + (1.76E + 12) = 1.11E + 14 \text{ sej}$$

$$\text{Emergy}_{\text{CO}_2} = (1.67E + 14) + (1.10E + 13) = 1.78E + 14 \text{ sej}$$

$$\text{Emergy}_{\text{NO}_x} = (1.09E + 14) + (1.76E + 12) = 1.11E + 14 \text{ sej}$$

(2) The power output emergy of Scenario B: Electricity output = $1.62E12 \times 4.50E05 = 7.29E17 \text{ sej}$.

(3) Products' economic benefit (brick plant) emergy of Scenario B: = $1.62E12 \times 3.97E05 = 6.43E17 \text{ sej}$.

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Declarations

Conflict of interest The authors declare that we have no conflict of interest.

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