

Article

# Ecological Assessment of Clay Brick Manufacturing in China Using Emergy Analysis

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**Abstract:** Clay brick is a commonly used building material in China. Due to the enormous land destruction and excessive consumption of resources, such as materials and energy in the manufacture of clay brick, it is important to study its overall sustainability, i.e., in terms of impact on the environment, services, and economy. In this study, emergy analysis is employed, which offers a holistic perspective, unlike typical environmental studies. A series of emergy indices such as renewability rate (R%), nonrenewability rate (N%), unit emergy values (UEVs), emergy yield ratio (EYR), environmental loading ratio (ELR), and emergy sustainability index (ESI) were used to study manufacturing of clay brick. In addition to calculating UEVs of clay brick manufacturing in China ( $7.18 \times 10^{12}$  sej/kg), our detailed analysis shows that the nonrenewable resources and imported energy have a dominant impact on the emergy contribution (50.6%) and within the nonrenewable resources, clay is the foremost item, accounting for 33.5% of local emergy inputs. Given different electricity UEVs, the change ranges of clay brick system UEVs are 14.9% (scenario 1), 7.24% (scenario 2), 8.91% (scenario 3), and 6.94% (scenario 4). Furthermore, several policy suggestions are discussed for improving the sustainability of the evaluated system, involving the energy structure adjustment, recycling material replacement, and promotion of energy-saving systems.

**Keywords:** sustainability; emergy analysis; clay brick; unit emergy values; emergy indices

## 1. Introduction

Before the advent of cement-based materials for buildings, clay bricks were one of the most commonly used materials for more than two thousand years in China, as seen in ancient buildings [1,2]. Despite China's rapid growth from the reform in the 1980s [3], clay bricks continued to be used in building construction in rural areas. While much attention has been aimed at cementitious bricks in terms of sustainability assessments, the research community has rarely focused on the overall sustainability, i.e., in a holistic perspective, of clay bricks in China.

Sustainability demonstrates the concept of the triple bottom line, which is a comprehensive dimension study related to the environment, society, and economy. Sustainability is an important concept and central issue which is widely used in various fields such as supply chain management [4], engineering analysis [5], building construction program [6], information aspect [7], tourism growth [8], agricultural directions [9], national sustainability [10], urban assessments [11], groundwater sustainability assessment [12], dryland regions [13], and campus culture [14].

In the case of the manufacturing of clay bricks, several approaches were used to assess the sustainability, namely, life cycle assessment (LCA), material flow analysis (MFA), energy analysis (EA), economic evaluation (EE), etc. Previous works [15–18] attempted to estimate the impact on land, water, and air due to the manufacturing of clay bricks. While MFA focused on coal ash, wastes additives, fabric reinforced cementitious mortar in bricks [19], EA estimated the energy consumption used in clay brick manufacturing. In EA, the coal and other primary energy resources that were used in the manufacturing were converted to a common unit base on power generation equipment, for example, electricity, diesel, and fuel oil [20]. EE focuses on the cost impact only, for example, reusing fly ash in the brick industry [21]. However, an integrated LCA and EE assessments offer insight both into cost impact as well as impact on the environment [22].

However, none of these approaches offers a comprehensive performance evaluation of clay bricks that takes into consideration the constructs of the triple bottom line, namely environment (resource), society (service), and economy. Emergy analysis (EMA), put forward by H.T. Odum, integrates mass flow, energy flow, currency flow, and information flow into a unified platform to compute the environment, service, and economy in emergy units [23]. Depending on a set of indicators, the sustainability of the targeted system can be displayed.

Needless to say, there is a strong need for a comprehensive assessment of clay brick manufacturing in China using emergy theory. However, at this time, there are no such assessments available for the manufacturing of clay brick in China using emergy analysis. This paper discusses the sustainability assessment of clay brick manufacturing in China using EMA, and more specifically by utilizing (i) unit emergy values and (ii) sustainability-based emergy indices such as emergy yield ratio (EYR), environmental loading ratio (ELR), and emergy sustainability index (ESI).

While unit emergy values (UEVs) of clay bricks can be used to calculate emergy of buildings and infrastructure that use clay brick in China, emergy indices are crucial to developing policies to ease the environmental load. The entire paper is organized as below. Section 1 is the introduction. Section 2 shows the evaluated methodology. Section 3 discusses the results of emergy analysis followed by a discussion. Finally, Section 4 draws conclusions of the study.

## 2. Emergy Analysis Method of Clay Brick Manufacturing in China

### 2.1. Emergy Methodology

Emergy analysis offers a holistic ecological evaluation of a system or product, including materials, energy, resources, and service over the entire lifespan of that system or product. As a unique concept, emergy was used to elucidate the sustainability of materials.

Emergy can realize the integration between environment and inputs, including resources, energy, and service [24]. Therein, unit emergy values (UEVs) are the key concept for calculating the emergy amount based on the unit of solar emergy joules (sej), which has three types, emergy/energy (sej/j), specific emergy (sej/g), and emergy/money (sej/\$) [25].

Emergy baseline is the base of emergy calculation, related to solar, tidal, and geothermal energy. To date, five versions have been put forward, which are  $9.44 \times 10^{24}$  sej/year [23],  $9.26 \times 10^{24}$  sej/year [26],  $15.83 \times 10^{24}$  sej/year [27],  $15.2 \times 10^{24}$  sej/year [28], and  $12 \times 10^{24}$  sej/year [29]. The latest emergy baseline ( $12 \times 10^{24}$  sej/year) combines the above four calculated methods of geobiosphere emergy baseline [29]. On the basis of the newest emergy baseline, several UEVs have been developed. For this work, an emergy baseline of  $12 \times 10^{24}$  sej/year was used.

The emergy accounting process comprises three steps, namely, Step 1: Establishing a system diagram to capture all inputs and outputs of the system; Step 2: Constructing an emergy value inventory table; and Step 3: Calculating ratios and emergy indices. Following Step 3, an in-depth analysis and relevant policy discussions can be made. Basic calculation formulas of emergy can be shown as:

$$U(\text{sej}) = N(J) \times \text{UEV}(\text{sej/J}) \quad (1)$$

$$U(\text{sej}) = M(\text{g}) \times \text{UEV}(\text{sej/g}) \quad (2)$$

$$U(\text{sej}) = V(\$) \times \text{UEV}(\text{sej}/\$) \quad (3)$$

where  $U$  is the energy (sej);  $N$ ,  $M$ ,  $V$  represent the units of Joules (J), grams (g), and money (\$), respectively. UEV is energy per unit of product, energy, service, or money. These are the definitions that illustrate the efficiency of an evaluation system [30].

## 2.2. Emergy Sustainability Indicators

The following emergy indices have been used in this study:

### (1) Basic indicators:

Renewability rate (R%), a ratio with a renewable emergy part and total emergy part. A higher renewability rate represents a better ecological level.

Nonrenewability rate (N%) signifies the ratio of the nonrenewable emergy part and total emergy part. A higher nonrenewability rate implies a worse ecological level.

Other related indicators are UEVs, imported resources, imported energy, and labor and service.

### (2) Emergy yield ratio (EYR):

EYR is defined as the ratio between total emergy and imported emergy, and it represents the ability to generate emergy. The less input of purchased emergy will lead to lower EYR, which expounds the competitive ability and economic status of the targeted object.

### (3) Environmental loading ratio (ELR):

ELR is the ratio between nonrenewable resources and imported emergy to renewable emergy. ELR has been used to formulate the ecological pressure of targeted ecosystems. Environmental loads are made up of non-resource emergy, imported emergy, and others, such as gas emissions, waste discharge, etc. Some researchers have already given the related standard for different environmental load situations [31].

### (4) Emergy sustainability index (ESI):

ESI is the ratio of two emergy indicators, EYR and ELR. It implies the integral sustainable situation of one system, which can be used to assess the overall effect. Generally speaking, in view of the literature [31], there are three numerical segments to signify the sustainable degrees, which contain  $ESI < 1$  (sustainable),  $1 < ESI < 5$  (medium sustainability), and  $ESI > 5$  (unsustainable), in the long term.

## 2.3. Clay Brick Manufacturing Process and Data in China

As clay bricks are still used as a primary building material in China, there are over 60,000 clay brick manufacturing plants in operation today, producing 800 billion clay bricks on an annual basis [32]. For the purposes of this work, a medium-sized clay brick manufacturing plant located in Shijiazhuang City of Hebei Province in China was selected. The manufacturing plant has an area of 5000 square meters. The annual manufacturing of this plant is approximately 6 million standard sized bricks (240 mm × 115 mm × 53 mm) in a year [33]. Data used in this work were obtained from this manufacturing plant. Figure 1 shows the process of the manufacturing of clay brick.

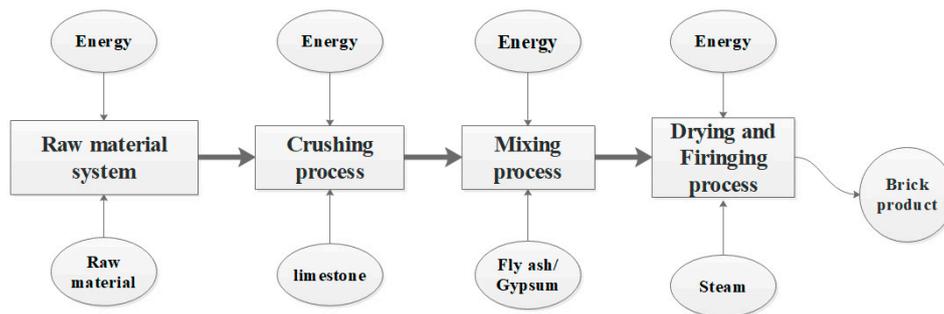


Figure 1. Core processes of clay brick manufacturing in China.

The traditional manufacturing processes of brick product (Figure 1) are composed of the raw material preparation process, crushing process, mixing process, drying, and firing process. The entire process can be simplified to four major processes, namely raw material, crushing, mixing, and drying and firing processes, in that order [34].

#### 2.4. Energy Flow Diagram of Clay Brick Manufacturing Process in China

Figure 2 shows the energy diagram of manufacturing of clay brick. The system boundary of clay brick manufacturing includes renewable, nonrenewable, and imported resources, imported energy, and labor and service. Energy is used in four main processes of brick manufacturing, including the ingredient, crushing, and mixing processes, as well as the drying and firing process.

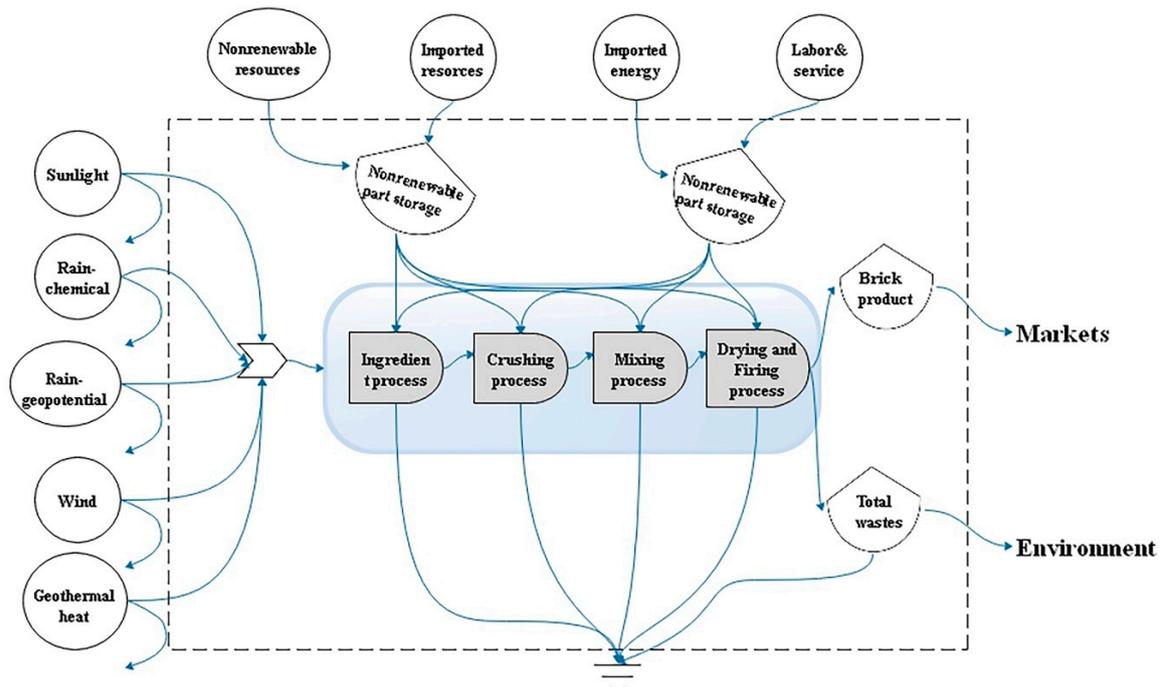


Figure 2. Energy diagram of clay brick manufacturing.

#### 2.5. Energy Analysis and Calculation of UEV

The sustainability assessment of clay brick manufacturing takes into account environment, service, and economical factors. For this work, in addition to typical energy analysis, we can include air pollutant emission and its environmental impact (in sej), ecological service accounting, and economy accounting with an emphasis on disability-adjusted life years (DALYs) lost [24].

### 2.5.1. Air Pollutants and Related Emissions

According to the China's National Mandatory Standard [35], there are three main air pollutants in building brick manufacturing, namely dust, sulfur dioxide (SO<sub>2</sub>), and nitrogen oxides (NO<sub>x</sub>). The exhaust can cause severe effects on human health and ecosystem sustainability, specifically by causing respiratory disease and disrupting ecological balance aspects. To obtain a careful consideration, the ecological service and economic loss calculations have been performed in this study. The initial emission data contain 80 mg/m<sup>3</sup> (dust), 20 mg/m<sup>3</sup> (SO<sub>2</sub>), and 50 mg/m<sup>3</sup> (NO<sub>x</sub>) based on the GB 3095-2012 standard.

### 2.5.2. Economic Loss Accounting

In this paper, the economic loss due to the air pollutants of brick manufacturing needs to be considered and computed. Given the study of Bakshi (2002), human health influence has been accounted for by using DALYs (Table 1), as shown in Equation (4) [36].

$$L = \sum W_i \times DALY_i \times \alpha \quad (4)$$

$L$  represents economic emery loss.  $i$  is the exhaust gas species.  $W_i$  shows the waste gas values.  $DALY$  is disability-adjusted life years on the basis of exhaust gas, a/kg of emission (in Table 1).  $\alpha$  means damage parameter for one year:  $1.68 \times 10^{16}$  sej/(a-person) [24].

**Table 1.** Disability-adjusted life year (DALY) data of air pollutant emissions in this paper (Yan et al., 2018).

Element	Damage Impact	DALYs (a/Kg of Emissions)
Dust	Respiratory	$5.46 \times 10^{-5}$
SO <sub>2</sub>	Respiratory	$8.87 \times 10^{-5}$
NO <sub>x</sub>	Respiratory	$3.75 \times 10^{-4}$

### 2.5.3. Ecological Services Accounting

There is a close relationship between the ecological services calculation and environmental impacts. Therefore, three air pollutants have been chosen (dust, SO<sub>2</sub>, and NO<sub>x</sub>) for emery assessment. For the estimate of the ecological service, as a first step, the waste gas amount must be estimated according to Equation (5) [24].

$$M_i = c \times \left( \frac{U_i \times 10^6}{s_i} \right) \quad (5)$$

Secondly, the emery of ecological services is calculated as below.

$$R_{air,i} = 0.5 \times M_i \times v^2 \times T_w \quad (6)$$

where  $M_i$ ,  $i$ ,  $c$ ,  $U_i$ , and  $s_i$  are air dilution (Kg/a), gas species, air density (1.23 Kg/m<sup>3</sup>), the amount of air pollution each year, and acceptable concentration (dust, 0.08 mg/m<sup>3</sup>; SO<sub>2</sub>, 0.02 mg/m<sup>3</sup>; NO<sub>x</sub>, 0.05), respectively [35].  $R_{air,i}$ ,  $v$ , and  $T_w$  are environmental emery, wind speed (2.8 m/s), and transformity of wind ( $1.86 \times 10^3$  sej/J) [24].

## 3. Results and Discussion

### 3.1. Emery Table Calculations

The emery analysis calculations of clay brick manufacturing in China are given in Table 2. The calculated items comprise renewable resources, nonrenewable resources, imported resources, imported energy, and labor and service. In the evaluated system, five renewable inputs are considered, such as sunlight, rain (chemical energy), rain (geopotential), wind (kinetic energy), and geothermal heat.

Nonrenewable resources consist of clay and shale. Imported resources are mainly purchased resources, gypsum, limestone, steam, and fly ash. Imported energy is electricity. Based on local economic conditions, labor and service were included in emergy calculation.

**Table 2.** Emergy calculation of clay brick manufacturing (refer to Appendix A for detailed calculations).

No.	Item	Unit	Amount	Ref. for Data	UEVs (sej/unit)	Emergy (sej/year)	Ref. for UEVs	%
1. Renewable resources								
	Sunlight		$2.1 \times 10^6$ J/y	Calculated	1	$2.07 \times 10^6$	[37]	0.00
	Rain (chemical energy)		$1.1 \times 10^{13}$ J/y	Calculated	$2.35 \times 10^4$	$2.47 \times 10^{17}$	[37]	0.01
	Rain (geopotential)		$6.6 \times 10^9$ J/y	Calculated	$2.79 \times 10^4$	$1.84 \times 10^{14}$	[37]	0.00
	Wind (kinetic energy)		$6.44 \times 10^8$ J/y	Calculated	$1.9 \times 10^3$	$1.22 \times 10^{12}$	[37]	0.00
	Geothermal heat		$5.5 \times 10^8$ J/y	Calculated	$3.44 \times 10^4$	$1.9 \times 10^{14}$	[37]	0.00
2. Nonrenewable resources								
	Clay		$7.2 \times 10^7$ kg	Collected	$2 \times 10^{12}$	$1.44 \times 10^{20}$	[38]	33.5
	Shale		$3 \times 10^7$ kg	Collected	$2.46 \times 10^{12}$	$7.38 \times 10^{19}$	[38]	17.1
3. Imported resources								
	Gypsum		$6 \times 10^6$ kg	Collected	$1.27 \times 10^{12}$	$7.62 \times 10^{18}$	[38]	1.77
	Limestone		$6 \times 10^6$ kg	Collected	$1.27 \times 10^{12}$	$7.62 \times 10^{18}$	[38]	1.77
	Fly ash		$5 \times 10^5$ kg	Collected	$1.4 \times 10^{13}$	$7 \times 10^{18}$	[39]	1.63
	Water		$2.63 \times 10^7$ kg	Collected	$1.26 \times 10^9$	$3.31 \times 10^{16}$	[39]	0.01
4. Imported energy								
	Electricity		$1.73 \times 10^{14}$ J	Collected	$4.5 \times 10^5$	$7.79 \times 10^{19}$	[39]	18.1
5. Labor and service								
	Labor and service		$1.5 \times 10^8$ ¥	Collected	$7.42 \times 10^{11}$	$1.11 \times 10^{20}$	[40]	25.9
6. Emissions								
	Air pollutants	Dust	$80 \text{ mg/m}^3$	[35]	~	$5.15 \times 10^{11}$	See note 6	0.00
		SO <sub>2</sub>	$20 \text{ mg/m}^3$	[35]	~	$1.53 \times 10^{11}$	See note 6	0.00
		NO <sub>x</sub>	$50 \text{ mg/m}^3$	[35]	~	$1.19 \times 10^{11}$	See note 6	0.00
	UEV				$7.18 \times 10^{12}$ sej/kg			100

In Table 2, there are six emergy sections in the brick manufacturing system and have vital effects on sustainability. Based on this background, a few important emergy values are  $4.97 \times 10^{17}$  sej/year for renewable resources,  $2.18 \times 10^{20}$  sej/year for nonrenewable resources,  $2.23 \times 10^{19}$  sej/year for imported resources,  $7.79 \times 10^{19}$  sej/year for imported energy, and  $1.11 \times 10^{20}$  sej/year for labor and service.

The emergy results shown in Table 2 reveal that the most important factors are nonrenewable resources (50.7%), followed by labor and service (25.8%) and imported energy (18.1%). Compared with those items, renewable resources play a minor role in the input emergy.

For nonrenewable resources, clay is the major contributor, accounting for about 66.1% of nonrenewable resources in emergy terms and 33.5% of the total emergy needed. Shale emergy, in second place, uses 33.9% and 17.1%, respectively. For the imported resources, the contribution ratios are 1.78% for limestone emergy, 1.78% for gypsum emergy, and 1.63% for fly ash emergy. Low quantities of renewable resources were used as inputs. Overall, results show that, in emergy terms, clay, shale, electricity, and labor and service are dominant components for clay brick manufacturing in China.

### 3.2. Emergy-Based Indicators

A series of indicators, namely, renewability rate, nonrenewability rate, emergy yield ratio, environmental loading ratio, and emergy sustainability index, were calculated and are shown in Table 3; details are as follows.

**Table 3.** Emery sustainable indexes of brick product.

Note	Items	Index	Results
1	Renewability rate	%R	0.01%
2	Nonrenewability rate	%N	50.6%
3	Emery yield ratio	EYR	18.3
4	Environmental loading ratio	ELR	486
5	Emery sustainability index	ESI	0.038

## (1) Renewability rate (%R)

The renewability rate of clay brick manufacturing in China is calculated as 0.01%. This value symbolizes the sustainable level for the evaluated system and represents the proportion of renewable resources. The renewability rate is too low for clay brick manufacturing in China. Because of the high emery costs of energy and resources, a large number of nonrenewable resources are used in the brick plant, resulting in a high non-renewable rate.

Therefore, enhancing the renewability rate is an urgent task for clay brick manufacturing plants in China. In light of recent research results, some measures have been put into practice to improve the clay brick manufacturing process, such as the use of rainwater recycling technology [41] and wastewater reuse technology [42,43]. For example, if the renewable resource can be increased by 10%, %R can be improved by 50%.

## (2) Nonrenewability rate (%N)

The nonrenewability rate of clay brick manufacturing in China is 50.6%. This large percentage shows the share of negative strain on the sustainability of the evaluated system. The higher the nonrenewability rate, the worse its sustainability. There are two approaches to mitigate this situation, i.e., reduce %N, namely, by enhancing energy utilization efficiency and using alternative materials to replace nonrenewable resources. For example, if energy utilization efficiency can be enhanced by 10%, the nonrenewability rate can be reduced by 0.76%; meanwhile, if 10% of the clay can be replaced by brick fragments, the nonrenewability rate will be reduced by 3.21%. In the case of alternative materials, for instance, when clay is decreased by 10%, the nonrenewability rate (%N) can be reduced by 5.07%. Therefore, using alternative materials is critical to improve %N.

Other studies have implemented similar approaches to realize sustainable development. According to Prafulla et al. [44], the activated alumina was used to substitute clay to for brick making, and, to a certain extent, the sustainable development model of the brick factory was improved. Taking advantage of fly ash and fly ash wastes, eco-friendly clay brick manufacturing was attempted by Mucahit et al. [45].

## (3) Unit emery values (UEVs)

The unit emery value of building clay brick manufacturing is calculated as  $7.18 \times 10^{12}$  sej/kg, which is different from other researchers' results, see Table 4. The UEV based on this study differs from existing studies due to the emery baseline used ( $12.0 \times 10^{24}$  sej/year), evaluated system boundaries, specific manufacturing processes, UEVs of input items, brick types, labor and service situations, energy structure and efficiency, etc.

**Table 4.** Unit emery values (UEVs) for clay brick.

Author	UEVs (sej/kg)	Baseline (sej/year)	Region
Buranakarn [46]	$2.03 \times 10^{12}$	$9.44 \times 10^{24}$	USA
Hwang Yi et al. [47]	$3.33 \times 10^{12}$	$9.44 \times 10^{24}$	USA
R.M. Pulselli et al. [48]	$3.68 \times 10^{12}$	$9.44 \times 10^{24}$	Italy
This study, 2020	$7.18 \times 10^{12}$	$12.0 \times 10^{24}$	China

## (4) Energy yield ratio (EYR)

The Energy yield ratio of clay brick manufacturing in China is 18.3. This signifies that the imported energy item is far less than total energy. The local resource (clay) is the main source of non-resource energy causing serious clay waste and vast environmental pollution.

## (5) Environmental loading ratio (ELR):

The environmental loading ratio for clay brick manufacturing in China is 486, which is far greater than the relevant standard and empirical values, which indicates serious environmental burden. It is to be noted that, based on energy analysis, clay brick manufacturing will bring greater damage to the local ecological environment. One option is to, among others, to use sustainable raw materials for brick manufacturing to reduce the impact to the environment.

## (6) Energy sustainability index (ESI):

The energy sustainability index of clay brick manufacturing in China is 0.038. Based on the ESI, the manufacturing process is not a sustainable state in the long run. In order to improve the unsustainable state of the brick factory, several environmentally friendly brick products (shale, gypsum, limestone, etc.) can be used as alternatives.

## 3.3. Sensitivity Analysis

As shown in Table 2, the total energy input is divided into five parts, involving renewable resources, nonrenewable resources, imported resources, imported energy, and labor and service. The accuracies of basic data and UEVs can be impacted by various sources. Therefore, it is necessary to conduct the sensitivity analysis.

For the purposes of sensitivity analysis, the nonrenewable resources and imported energy are prioritized owing to their major influence on total energy. Here, four scenarios are tested for sensitivity; scenario 1: the UEVs of nonrenewable resources change by  $-5\%$  (i.e., reducing the nonrenewable resources by  $5\%$ ); scenario 2: the UEVs of nonrenewable resources vary by  $+5\%$ ; scenario 3: the UEVs of imported energy are the target that have a  $-5\%$  range of change; and scenario 4: the UEVs of imported energy are altered by  $+5\%$ . The resultant sensitivity data of four scenarios are shown in Figures 3 and 4.

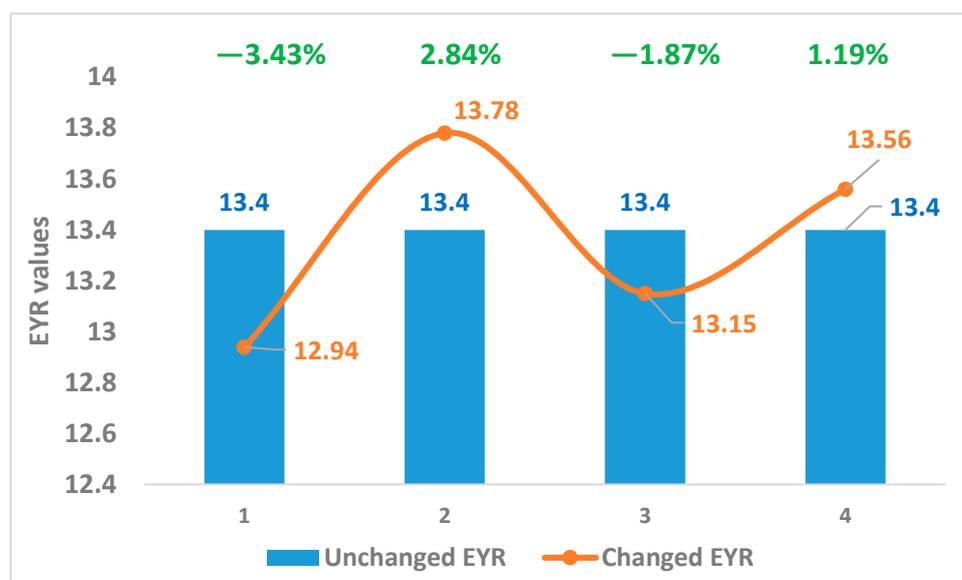
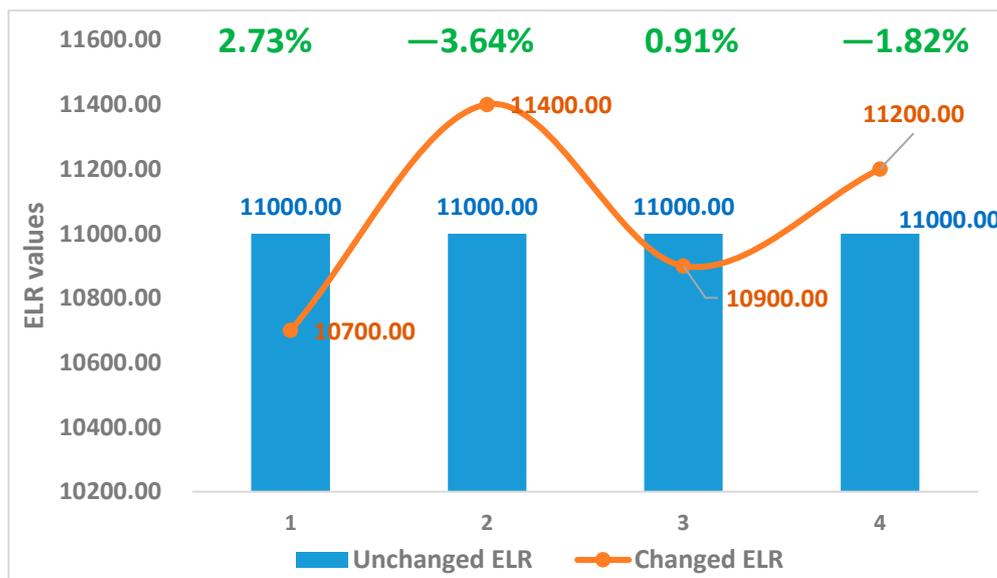


Figure 3. Four scenarios used for sensitivity analysis of energy yield ratio (EYR).



**Figure 4.** Four scenarios for sensitivity analysis of environmental loading ratio (ELR).

Scenario 1 has the biggest fluctuation (−3.43%), followed by scenario 2 (2.84%), scenario 3 (−1.87%), and scenario 4 (1.19%), in this order. Based on −5% changes of four scenarios, the UEVs of nonrenewable resources have a greater influence than imported energy (from −3.43% to −1.87%). It means that a 5% reduction of nonrenewable resources and imported energy can cause 3.43% and 1.87% decreases for the entire energy input, respectively. For a +5% variation in EYR, a similar trend is seen, as shown in Figure 3 (from 2.84% to 1.19%). Nonrenewable resources play a major role, as can be seen in the energy contribution ratio, accounting for 50.6% of total energy in the evaluated system. The higher the energy ratio, the greater the sensitivity results. In addition, based on EYR and ELR calculations, the ESI can be computed through a formula (EYR was divided by ELR). Because ELR is much larger than EYR, this results in an essentially unchanged ESI for this paper.

To improve overall sustainability of clay brick manufacturing, we recommend the use of clean energy as well as increased use of recycled materials.

#### 3.4. Different Electricity UEV Effects Based on Multiple Literature Sources

In terms of Table 2, there are four primary inputs, which are clay, shale, electricity, and labor and service, accounting for 33.5%, 17.1%, 18.1%, and 25.9% of the total energy in the brick plant, respectively. Owing to the large variations in different pieces of literature within the context of China, four groups of new electricity UEVs were selected and calculated from other studies in the last five years [49–52]. Specific data can be found in Table 5.

**Table 5.** Electricity UEV selections of five scenarios based on other studies [49–52].

Item	UEVs	Unit	Country	Year	Ref.
Scenario 1	$8.00 \times 10^4$	sej/j	China	2016	[49]
Scenario 2	$2.68 \times 10^5$	sej/j	China	2018	[50]
Scenario 3	$2.31 \times 10^5$	sej/j	China	2018	[51]
Scenario 4	$2.78 \times 10^5$	sej/j	China	2016	[52]

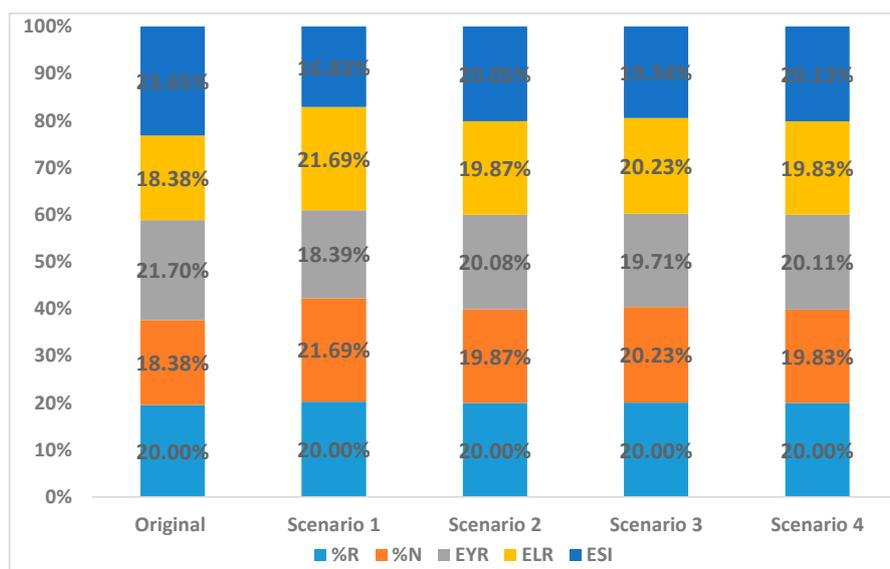
Based on different electricity UEV selections from other studies (in Table 5), the four scenarios previously mentioned were considered and calculated in this paper. All input proportions of the

four new scenarios have been computed to analyze the disparate electricity UEV impacts on the sustainability of clay brick plants.

Table 6 lists the final energy sustainability results and Figure 5 shows the comparison of the scenarios. Firstly, given the small renewability rate (R%) input for all scenarios, its proportion has no change. In all cases, it is 0.01%. In addition to renewable inputs, other cases have different variations, such as %N (from 18.38% input to 21.69%), EYR (from 18.39% input to 21.7%), ELR (from 18.38% input to 21.69%), and ESI (from 16.83% input to 23.65%). On the whole, the ranges of variation are from 3.31% to 6.82%, which demonstrate that different electricity UEVs of multiple literature sources have a greater impact on the assessment results. In this paper, taking the ESI as an example, the biggest gap was 6.8%, resulting in inaccurate sustainability results.

**Table 6.** Energy sustainable indexes of four new scenarios.

Note	Items	Original	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	Renewability rate	0.01%	0.01%	0.01%	0.01%	0.01%
2	Nonrenewability rate	50.6%	59.7%	54.7%	55.7%	54.6%
3	Energy yield ratio	18.3	15.511	16.928	16.624	16.959
4	Environmental loading ratio	486	573.403	525.379	534.984	524.419
5	Energy sustainability index	0.038	0.02705	0.03222	0.03107	0.03234

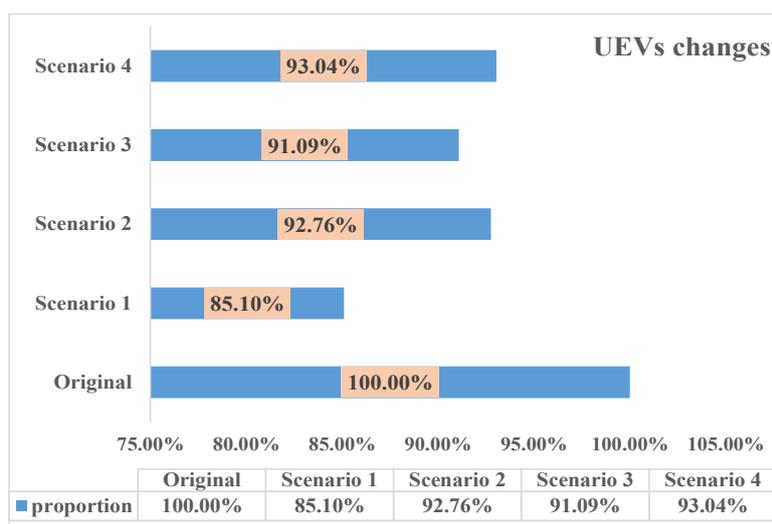


**Figure 5.** Sustainable indicator comparison of four scenarios.

Table 7 reveals the UEVs of a clay brick system on the basis of five scenarios. All calculations were conducted in view of the latest baseline in this paper. Taking the original version as the calculation basis, four new change scenarios are illustrated in Figure 6, which are 85.1% for scenario 1, 92.76% for scenario 2, 91.09% for scenario 3, and 93.04% for scenario 4. The change ranges of clay brick system UEVs are from 6.94% (scenario 4) to 14.9% (scenario 1). Hence, based on four new scenarios from different literature data, single input element UEVs have a significant influence on the accuracy. In order to enhance the accuracy of calculation results, all unit UEVs of input elements should be considered carefully in the calculation.

**Table 7.** UEVs of clay brick based on four new scenarios.

Item	UEVs (sej/kg)	Baseline (sej/year)	Region
Original	$7.18 \times 10^{12}$	$12.0 \times 10^{24}$	China
Scenario 1	$6.11 \times 10^{12}$	$12.0 \times 10^{24}$	China
Scenario 2	$6.66 \times 10^{12}$	$12.0 \times 10^{24}$	China
Scenario 3	$6.54 \times 10^{12}$	$12.0 \times 10^{24}$	China
Scenario 4	$6.68 \times 10^{12}$	$12.0 \times 10^{24}$	China

**Figure 6.** UEV changes of clay brick system within different electricity UEV scenarios.

#### 4. Policy Implications

In light of the studies in this article, three policies are suggested to improve the overall sustainability of clay brick manufacturing in China:

##### (1) Adjustment of primary energy resources

Unbalanced energy resources are one of the main problems for clay brick manufacturing in China. To date, there are five types of power energy resources in China: thermal power (75.08%), hydroelectric power (13.15%), wind power (6.1%), nuclear power (4.17%), and the other types (1.49%) [53]. In this paper, the main source of electricity is thermal power generation. If 10% of electricity supplied by thermal energy (primarily generated using coal) was replaced by wind power, the environmental load ratio can be reduced by approximately 3.1%. Hence, several renewable energy resources should be carefully considered, including solar power [54], hydropower [55], and wind power [56], which are the most common and important sources of renewable energy in China. However, a few shortcomings restrict the use of these renewable energy resources, particularly those related to huge investment, professional and technical barriers, and geographical conditions, which can be only managed effectively by local governments in China. For instance, necessary financial subsidies and advantageous tax policies needs to be offered so as to strengthen the promotion of clean energy.

##### (2) Recycling materials

Owing to over dependence on clay in clay brick manufacturing, heavy environmental loading can be observed. Material substitution is currently proving to be effective, especially focusing on industrial waste and by-products. If 10% of clay is replaced by construction material waste while still maintaining strength, as per, the UEVs will be reduced to  $3.99 \times 10^{12}$  sej/kg; this is a 5.67% reduction from the current UEV calculation. Moreover, the environmental loading ratio will be lowered by 4.1%. Several

researchers have attempted material substitution in the brick industry [57–60]. Munz et al. (2014) reviewed sustainable construction material wastes for the fired clay brick industry and 44 sustainable alternative wastes with an aim to achieve sustainable brick manufacturing [57]. Taking asphalt mix as an added material, Eduardo (2018) carried out a study to design an innovative and new building brick [58]. Armando (2017) made use of construction wastes to bring about the manufacturing of ecological bricks [59]. Mamdooh et al. (2019) used aluminum recycling raw material to manufacture ecological clay bricks [60]. We suggest that China's clay brick factories should continue to increase the proportion of alternative material applications.

### (3) Promotion of energy-saving systems

According to the sustainability assessment of clay brick manufacturing, imported energy is the third largest contributor to the unsustainable state, so it is necessary to take some measures to mitigate the negative effect. In this study, if electricity consumption was reduced by 5%, the factory's sustainability indicators may be improved by 1.1%. The residual energy reutilization of advanced systems should be deemed as the optimal sustainable approach and be adopted to realize the reduction of imported energy [61–63]. Other new energy-saving systems can be given priority for application and promotion, which consist of waste water recovery systems, waste heat recovery systems, cooling recovery systems, kiln top heat exchange and reuse systems, etc.

## 5. Conclusion

In this paper, emergy analysis was used to assess manufacturing of clay brick in China. The main conclusions are summarized as follows.

- (1) Emergy contributors: nonrenewable resources (approximately 50.6%), labor service (approximately 25.9%), and imported energy (approximately 18.1%).
- (2) For the nonrenewable resources, clay accounts for 66.1% of local emergy input and 33.5% of the total emergy needed, considered to have paramount status in the evaluated brick plant system.
- (3) A series of indicators are 0.01% (renewability rate); 50.6% (nonrenewability rate); 18.3 (emergy yield ratio); 486 (environmental loading ratio); 0.038 (emergy sustainability indicator).
- (4) The unit emergy value of the building clay brick plant is  $7.18 \times 10^{12}$  sej/kg, which is twice the value of other studies conducted primarily in the U.S.
- (5) Based on different electricity UEV selections from multiple literature sources, four new scenarios have been considered and calculated in this paper.
- (6) The R% proportion has no change. In addition to renewable inputs, other cases have different variations, such as %N (from 18.38% input to 21.69%), EYR (from 18.39% input to 21.7%), ELR (from 18.38% input to 21.69%), and ESI (from 16.83% input to 23.65%).
- (7) Given different electricity UEVs, the change ranges of clay brick system UEVs are 14.9% (scenario 1), 7.24% (scenario 2), 8.91% (scenario 3), and 6.94% (scenario 4), which remind us that the different sources of UEV data should be considered and selected fully and carefully.

Several policy suggestions were discussed for improving the sustainability of the evaluated system; they include the energy structure adjustment, recycling material replacement, and promotion of energy-saving systems.

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## Appendix A

The calculated emergy baseline is  $12 \times 10^{24}$  sej/yr in Table 2.

### 1. Renewable energy calculation:

#### 1-Renewable Energy calculation:

Solar energy calculation: Area of brick plant =  $5000\text{m}^2$ ; Insolation (Hubei Province, China) =  $5.00 \times 10^9 \sim 5.85 \times 10^9$  J/m<sup>2</sup>/y [64]; Albedo = 0.30 [64]. Energy = (insolation)  $\times$  (1 – albedo)  $\times$  (area) =  $(5.43 \times 10^9$  J/m<sup>2</sup>/y)  $\times$  (1 – 0.30)  $\times$  ( $5000\text{m}^2$ ) =  $2.07 \times 10^6$  J/y. UEV = 1.00 sej/J by definition. Emergy of one year =  $2.07 \times 10^6$  J/y  $\times$  1 y  $\times$  1.00 sej/J =  $2.07 \times 10^6$  sej.

Rain (geopotential energy) calculation: Area of brick plant =  $5000\text{m}^2$ ; Rainfall (annual average, n = 5) = 0.68 m/year; Average elevation = 316 m [65]; water density =  $1.00 \times 10^3$  kg/m<sup>3</sup>; Runoff rate = 40.00%. Energy = (area)  $\times$  (rainfall)  $\times$  (runoff rate)  $\times$  (water density)  $\times$  (average elevation)  $\times$  (gravity) =  $(5000\text{m}^2) \times (0.71\text{m/y}) \times (40\%) \times (1 \times 10^3\text{kg/m}^3) \times (316\text{m}) \times (9.8\text{kg/m}^2)$  =  $6.59 \times 10^9$  J/y. UEV =  $2.79 \times 10^4$  sej/J [37]. Emergy of one year =  $6.59 \times 10^9$  J/y  $\times$  1 y  $\times$   $2.79 \times 10^4$  sej/J =  $1.84 \times 10^{14}$  sej.

Rain (chemical potential energy) calculation: Area of brick plant =  $5000\text{m}^2$ ; Rainfall (annual average, n = 5) = 0.68 m/year [66]; Water density =  $1.00\text{kg/m}^3$ ; Evapotranspiration rate = 60%; Gibbs free energy of water =  $4.94 \times 10^3$  J/kg. Energy = (area)  $\times$  (rainfall)  $\times$  (evapotranspiration rate)  $\times$  (water density)  $\times$  (Gibbs free energy of water) =  $(5000\text{m}^2) \times (0.71\text{m/y}) \times (1 \times 10^3\text{kg/m}^3) \times (60\%) \times (1 \times 10^3\text{kg/m}^3) \times (4.94 \times 10^3\text{J/kg})$  =  $1.05 \times 10^{13}$  J/year. UEV =  $2.35 \times 10^4$  sej/J [67]. Emergy of one year =  $1.05 \times 10^{13}$  J/y  $\times$  1 y  $\times$   $2.35 \times 10^4$  sej/J =  $2.47 \times 10^{17}$  sej

Wind energy calculation: Area of brick plant =  $5000\text{m}^2$ ; Air density =  $1.29\text{kg/m}^3$ ; Wind velocity (annual average, n = 2) = 1.95 m/s [68]; Velocity of geostrophic wind = 3.25 m/s, surface winds are considered as 0.6 of geostrophic wind; Drag coefficient =  $1.00 \times 10^{-3}$  [69]. Energy = (area)  $\times$  (air density)  $\times$  (drag coefficient)  $\times$  (velocity of geostrophic wind)<sup>3</sup> =  $(5000\text{m}^2) \times (1.29\text{kg/m}^3) \times (1.00 \times 10^{-3}) \times (3.17\text{m/s})^3 \times (3.15 \times 10^7\text{s/year})$  =  $6.44 \times 10^8$  J/y. UEV =  $1.90 \times 10^3$  sej/J. Emergy of one year =  $6.44 \times 10^8$  J/y  $\times$  1 y  $\times$   $1.90 \times 10^3$  sej/J =  $1.22 \times 10^{12}$  sej

Geothermal heat calculation: Area of brick plant =  $5000\text{m}^2$ ; Heat flow (average) =  $3.50 \times 10^{-2}$  J/m<sup>2</sup>/s. Energy = (area)  $\times$  (heat flow) =  $(5000\text{m}^2) \times (3.50 \times 10^{-2}\text{J/m}^2/\text{s}) \times (3.15 \times 10^7\text{s/year})$  =  $5.51 \times 10^9$  J/y. UEV =  $3.44 \times 10^4$  sej/J. Emergy of one year =  $5.51 \times 10^9$  J/y  $\times$  1 y  $\times$   $3.44 \times 10^4$  sej/J =  $1.90 \times 10^{14}$  sej

### 2. Nonrenewable resource emergy

Clay emergy calculation: annual clay consumption =  $7.20 \times 10^7$  kg.

$$\text{Annual clay emergy} = 7.20 \times 10^7 \text{ kg} \times 2.00 \times 10^{12} = 1.44 \times 10^{20} \text{ sej}$$

Shale emergy calculation: annual shale consumption =  $1.00 \times 10^7$  kg.

$$\text{Annual shale emergy} = 1.0 \times 10^7 \text{ kg} \times 2.46 \times 10^{12} = 7.38 \times 10^{19} \text{ sej}$$

### 3. Imported resource emergy

Gypsum emergy calculation: annual Gypsum consumption =  $6.00 \times 10^6$  kg.

$$\text{Annual gypsum emergy} = 6.0 \times 10^6 \text{ kg} \times 1.27 \times 10^{12} = 7.62 \times 10^{18} \text{ sej}$$

Limestone emergy calculation: annual Limestone consumption =  $6.00 \times 10^6$  kg.

$$\text{Annual limestone emergy} = 6.0 \times 10^6 \text{ kg} \times 1.27 \times 10^{12} = 7.62 \times 10^{18} \text{ sej}$$

Fly ash emergy calculation: annual fly ash consumption =  $5.00 \times 10^5$  kg.

$$\text{Annual fly ash emergy} = 5.00 \times 10^5 \text{ kg} \times 1.4 \times 10^{13} = 7.00 \times 10^{18} \text{ sej}$$

water basic data include 50 tons of water reuse every day

$$\begin{aligned}\text{Annual water reuse} &= 50 \times 365 \text{ tons} = 1.825 \times 10^7 \text{ kg} \\ \text{Annual water energy} &= 2.67 \times 10^7 \text{ kg} \times 1.26 \times 10^9 = 3.31 \times 10^{16} \text{ sej}\end{aligned}$$

#### 4. Imported energy

Electricity energy calculation: actual manufacturing line energy consumption =  $4.8 \times 10^8$  kW·h

$$\begin{aligned}\text{Annual electricity consumption} &= 4.8 \times 10^8 \times 3.6 \times 10^6 = 1.73 \times 10^{14} \text{ j} \\ \text{Annual electricity energy} &= 1.73 \times 10^{14} \times 4.5 \times 10^5 = 7.79 \times 10^{19} \text{ sej}\end{aligned}$$

#### 5. Labor and service

Labor and services energy calculation: annual labor and services cost =  $1.50 \times 10^8$  yuan

$$\text{Annual labor and services energy} = 1.5 \times 10^8 \times 7.42 \times 10^{11} = 1.11 \times 10^{20} \text{ sej}$$

#### 6. Air pollutant energy

##### (1) The economic loss energy:

$$\begin{aligned}L_{Dust} &= \sum W_i \times DALY_i \times \alpha = 0.08 \times 3.75 \times 10^{-4} \times 1.68 \times 10^{16} = 5.04 \times 10^{11} \text{ sej} \\ L_{SO_2} &= \sum W_i \times DALY_i \times \alpha = 0.02 \times 5.46 \times 10^{-5} \times 1.68 \times 10^{16} = 1.83 \times 10^{10} \text{ sej} \\ L_{NO_x} &= \sum W_i \times DALY_i \times \alpha = 0.05 \times 8.87 \times 10^{-4} \times 1.68 \times 10^{16} = 7.46 \times 10^{10} \text{ sej}\end{aligned}$$

##### (2) The ecological service energy:

$$\begin{aligned}M_{Dust} &= c \times \left( \frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left( \frac{0.1 \times 1.0 \times 10^6}{0.08} \right) = 1.54 \times 10^6 \text{ kg/a} \\ M_{SO_2} &= c \times \left( \frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left( \frac{0.3 \times 1.0 \times 10^6}{0.02} \right) = 1.85 \times 10^7 \text{ kg/a} \\ M_{NO_x} &= c \times \left( \frac{U_i \times 10^6}{s_i} \right) = 1.23 \times \left( \frac{0.25 \times 1.0 \times 10^6}{0.05} \right) = 6.15 \times 10^6 \text{ kg/a} \\ R_{SO_2} &= 0.5 \times M_{SO_2} \times v^2 \times T_w = 0.5 \times 1.85 \times 10^7 \times 2.8^2 \times 1.86 \times 10^3 = 1.35 \times 10^{11} \text{ sej} \\ R_{Dust} &= 0.5 \times M_{Dust} \times v^2 \times T_w = 0.5 \times 1.54 \times 10^6 \times 2.8^2 \times 1.86 \times 10^3 = 1.12 \times 10^{10} \text{ sej} \\ R_{NO_x} &= 0.5 \times M_{NO_x} \times v^2 \times T_w = 0.5 \times 6.15 \times 10^6 \times 2.8^2 \times 1.86 \times 10^3 = 4.48 \times 10^{10} \text{ sej}\end{aligned}$$

##### (3) The sum:

$$\begin{aligned}\text{Dust energy} &= 5.04 \times 10^{11} + 1.12 \times 10^{10} = 5.15 \times 10^{11} \text{ sej} \\ \text{SO}_2 \text{ energy} &= 1.83 \times 10^{10} + 1.35 \times 10^{11} = 1.53 \times 10^{11} \text{ sej} \\ \text{NO}_x \text{ energy} &= 7.46 \times 10^{10} + 4.48 \times 10^{10} = 1.19 \times 10^{11} \text{ sej}\end{aligned}$$

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