A Systematic Approach to Calculate Unit Emergy Values of Cement Manufacturing in China Using Consumption Quota of Dry and Wet Raw Materials

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Abstract: The Chinese cement industry produced 2150 million metric tons of cement in 2014, accounting for 58.1% of the world’s total. This industry has a hugely destructive effect on the environment owing to its pollution. The environmental impact of cement manufacturing is a major concern for China. Although researchers have attempted to estimate impacts using life cycle assessment approaches, it lacks the ability to provide a holistic evaluation of the impacts on the environment. Emergy analysis, through ecological accounting, offers environmental decision making using elaborate book keeping. In spite of the high environmental impact of the cement industry, there has only been a handful of research work done to compute the unit emergy values (UEVs) of cement manufacturing in China. A thorough study of existing UEVs of cement manufacturing in China showed pitfalls that may lead to inaccurate estimations if used in emergy analysis. There is a strong need for a new, updated UEV for cement manufacturing in China, particularly reflecting both the dry and wet raw materials in the manufacturing process. This paper develops a methodology to calculate the nonrenewable resources used in cement manufacturing, particularly using mainstream cement production line. Our systematic approach-based UEV estimates of cement manufacturing in China using the quota method are $2.56 \times 10^{12}$ sej/kg (wet material) and $2.46 \times 10^{12}$ sej/kg (dry material). Emergy indicators such as environmental loading ratios which were calculated at 2390 (wet material) and 2300 (dry material); emergy yield ratios at 15.7 and 15.8; and emergy sustainability indices at 0.0066 and 0.0069 for dry and wet materials used in cement manufacturing, respectively; these show the immense impact on the environment in China.

Keywords: emergy analysis; unit emergy values; quota method; cement manufacturing; China

1. Introduction

More often than not, researchers have embarked on the environmental accounting of buildings using life cycle assessments (LCAs) that focus on the impact of emissions and resource consumption. Cátia et al. (2019) assessed the environmental influence of the prefabricated concrete elements for buildings based on the LCA method [1]; Marcella et al. (2020) discussed whole building LCAs and the associated environmental impacts [2]; Mohammad et al. (2019) used the LCA approach to estimate the environmental impacts of conventional construction approaches [3]; Yang et al. (2019) carried out the LCA method to evaluate the building construction sector in China to calculate the energy consumption
and related carbon emissions [4]; and Michele et al. (2019) implemented the LCA methodology on building in Brazil for the assessment of its environmental impact [5]. These environmental impact studies focused on the impact on air, water, and land and did not include the impact on ecology.

However, another comprehensive evaluation approach is ecological accounting, e.g., emery analysis which offers environmental decision-making solutions using elaborate bookkeeping. The emery theory, founded by H. T. Odum, originated in ecology and has been applied in several fields including those of agriculture [6], urban buildings [7], built environments [8], industry [9] and natural landscapes [10], whereas Srinivasan et al., 2014 compared the ecological accounting model (emergy analysis) with LCAs, which mainly focuses on the full-service life of the building, including the building material, construction, use, and the end of life [11].

The emery method is an eective tool for qualitative and quantitative analysis. By measuring the energy efficiency of different systems, the assessments can derive the economic benefits and competitiveness of the system [12] and reflect the level of development of specific systems for sustainability [13]. Emery is used to conduct a comprehensive analysis and evaluation of the system’s energy flow, currency flow, population flow, and information flow.

The core of emery is solar energy [14]. All resources and energy are derived from the sun, so the value can be used to evaluate the sustainability of products, services, systems, and the economy. It can unify resources, energy, and services into one platform to calculate and compare [15,16]. Emery, therefore, is defined as the available solar energy directly or indirectly used to be provided to a product or to provide a service. The unit of emery is solar emjoule (sej). Solar transformity represents the solar emery to produce one unit of available energy of a product and service, and the unit is solar emjoules per joule (sej/j). Solar transformities have three major unit emery intensity values, including transformity, specific emery, and emery per unit money [14]. Specific emery is the emery amount per unit mass of material (sej/kg). Emery per unit money connects the monetary benefit and emery value. Unit emery values (UEVs) explain the emery value of one unit of mass, energy, service, or money. UEVs are the efficiency of the evaluated system. The emery accounting process usually consists of four steps, namely, Step 1: establishing a system diagram; Step 2: constructing an emery value inventory table; Step 3: calculating the ratio and emery index; and Step 4: the in-depth analysis and policy discussions. The basic calculation formulas of emery can be shown as three equations:

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

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

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

where U is the emery; N, M, V represent the unit of Joule (J), grams (g), and money ($), respectively.

Emery indicators, listed below, can be used to evaluate the system with respect to the environment. These indicators, in other words, may be synonymous to mid-point indicators in a LCA study.

1. Renewability rate (R%): it is a ratio between the renewable element and the total element. A higher renewability rate means a better ecological level.
2. Non-renewability rate of the local resource (N%) displays the ratio within the local resource emery and total emery. Higher N% demonstrates worse ecological degrees.
3. Emergy yield ratio (EYR): EYR can be computed in the light of the total emery section and imported emery section, which shows an ability that can generate emery. The higher the EYR is, the better the consequent of the cement plant is. The higher input of purchased emery could bring about the lower EYR, revealing the competitive ability of the evaluated cement plant.
4. Environmental loading ratio (ELR): as the ratio of the non-renewable emery and purchased emery to the renewable emery, the EIR is defined, which can be used to elaborate the ecological load of the evaluated ecosystem, including a non-resource emery pressure, purchased emery pressure and others.
Emergy sustainability index (ESI): ESI demonstrates the ratio between the EYR and the ELR. It expresses the comprehensive effect of the environment and economy for the evaluated system.

1.1. Emergy Analysis of Construction of Buildings and Pavements in China

The application of emergy analysis in the field of building construction has been practiced in the U.S. For example, Srinivasan et al. (2015) discussed the renewable substitutability index or RSI [17], to identify and improve renewable resource usage in building based on solar emergy and the renewable emergy balance or REB [8]. A thorough comparison of LCA tools and emergy analysis was conducted by Srinivasan et al. (2014) [11] which was concluded with a detailed discussion of the advantages and disadvantages of existing tools. By integrating the energy method and emergy approach, a comprehensive methodology was developed by Hwang et al. to study the optimal building form [18]. Hwang et al. (2017) [19] also utilized a series of indices to evaluate the sustainability of a net-zero energy building based on the global environmental perspective. To have the entire demonstration of building sustainability, Hwang et al. (2017) attempted to integrate the emergy method and information metrics and simulate the environment of the building model [20,21]. A thorough review of the existing literature by the authors showed that there is only one article that focused on the emergy analysis of building construction in China, Table 1. Similarly, there is only one emergy study related to cement pavement that was conducted in China [22].

**Table 1. Emergy analysis of building construction in China.**

| Author, Year | Building Type | Remarks |
|--------------|---------------|---------|
| Dezhi et al., 2011 [23] | Concrete building, 5 storeys, 3225 m² | Beijing city |
| 2 | Concrete building, 12 storeys, 9903.44 m² |
| 3 | Concrete building, 21 storeys, 0.59 m² |
| 4 | Concrete building, 4 storeys, 2017.21 m² |
| 5 | Concrete building, 11 storeys, 5011.95 m² |
| 6 | Concrete building, 15 storeys, 7435.88 m² | Shanghai city |

In China, the cement industry produced 2330 million metric tons of cement in 2019, accounting for more than 51.4% of the world’s total [24]. Needless to say, as a heavy industry with serious pollution, the cement industry has a hugely destructive effect on the environment.

For example, due to the huge nonrenewable resource consumption in the manufacturing of cement, there are 15.5 million tons of sulfur dioxide (SO₂), 11.8 million tons of nitrogen oxides (NOx), and 15.3 million tons of particulates [25]. In addition to exhaust gases, industrial wastewater and solid wastes are also the major pollutants, which are 22.23 million tons and 39.76 million tons, respectively [25].

In spite of the high resource input and the high pollution emission of the cement industry, there is only a handful of research work done to compute the UEVs of cement manufacturing in China; they are: Wei et al. (2016) [26], who studied the life cycle emergy assessment of China’s cement industry and Xiao et al. (2017) [27], who conducted a sustainable assessment of China’s cement industry in 2010 based on emergy, and the results show that the proportion of fossil fuels is enormous, and such consumption cannot be sustained.

1.2. A Need for an Updated UEV for Cement Manufacturing in China

As discussed previously, there are only a handful of studies that have focused on the UEVs of cement manufacturing in China [26,27]. Table 2 lists these three research works by source data, emergy baseline used, raw materials, and their respective UEVs. It is to be noted that while Wei et al. (2016) used the 2015 data of one cement plant in China [26], Xiao et al. (2017) used the 2010 data that relate to the entire cement manufacturing in China. It is to be noted that although Song and Chen’s (2016) work does not explicitly calculate the UEV of cement manufacturing [28], their work is added to Table 2.
Although these were the first ever UEVs calculated for cement manufacturing, they may not adequately reflect owing to the following, Table 2.

1.3. Primary vs. Secondary Raw Materials in Cement Manufacturing

At present, there are no UEV calculations by researchers using cement production based on primary raw material proportions, of raw materials such as SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, CaO, MgO, and SO$_3$. These primary raw materials are used in specific proportions to form secondary raw materials such as limestone, gypsum, slag, clay, and sulfuric acid residue, which are used in cement manufacturing. For example, limestone (secondary raw material) is a mix of SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, CaO, MgO, and SO$_3$ (primary raw materials). Cement manufacturing industries provide the quantities of primary raw materials; the quantities of secondary raw materials used in cement manufacturing are, in most cases, classified to maintain the secrecy of their product. That said, it is critical to calculate and validate the quantities of secondary raw materials, which will then be used in the calculation of the UEV of cement. Moreover, as shown in Table 2, some of the secondary raw materials used in cement manufacturing were left out; for example, while clay is not used in Wei et al. (2016), limestone, pyrite cinder, and fly ash were left out in Xiao et al. (2017). It is vital to include all the raw materials used in the calculation of UEV as each of these contribute to the overall emergy of the final product.

Dry vs. wet secondary raw materials: cement manufacturing may use either dry or wet raw materials based on the water content. This classification, i.e., dry or wet, affects the overall energy used in the manufacturing of cement. The UEVs listed in Table 2, unfortunately, do not provide the specifics related to water content, i.e., dry or wet.

1.4. Emergy Baseline

The most updated, current emergy baseline is $12.0 \times 10^{24}$ sej/yr per Brown et al. (2016) [29]. Among the three UEVs listed in Table 2, only Wei et al. (2016) used this current emergy baseline.

There is a strong need for a new, updated UEV for cement manufacturing in China, particularly reflecting both dry and wet raw materials in the manufacturing process. This paper develops a methodology to calculate the nonrenewable resources used in cement manufacturing. For the purposes of this study, the geo-biosphere emergy baseline uses the latest standards of $12.0 \times 10^{24}$ sej/yr [29]. This paper is organized as follows: Section 2 discusses the emergy analysis of dry and wet cement manufacturing in China; this section comprises two sub-sections, namely the emergy flow diagram (Section 2.1) and the data quantity calculation and sources (Section 2.2). Section 2.2 elaborates on the individual components of the emergy analysis table, i.e., renewable resources (Section 2.2.1), nonrenewable resources (Section 2.2.2), energy (Section 2.2.3), transport (Section 2.2.4), and labor and service (Section 2.2.5). As noted earlier, the crux of this paper is the development of a methodology to systematically calculate the secondary raw materials (dry and wet) used in cement manufacturing in China, given that only the primary raw material data are provided by a manufacturing facility. That said, the nonrenewable resources section is further divided into sub-sections to reflect Step 1: identify the composition of the primary raw materials used in the preparation of secondary raw materials (Figure 3 step 1), Step 2: calculate the proportion of secondary raw materials used in cement manufacturing (Figure 3 step 2), Step 3: validate the calculated proportion of secondary raw materials using theoretical target values for cement (Figure 3 step 3), Steps 4A and 4B: calculate the consumption quota of dry and wet raw materials (Figure 3 step 4A and 4B), and Step 5: calculate the consumption quota of water. The results and discussions (Section 3) are elaborated in two sub-sections, namely, Emergy Analysis Table (Section 3.1) and Emergy Indicators (Section 3.2), which are followed by conclusions (Section 4).
Table 2. Comparison of the unit emergy values (UEVs) of cement manufacturing in China.

| Author | Basic Data Source | Emergy Baseline (Sej/yr) | Raw materials | UEVs of Cement (Sej/kg) |
|--------|------------------|--------------------------|---------------|------------------------|
| Wei et al., 2016 [26] | One cement plant | $12.0 \times 10^{24}$ | ✓ ✓ ✓ × ✓ ✓ ✓ ✓ | $1.93 \times 10^{12}$ |
| Xiao et al., 2017 [27] | The entire data of 2010 | $15.83 \times 10^{24}$ | × ✓ ✓ ✓ × ✓ ✓ | $3.64 \times 10^{12}$ |
| Song and Chen, 2016 [28] | One cement plant | $15.83 \times 10^{24}$ | ✓ ✓ ✓ × ✓ ✓ × ✓ | $3.05 \times 10^{12}$ |
2. Emergy Analysis of Cement Manufacturing in China Using Dry and Wet Raw Materials

The cement manufacturing process is shown in Figure 1. The process includes the raw material system, the sintering process, grinding process, and finally, the packaging process. The main equipment are the cooling equipment, rotary kiln, preheater, and the decomposition furnace.

![Figure 1. Core steps of the cement manufacturing process.](image)

At present, there are several different cement production lines in China. However, for this paper, we obtained the data related to primary raw materials from one of the largest cement manufacturing industries. At this facility, on a typical day, 5000 tons of cement is manufactured.

2.1. Emergy Flow Diagram of Cement Manufacturing

Drawing emergy flow diagrams can help understand and analyze the emergy flow system of a specific object. Emergy is used in four main processes of cement manufacturing, namely the ingredient process, sintering process, grinding process, and packaging process. The relationship between the specific process of cement and emergy is shown in Figure 2.

![Figure 2. Cement product emergy diagram.](image)

2.2. Data Quantity Calculation and Sources

The emergy analysis shown below follows the sequence as discussed in the emergy theory, i.e., renewable resources (Section 2.2.1), nonrenewable resources (Section 2.2.2), energy (Section 2.2.3), and labor and service (Section 2.2.4). It is to be noted that truck transportation is not included in the emergy analysis owing to a lack of data.
2.2.1. Renewable Resources

All the UEVs were selected according to the latest baseline of $12.00 \times 10^{24} \text{ sej/yr}$ \[29\].

(1) Solar energy calculation:

Area of cement plant = 13,424 m$^2$ (collected data);
Insolation (jiangsu Province, China) = $5.00 \times 10^9$–$5.85 \times 10^9$ J/m$^2$/yr \[30\];
Albedo = 0.30 \[30\];
Energy = (insolation) $\times$ (1-albedo) $\times$ (area) = $(5.43 \times 10^9$ J/m$^2$/yr) $\times$ $(1 - 0.30) \times (13,424$ m$^2$) = $5.10 \times 10^{13}$ J/yr;
UEV = $1.00 \text{ sej}$/yr by definition \[14\];
Emery of one year = $5.10 \times 10^{13}$ J/yr $\times$ 1 yr $\times$ 1.00 sej/j = $5.10 \times 10^{13}$ sej;
Emery of one day = $5.10 \times 10^{13}$ sej/365 = 1.39 $\times 10^{11}$ sej.

(2) Rain (geopotential energy) calculation:

Area of cement plant = 13,424 m$^2$ (collected data);
Rainfall (annual average, $n = 5$) = 0.68 m/yr \[31\];
Average elevation = 316 m; water density = 1000 kg/m$^3$; runoff rate = 40.00% \[32,33\];
Energy = (area) $\times$ (rainfall) $\times$ (runoff rate) $\times$ (water density) $\times$ (average elevation) $\times$ (gravity) = $(13,424$ m$^2$) $\times$ $(0.68$ m/yr) $\times$ $(40\%) \times (1000$ kg/m$^3$) $\times$ $(316$ m) $\times$ $(9.8$ kg/m$^3$) = $1.13 \times 10^{10}$ J/yr;
UEV = $1.31 \times 10^4$ sej/j \[34\];
Emery of one year = $1.13 \times 10^{10}$ J/yr $\times$ 1 yr $\times$ $1.31 \times 10^4$ sej/j = $1.48 \times 10^{14}$ sej;
Emery of one day = $1.48 \times 10^{14}$ sej/365 = $4.09 \times 10^{11}$ sej.

(3) Rain (chemical potential energy) calculation:

Area of cement plant = 13,424 m$^2$ (collected data);
Rainfall (annual average, $n = 5$) = 0.68 m/yr;
Water density = 1000 kg/m$^3$;
Evapotranspiration rate = 60% \[32,33\];
Gibbs free energy of water = 4940 J/kg;
Energy = (area) $\times$ (rainfall) $\times$ (evapotranspiration rate) $\times$ (water density) $\times$ (Gibbs free energy of water) = $(13,424$ m$^2$) $\times$ $(0.68$ m/yr) $\times$ $(1000$ kg/m$^3$) $\times$ $(60\%) \times (4.40$ J/kg) = $2.71 \times 10^{10}$ J/yr;
UEV = $2.35 \times 10^4$ sej/j \[35\];
Emery of one year = $2.71 \times 10^{10}$ J/yr $\times$ 1 yr $\times$ $2.35 \times 10^4$ sej/j = $6.37 \times 10^{14}$ sej;
Emery of one day = $6.37 \times 10^{14}$ sej/365 = $1.75 \times 10^{11}$ sej.

(4) Wind energy calculation:

Area of cement plant = 13,424 m$^2$ (collected data);
Air density = 1.29 kg/m$^3$;
Wind velocity (annual average, $n = 2$) = 1.95 m/s \[35\];
Velocity of geostrophic wind = 3.25 m/s (surface winds are considered as 0.6 of geostrophic wind \[35\]);
Drag coefficient = 0.001 \[36,37\];
Energy = (area) $\times$ (air density) $\times$ (drag coefficient) $\times$ (velocity of geostrophic wind)$^3$ = $(13,424$ m$^2$) $\times$ (1.29 kg/m$^3$) $\times$ $0.001 \times (3.25$ m/s)$^3$ $\times (3.15 \times 10^7$ s/yr) = $1.77 \times 10^9$ J/yr;
UEV = $1.90 \times 10^3$ sej/j \[14\];
Emery of one year = $1.77 \times 10^9$ J/yr $\times$ 1 yr $\times$ $1.90 \times 10^3$ sej/j = $3.36 \times 10^{12}$ sej;
Emery of one day = $3.36 \times 10^{12}$ sej/365 = $9.21 \times 10^9$ sej.
(5) Geothermal heat calculation:

Area of cement plant = 13,424 m² (collected data);
Heat flow (average) = 0.035 J/m²/s. Energy = (area) × (heat flow) = (13,424 m²) × (0.035 J/m²/s) × (3.15 × 10⁷ s/yr) = 1.48 × 10¹⁰ J/yr;
UEV = 4.37 × 10⁴ sej/j [38];
Emergy of one year = 1.48 × 10¹⁰ J/yr × 1 yr × 4.37 × 10⁴ sej/j = 6.47 × 10¹⁴ sej;
Emergy of one day = 6.47 × 10¹⁴ sej/365 = 1.77 × 10¹¹ sej.

2.2.2. Nonrenewable Resources

A. Consumption Quota of Dry and Wet Secondary Raw Materials Used in Cement Manufacturing

Previous studies [26,27] used the data related to secondary raw materials directly to calculate UEVs. However, as previously stated, the manufacturing facilities maintain a log of primary raw materials (e.g., SiO₂, Al₂O₃, Fe₂O₃, CaO, MgO, SO₃) rather than the secondary raw materials (e.g., limestone) used in cement manufacturing. Besides, these facilities may use dry or wet raw materials for cement production. Hence, it is essential to calculate the consumption quota of dry and wet secondary raw materials to calculate UEVs. For this purpose, a systematic step-by-step approach was developed, see Figure 3. Using these six steps (1–3, 4A, 4B, and 5), the consumption quota of dry and wet secondary raw materials was calculated.

![Figure 3](image_url)

**Figure 3.** The consumption quota calculated steps of the dry and wet secondary raw materials.

Step 1. Identify the composition of primary raw materials used in the preparation of secondary raw materials.

Step 2. Calculate proportion of secondary raw materials used in cement manufacturing.

Step 3. Validate calculated proportion of secondary raw materials using theoretical target values for cement.

Step 4A. Calculate consumption quota of dry raw materials (limestone, clay, sandstone, sulfuric acid residue), gypsum, and slag.

Step 4B. Calculate consumption quota of wet raw materials (limestone, clay, sandstone, sulfuric acid residue), gypsum, and slag.

Step 5. Calculate consumption quota of water.

Step 1. Identify the composition of primary raw materials used in the preparation of secondary raw materials.

The production of standard cement [39] requires calcareous raw materials, clay raw materials, calibration raw materials, and auxiliary raw materials. China’s cement energy consumption mainly uses coal and electricity. The details of the raw materials are shown in Tables 3–5.
Table 3. Chemical composition of the secondary raw materials: limestone, clay, sandstone, sulfuric acid residue, and coal (%).

| Secondary Raw Materials Used in Cement | Primary Raw Materials (Chemical Composition) |
|--------------------------------------|---------------------------------------------|
|                                      | Loss | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | Σ    |
| Limestone                            | 41.98 | 3.20 | 0.52  | 0.11  | 53.10 | 0.53 | 0.05 | 99.62 |
| Clay                                 | 13.37 | 31.42 | 33.21 | 15.16 | 0.48 | 1.13 | -   | 94.95 |
| Sandstone                            | 3.53  | 83.83 | 8.66  | 1.65  | 0.15 | 0.16 | 0.02 | 99.60 |
| Sulfuric acid residue                | 0.58  | 5.00  | 5.29  | 68.21 | 5.96 | 3.12 | 8.59 | 97.03 |

Note: basic data (of limestone clay, sandstone, and sulfuric acid residue) came from Ref. [40–44].

Table 4. Chemical analysis of the secondary raw material gypsum (%).

| Secondary Raw Materials Used in Cement | Loss | SiO₂ | Fe₂O₃ | Al₂O₃ | CaO | MgO | K₂O | Na₂O | SO₃ | Σ    |
|--------------------------------------|------|------|------|------|-----|-----|-----|------|------|------|
| Gypsum                               | 9.12 | 16.75| 0.97 | 4.85 | 25.12| 1.02| 0.88| 0.50 | 39.64| 99.80|

Note: basic data of gypsum came from Ref. [45].

Table 5. The natural moisture of raw materials (%).

| Limestone  | Clay  | Sandstone | Sulfuric Acid Residue | Coal | Gypsum | Slag |
|------------|-------|-----------|-----------------------|------|--------|------|
| 1.50       | 1.00  | 15.00     | 17.60                 | 8.00 | 4.00   | 8.00 |

Note: basic data (of limestone clay, sandstone, sulfuric acid residue, coal, gypsum and slag) came from Ref. [40–46].

Step 2. Calculate the proportion of secondary raw materials used in cement manufacturing.

The lime saturation coefficient, silicon rate, and aluminum rate are calculated and compared with theoretical values. For this purpose, according to the assumed raw material mix ratio [47], the clinker composition is calculated. If the calculation result does not meet the requirement, it is required to adjust the raw material ratio and calculate again until it fulfills the requirements. The raw material calculation results are shown in Tables 6 and 7.

Table 6. Raw material ratio calculation (unit: 100 kg).

| Raw Material       | Proportion | Loss | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | Σ    |
|--------------------|------------|------|------|------|------|-----|-----|-----|------|
| Limestone          | 0.82       | 35.12| 2.75 | 0.47 | 0.09 | 44.23| 0.51| 0.07| 83.24|
| Clay               | 0.05       | 0.56 | 1.31 | 1.33 | 0.62 | 0.02 | 0.06| 0.98| 3.90 |
| Sandstone          | 0.12       | 0.42 | 9.63 | 0.98 | 0.19 | 0.03 | 0.03| 0.00| 11.28|
| Sulfuric acid residue | 0.02       | 0.01 | 0.07 | 0.09 | 1.05 | 0.11| 0.05| 0.14| 1.52 |
| Dry raw material   | 1.00       | 36.11| 13.76| 2.87 | 1.95 | 44.39| 0.65| 0.21| 99.94|
| Raw material after burning | -         | -    | 21.53| 4.49 | 3.05 | 69.47| 1.02| 0.33| 99.89|

Table 7. The calculated value of the clinker composition.

| Program                      | Proportion | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | Σ    |
|------------------------------|------------|------|------|------|-----|-----|-----|------|
| Burning base material        | 96.54%     | 20.79| 4.33 | 2.94 | 67.07| 0.98| 0.32| 96.43|
| Coal ash composition        | 3.46%      | 1.94 | 0.91 | 0.35 | 0.04| 0.04| 0.10| 3.38 |
| Clinker composition         | 100%       | 22.64| 5.24 | 3.29 | 67.11| 1.02| 0.42| 99.81|
Incorporation of coal ash [48]:

$$G_A = \frac{qA_y s Q_y \times 100}{Qy \times 100} = 3.46\%$$  \hspace{1cm} (4)

where $G_A$—goal ash of clinker, %;
$q$—heat consumption of clinker, KJ/Kg-cl;
unit heat consumption of clinker $= 0.12 \times 20,900 = 2508$ KJ/Kg-cl;
$A_y$—ash of fuel air, %;
s—coal ash sinking rate, 100%;
$Q_y$—low calorific value of coal, 20,900 KJ/Kg.

Step 3. Validate the calculated proportion of secondary raw materials using theoretical target values for cement.

In this calculation, three theoretical standards can be used to verify the calculated proportion of secondary raw materials, which are lime saturation coefficient ($KH = 0.92 \pm 0.1$), silicon rate ($SM = 2.6 \pm 0.1$) and aluminum rate ($IM = 1.6 \pm 0.1$), respectively [47].

Calculated values:

$$KH = \frac{CaO - 1.65 \times Al_2O_3 - 0.35 \times Fe_2O_3}{2.8 sio2} = \frac{65.15 - 1.65 \times 5.85 - 0.35 \times 3.48}{2.8 \times 23.68} = 0.82$$  \hspace{1cm} (5)

$$SM = \frac{SiO_2}{Fe_2O_3 + Al_2O_3} = \frac{23.68}{3.48 + 5.85} = 2.54$$  \hspace{1cm} (6)

$$IM = \frac{Al_2O_3}{Fe_2O_3} = \frac{5.85}{3.48} = 1.68$$  \hspace{1cm} (7)

The calculated ratio is close to the target value, so that the final ratio of raw materials is determined as Table 8:

| Limestone | Clay | Sandstone | Sulfuric Acid Residue |
|-----------|------|-----------|----------------------|
| 82%       | 5.0% | 12%       | 2.0%                 |

Step 4. A. Calculate the consumption quota of dry raw materials.

Taking 1 g cement clinker as an example, the total dry material can be calculated to obtain the calculated values, including limestone, clay, sandstone, and sulfuric acid slag. If 1 g cement needs to be calculated, other auxiliary materials such as standard coal, gypsum, and slag should be included.

Consumption quota of secondary raw materials (limestone, clay, sandstone, sulfuric acid residue)
Considering the amount of coal ash incorporation, the dry raw materials’ theoretical consumption of 1 g cement clinker [47]:

$$K_1 = \frac{100 - S}{100 - I} = \frac{100 - 6.22}{100 - 36.11} = 1.468 \text{ g/g-cl}$$  \hspace{1cm} (8)

where $K_1$—theoretical consumption of the dry raw material (g/g-cl);
$I$—Loss of dry raw material (%);
$s$—coal ash amount (%).
Considering the amount of coal ash incorporation, the dry raw materials consumption quota of 1 g clinker:

\[
K_2 = \frac{100K_1}{100 - P} = \frac{100 \times 1.468}{100 - 3} = 1.513 \text{ g/g-cl}
\]

(9)

where \(K_2\)—dry raw materials consumption quota (g/g-cl);

\(P\)—loss of the dry raw materials (%), Reasonable value is 3%;

\[
K_{\text{quota}} = K_2 \times A
\]

(10)

where \(K_{\text{quota}}\)—consumption quota of the dry raw materials (g/g-cl);

\(A\)—proportion of dry raw materials (%).

Four dry raw material consumption quotas:

\(K_{\text{limestone}} = 1.513 \times 0.82 = 1.241 \text{ g/g-cl}\);

\(K_{\text{clay}} = 1.513 \times 0.05 = 0.076 \text{ g/g-cl}\);

\(K_{\text{sandstone}} = 1.513 \times 0.12 = 0.182 \text{ g/g-cl}\);

\(K_{\text{sulfuric acid residue}} = 1.513 \times 0.02 = 0.030 \text{ g/g-cl}\).

The consumption quota of the wet material is displayed in Table 9.

| Consumption Quota g/g-cl | Limestone | Clay | Sandstone | Sulfuric Acid Residue | ∑      |
|-------------------------|-----------|------|-----------|----------------------|--------|
|                         | 1.260     | 0.077| 0.214     | 0.033                | 1.584  |

Gypsum consumption quota [49]:

\[
K_{\text{dry gypsum}} = \frac{100d}{(100 - d - e) \times (100 - p)} = \frac{100 \times 5}{(100 - 5 - 4) \times (100 - 3)} = 0.057 \text{ g/g-cl}
\]

(11)

where \(K_{\text{dry gypsum}}\)—gypsum consumption quota (g/g-cl);

\(d, e\)—gypsum amount and mixed materials in cement (%);

\(p\)—cement production loss (%), value = 3%.

Slag consumption quota (Chen, 2004):

\[
K_{\text{slag}} = \frac{100e}{(100 - d - e) \times (100 - p)} = \frac{100 \times 4}{(100 - 5 - 4) \times (100 - 3)} = 0.045 \text{ g/g-cl}
\]

(12)

where \(K_{\text{slag}}\)—slag consumption quota (g/g-cl);

\(d, e\)—slag amount and mixed materials in cement (%);

\(p\)—Cement production loss (%), value = 3% [46].

B. Calculate Consumption Quota of Wet Raw Materials

The consumption quota of secondary raw materials (limestone, clay, sandstone, and sulfuric acid residue).

In addition to the quota calculation of the dry materials, the quota of the wet materials can also be calculated based on the ratio of water content, Table 10. Through Equations (13)–(15) [50], the consumption quota of slag has been calculated, and the specific results are shown in Table 11.

\[
\text{Wet raw material} = \text{dry raw material} \times \frac{100}{100 - \text{Moisture ratio}}
\]

(13)
Table 10. Wet raw material ratio.

| Wet Raw Material | Limestone | Clay | Sandstone | Sulfuric Acid Residue | ∑   |
|------------------|-----------|------|-----------|----------------------|-----|
| Proportion       | 0.832     | 0.051| 0.141     | 0.024                | 1.048|
| Percentage       | 79.4%     | 4.9% | 13.5%     | 2.2%                 | 100%|

Table 11. Consumption quota of slag.

| Cement         | e % | d % | P % | K Dry Slag (g/g-cl) | Kwet Slag (g/g-cl) |
|----------------|-----|-----|-----|--------------------|-------------------|
| Standard cement| 4   | 5   | 3   | 0.0453             | 0.0492            |

Gypsum consumption quota:

\[
K_{\text{wet gypsum}} = K_{\text{dry gypsum}} \times \frac{100}{100-M} = 0.059 \frac{g}{g-cl}
\]  

where \( M \) is the water ratio of gypsum (4%).

Slag consumption quota:

\[
K_{\text{wet slag}} = K_{\text{slag}} \times \frac{100}{100-M} = 0.12 \times \frac{100}{100-8} = 0.049 \frac{g}{g-cl}
\]

where \( M \) is the water ratio of slag (8%).

Step 5. Calculate consumption quota of water.

The natural moisture of the raw materials is revealed in Table 12.

Table 12. The natural moisture of the raw materials (%).

| Limestone | Clay | Sandstone | Sulfuric Acid Residue | Coal | Gypsum | Slag |
|-----------|------|-----------|----------------------|------|--------|------|
| 1.50      | 1.00 | 15.00     | 17.60                | 8.00 | 4.00   | 8.00 |

Note: basic data of (limestone clay, sandstone, sulfuric acid residue, coal, gypsum and slag) came from Ref. [40–46].

2.2.3. Energy

In this subsection, we calculate the energy used in the manufacture of cement. The calorific value of cement is 20,900 kJ/kg based on the Chinese national standard. Table 13 illustrates the chemical composition of secondary raw materials, and Table 14 is the raw coal industry analysis.

Table 13. Chemical composition of the secondary raw materials: limestone, clay, sandstone, sulfuric acid residue, coal (%).

| Secondary Raw Material Used in Cement | Loss | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | Sum |
|--------------------------------------|------|------|-------|-------|-----|-----|-----|-----|
| Coal                                 | -    | 56.12| 26.40 | 10.00 | 1.12| 1.19| 3.02| 98.25|

Note: basic data of coal came from Ref. [44].

Table 14. Raw coal industry analysis (%).

| Name | Moisture | Ash | Volatile Ratio | Calorific Value |
|------|----------|-----|---------------|-----------------|
| coal | 1.10     | 25.30 | 8.80       | 20,900 kJ/kg    |

Note: basic data of coal came from Ref. [44]. The basic data of the calorific value came from Ref. [51].
This paper utilizes the raw coal industry analysis as follows:

Standard coal used in the dry materials-based cement manufacturing:

\[ K_{\text{coal}} = 0.12 \text{ g/g-cl} \] [52].

Standard coal used in the wet materials-based cement manufacturing [50]:

\[
K_{\text{wet coal}} = K_{\text{coal}} \times \frac{100}{100 - M} = 0.12 \times \frac{100}{100 - 8} = 0.131 \text{ g/g-cl}
\] (16)

where \( M \) is the water ratio of coal (8%).

### 2.2.4. Electricity Used in Both Dry and Wet Materials-Based Cement Manufacturing

Quota calculation of the 5000 t/d product line and the standard cement chemical composition has been shown in Appendix A.

This part is the actual scale calculation of the 5000 t/d production line, embracing the annual output of the cement clinker, the number of cement kiln calculation, and the production capacity of cement products. Following the 5000 t/d cement production line, the energy consumption standards were selected to compute the emergy of the whole cement production line.

The annual output of the cement Clinker

The production data are assumed to be as follows: production loss = 3%; gypsum amount = 5%; mixed material amount = 4%. The design clinker production is 5000 t/day, and the hourly output is 208.3 t/h. The factual output of the clinker is 5500 t/day, and the hourly output is 230 t/h.

The daily production of clinker can be calculated as follows [49]:

\[
Q_d = \frac{100 - d - e}{100 - p} \times G_y = \frac{100 - 5 - 4}{100 - 5} \times 5500 = 5286 \text{ t/day}
\] (17)

where \( Q_d \)—required annual output of clinker (t/a);

\( G_y \)—cement factory-scale (t/a);

\( d \)—slag amount in cement (%);

\( e \)—mixed materials in cement (%);

\( p \)—cement production loss (%), value = 5%.

The number of cement kiln can be calculated as follows [49]:

\[
n = \frac{Q_y}{8760 \times \beta \times Q_h} = \frac{5286 \times 360}{8760 \times 0.85 \times 230} = 0.988 \approx 1
\] (18)

where \( n \)—number of the pre-calciner kilns;

\( Q_y \)—required annual output of clinker (t/a);

\( Q_h \)—production of selected kiln (t/(n-h));

\( \beta \)—annual utilization rate of the kiln (0.85);

8760—the number of hours throughout the year.

The production capacity of the 5000 t/d cement line can be calculated as follows [49]:

\[
Q_h = n \times Q_h = 1 \times 230 = 230 \text{ (t/h)}
\] (19)

\[
Q_d = 24 \times Q_h = 230 \times 24 = 5500 \text{ (t/d)}
\] (20)

where \( Q_h \)—hourly output of clinker (t/h);

\( Q_d \)—daily output of clinker (t/d).

Manual quota and machine quota
The main facilities of the entire cement production line comprise the limestone crusher, raw mill, rotary kiln, coal mill, dryer, cement mill, and the cement packaging machine. Based on the consumed electric power of all devices, the emergy of the machine quota can be computed. All the device types are shown in Table 15.

Table 15. Main equipment for the cement production process.

| Name                      | Type                  | Production (t/h) | Number (n) | Running Time per Week (h/w) |
|---------------------------|-----------------------|------------------|------------|-----------------------------|
| Limestone crusher         | TKLPC2022.F           | 700              | 1          | 72                          |
| Raw mill                  | TRM53.4               | 430              | 1          | 157                         |
| Rotary kiln              | Φ4.8 × 72 m           | 229.2            | 1          | 168                         |
| Coal mill                 | HRM2200               | 45               | 1          | 168                         |
| Dryer                     | ϕ2.4 × 18 m           | 24.4             | 2          | 157                         |
| Cement mill               | ϕ4.2 × 13 m           | 155              | 2          | 157                         |
| Cement packaging machine | BX-8WY                | 100              | 4          | 84                          |

2.2.5. Labor and Service

As the largest cement company in China, Anhui Conch Cement Company Limited has a qualified cement production line of 5500 t/d. According to the annual report of the company, the manual quota is CNY 25.58/t.
Calculation standard = CNY 25.58/t [31].

3. Results and Discussions

Table 16 contains the raw materials and energy required for a 5500 t/d cement production line in China. The raw material ratio is divided into a wet material ratio and a dry material ratio.

Table 16. Consumption quota calculation table of the raw materials (5000 t/d).

| Name             | Moisture (%) | Loss (%) | Consumption Quota (g/g-cl) | Material Calculation Table (t) |
|------------------|--------------|----------|---------------------------|--------------------------------|
|                  |              |          | Dry Material | Wet Material | Dry Material | Wet Material |
|                  |              |          | Day | Day | Day | Day |
| Limestone        | 1.50         | -        | 1.241 | 1.26 | 3681.49 | 3583.25 |
| Clay             | 1.00         | -        | 0.076 | 0.077 | 225.46 | 218.98 |
| Sandstone        | 15.00        | -        | 0.182 | 0.214 | 539.91 | 608.58 |
| Sulfuric acid    | 17.60        | -        | 0.03  | 0.033 | 88.99  | 93.847 |
| Raw material     | -            | 3.00     | 1.529 | 1.584 | 4535.87 | 4504.65 |
| Gypsum           | 4.00         | 3.00     | 0.057 | 0.059 | 169.09 | 167.79 |
| Slag             | 8.00         | 3.00     | 0.045 | 0.049 | 133.49 | 139.35 |
| Coal             | 8.00         | 3.00     | 0.12  | 0.131 | 660    | 720.5 |
| Standard cement  | -            | -        | -     | -     | 5500   | 5500   |
| Electricity      | -            | -        | 88 kWh/t [32] | 4.84 × 10^5 kWh | 4.84 × 10^5 kWh |

3.1. UEVs’ Calculation of a Whole Cement Production Line of 5500 t/d

Through the above calculation of the raw material quota, energy quota, and the manual quota, and equipment quota, the emergy calculations of the 5500 t/d production line were completed. The specific calculation process is shown in Tables 17–19. The final calculated UEVs are 2.56 × 10^{12} sej/kg (wet material) and 2.46 × 10^{12} sej/kg (dry material).
Table 17. Emergy calculation of the cement products based on nonrenewable resources.

| Item                  | Wet Material Quantity | Dry Material Quantity | UEVs (sej/unit) | Ref. | Wet Material Emergy (sej) | Dry Material Emergy (sej) |
|-----------------------|-----------------------|-----------------------|-----------------|------|---------------------------|---------------------------|
| Limestone             | 1260 kg               | 1241 kg               | $1.27 \times 10^{12}$ | [12] | $1.60 \times 10^{15}$     | $1.58 \times 10^{15}$     |
| Clay                  | 77 kg                 | 76 kg                 | $1.27 \times 10^{12}$ | [12] | $9.78 \times 10^{13}$     | $9.65 \times 10^{13}$     |
| Sandstone             | 214 kg                | 182 kg                | $1.42 \times 10^{12}$ | [14] | $3.04 \times 10^{14}$     | $2.58 \times 10^{14}$     |
| Slag                  | 49 kg                 | 48 kg                 | $1.68 \times 10^{12}$ | [12] | $5.49 \times 10^{13}$     | $5.38 \times 10^{13}$     |
| Gypsum                | 59 kg                 | 57 kg                 | $1.27 \times 10^{12}$ | [12] | $7.49 \times 10^{13}$     | $7.24 \times 10^{13}$     |
| Sulfuric acid residue | 33 kg                 | 30 kg                 | $1.68 \times 10^{12}$ | [12] | $5.54 \times 10^{10}$     | $5.04 \times 10^{10}$     |
| Standard coal         | $2.74 \times 10^9$ J  | $2.51 \times 10^9$ J  | $8.77 \times 10^4$  | [53] | $2.41 \times 10^{14}$     | $2.21 \times 10^{14}$     |
| Labor and service     | ¥25.68                | ¥25.68                | $1.06 \times 10^{11}$ | [33] | $2.72 \times 10^{12}$     | $2.72 \times 10^{12}$     |
| Electricity           | $3.168 \times 10^8$ J | $3.168 \times 10^8$ J | $4.5 \times 10^5$   | [54] | $1.43 \times 10^{14}$     | $1.43 \times 10^{14}$     |

The energy calculations of standard coal: $20,900 \times 131 \times 1000 = 2.74 \times 10^9$ J (wet material); $20,900 \times 120 \times 1000 = 2.51 \times 10^9$ J (dry material).
Table 18. Emergy calculation of the cement products based on the total resources.

| Materials Name     | Wet Material Quantity | Dry Material Quantity | UEVs (sej/unit) | Ref. | Wet Material Emergy (sej) | Dry Material Emergy (sej) |
|--------------------|-----------------------|-----------------------|-----------------|------|---------------------------|---------------------------|
| **Renewable Resources** |                       |                       |                 |      |                           |                           |
| Sunlight           | 1.39 × 10^{11} J      |                       | 1               | [14] | 1.39 × 10^{11}             |                           |
| Geothermal heat    | 4.05 × 10^{6} J       | 4.37 × 10^4           | [38]            |      | 1.77 × 10^{11}             |                           |
| Rain, geopotential| 3.12 × 10^{7} J       | 1.31 × 10^4           | [34]            |      | 4.09 × 10^{11}             |                           |
| Rain, chemical    | 7.45 × 10^{6} J       | 2.35 × 10^4           | [35]            |      | 1.75 × 10^{11}             |                           |
| Wind energy       | 4.85 × 10^{6} J       | 1.90 × 10^3           | [38]            |      | 9.21 × 10^9               |                           |
| **Nonrenewable Resources** |                   |                       |                 |      |                           |                           |
| Limestone         | 1260 kg               | 1241 kg               | 1.27 × 10^{12}  | [12] | 1.60 × 10^{15}             | 1.58 × 10^{15}           |
| Clay              | 77 kg                 | 76 kg                 | 1.27 × 10^{12}  | [14] | 9.78 × 10^{13}             | 9.65 × 10^{13}           |
| Sandstone         | 214 kg                | 182 kg                | 1.42 × 10^{12}  | [12] | 3.04 × 10^{14}             | 2.58 × 10^{14}           |
| Slag              | 49 kg                 | 48 kg                 | 1.68 × 10^{12}  | [12] | 8.23 × 10^{13}             | 8.06 × 10^{13}           |
| Gypsum            | 59 kg                 | 57 kg                 | 1.27 × 10^{12}  | [12] | 7.49 × 10^{13}             | 7.24 × 10^{13}           |
| Sulfuric acid Residue | 33 kg               | 30 kg                 | 1.68 × 10^{12}  | [12] | 5.54 × 10^{13}             | 5.04 × 10^{13}           |
| Water             | 369 kg                |                       | 4.94 × 10^{10}  | [55] |                           | 1.82 × 10^{13}           |
| **Energy**        |                       |                       |                 |      |                           |                           |
| Standard coal     | 2.74 × 10^{9} J       | 2.51 × 10^9           | 8.77 × 10^4     | [53] | 2.41 × 10^{14}             | 2.21 × 10^{14}           |
| Electricity       | 3.168 × 10^{8} J      | 3.168 × 10^{8} J      | 4.5 × 10^5      | [54] | 1.43 × 10^{14}             | 1.43 × 10^{14}           |
| **Labor and Service** |                     |                       |                 |      |                           |                           |
| Labor and service | ¥25.68                | ¥25.68                | 1.06 × 10^{11}  | [33] | 2.72 × 10^{12}             | 2.72 × 10^{12}           |

Note: all these unit emergy values were adjusted to the latest emergy baseline 12.00 × 10^{24} sej/yr. The UEVs of clay, water, slag, and sulfuric acid residue refer to Xiao [27] 1.27 × 10^{12} sej/kg, 4.94 × 10^{10} sej/kg, 1.68 × 10^{10} sej/kg and 1.68 × 10^{12} sej/kg, respectively.
Table 19. Emergy analysis table of cement manufacturing in China.

| Item                      | Wet Material Emergy (sej) | Dry Material Emergy (sej) | Total Emergy of Wet Material | Total Emergy of Dry Material | Wet Material Proportion (%) | Dry Material Proportion (%) |
|---------------------------|---------------------------|---------------------------|-------------------------------|-------------------------------|----------------------------|----------------------------|
| **Renewable Resources**   |                           |                           |                               |                               | 0.04%                      | 0.04%                      |
| Sunlight                  | 1.39 \times 10^{11}       |                           |                               |                               |                            |                            |
| Geothermal heat           | 1.77 \times 10^{11}       |                           |                               |                               |                            |                            |
| Rain, geopotential       | 4.09 \times 10^{11}       |                           | 9.09 \times 10^{11} sej       |                               | 0.04%                      | 0.04%                      |
| Rain, chemical           | 1.75 \times 10^{11}       |                           |                               |                               |                            |                            |
| Wind energy               | 9.21 \times 10^{9}        |                           |                               |                               |                            |                            |
| **Nonrenewable Resources**|                           |                           |                               |                               | 84.84%                     | 85.04%                     |
| Limestone                 | 1.60 \times 10^{15}       | 1.58 \times 10^{15}      | 2.17 \times 10^{15} sej       | 2.09 \times 10^{15} sej       | 62.56%                     | 64.29%                     |
| Clay                      | 9.78 \times 10^{13}       | 9.65 \times 10^{13}      | 3.22%                         |                               | 3.82%                      | 3.93%                      |
| Sandstone                 | 3.04 \times 10^{14}       | 2.58 \times 10^{14}      |                               |                               | 11.89%                     | 10.5%                      |
| Slag                      | 8.23 \times 10^{13}       | 8.06 \times 10^{13}      |                               |                               | 3.22%                      | 3.28%                      |
| Gypsum                    | 7.49 \times 10^{13}       | 7.24 \times 10^{13}      |                               |                               | 2.93%                      | 2.95%                      |
| Sulfuric acid residue     | 5.54 \times 10^{13}       | 5.04 \times 10^{13}      |                               |                               | 2.17%                      | 2.05%                      |
| **Energy**                |                           |                           |                               |                               | 15.01%                     | 14.81%                     |
| Coal                      | 2.41 \times 10^{14}       | 2.21 \times 10^{14}      | 2.41 \times 10^{14} sej       | 2.21 \times 10^{14} sej       | 9.42%                      | 8.99%                      |
| Electricity               | 1.43 \times 10^{14}       | 1.43 \times 10^{14}      | 1.43 \times 10^{14} sej       | 1.43 \times 10^{14} sej       | 5.59%                      | 5.82%                      |
| **Labor**                 |                           |                           |                               |                               | 0.11%                      | 0.11%                      |
| Labor                     | 2.72 \times 10^{12}       | 2.72 \times 10^{12}      | 2.72 \times 10^{12} sej       | 2.46 \times 10^{15}           | 0.11%                      | 0.11%                      |
| Total                     | -                         | -                         | 2.56 \times 10^{15}           | 2.46 \times 10^{15}           | 100%                       | 100%                       |
| **UEV**                   |                           |                           |                               |                               | 2.56 \times 10^{12} sej/kg for wet material; 2.46 \times 10^{15} sej/kg for dry material |
3.2. Emergy Indicators

All specific indicators have been listed in Table 20. According to the Table 20, the detailed analysis is shown below.

**Table 20.** All the indicators of the emergy assessment for cement manufacturing.

| No. | Items                                | Indicators | Calculated Results |
|-----|--------------------------------------|------------|--------------------|
| 1   | Renewability rate                    | R%         | 0.03% 0.04%        |
| 2   | Non-renewability rate of local resource | N%         | 82.62% 82.76%      |
| 3   | Environmental loading ratio          | ELR        | 2390 2300          |
| 4   | Emergy yield rate                    | EYR        | 15.7 15.8          |
| 5   | Emergy sustainability index          | ESI        | 0.0066 0.0069      |

(1) Renewability rate (R%) is 0.03% of wet material and 0.04% of dry material, which demonstrates the poor renewable energy input for the evaluated system.

(2) Non-renewability rate of local resource (N%) reveals the ratio (0.8262 and 0.8276) of wet material and dry material, and the result illustrates the excessive local resource input and has caused huge pressure on the local environment.

(3) Environmental loading ratios (ELR) are 2390 (wet material) and 2300 (dry material), which show the excessive pressure on the system and some measures should carefully considered to decrease the ELR.

(4) Emergy yield ratios (EYR) are 15.7 and 15.8, representing the competitive ability of the evaluated system. It needs to balance the relationship between the total emergy section and the purchased emergy for the sustainability of the evaluated cement manufacturing.

(5) Emergy sustainability index (ESI) are 0.0066 and 0.0069. They express the poor comprehensive effect on the environment for the evaluated system, and the ESI of cement manufacturing has an unsustainable status in the long term.

4. Conclusions

This paper applies the quota method to calculate the UEV of a mainstream cement production line of 5000 t/d in China. Based on cement chemical composition, the ratio of each main component is calculated, including limestone, clay, sandstone, gypsum, sulfuric acid residue, coal, slag and water. Both wet and dry proportions are considered and calculated in this paper, which can be compared and analyzed to improve the accuracy of the cement manufacturing system. Taking a typical 5000 ton cement production line as an example, the cement manufacturing system was evaluated in order to obtain a sustainable degree and unit emergy value. Based on this study, the UEV of wet material cement is $2.56 \times 10^{12}$ sej/kg and dry material cement is $2.46 \times 10^{12}$ sej/kg. The UEVs of cement manufacturing in China from this study are a significant improvement from the previous study [26–28] in two ways—(1) the calculation of the ratio of raw materials, i.e., the inclusion of sandstone and clay in addition to limestone, coal, and electricity, and (2) the different water contents of the ingredients, the two types of calculation of cement UEV was carried out, involving wet material and dry material.

Emergy indicators show that the renewability rates (R%) are 0.03% and 0.04% for wet material and dry material; the non-renewability rates of local resources (N%) are 0.8262 and 0.8276 for the wet material and dry material. R% and N% show that there is less renewable energy and a lot more non-renewable energy inputs, resulting in the extremely high ELR (2390 of wet material, 2300 of dry material) and the very low ESI (0.0066 of wet material, 0.0069 of dry material).

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Appendix A

A1. Cement Composition

Chemical formula of standard Portland cement:

Taking the Portland cement clinker of PO42.5 as an example (GB175-2007), the fluctuation range of each major oxide content is: CaO (62–67%); SiO$_2$ (20–24%); Al$_2$O$_3$ (4–7%); Fe$_2$O$_3$ (2.5–6%).

Four main mineral types of Portland cement clinker:

Usually, calcium oxide and silicon oxide are first reacted to produce the dicalcium silicate at high temperatures. Then, calcium oxide and dicalcium silicate can generate tricalcium silicate.

The reaction formula is as follows (GB175-2007):

\[
2\text{CaO} + \text{SiO}_2 = 2\text{CaO}\cdot\text{SiO}_2 \quad (\text{C}_2\text{S})
\]

\[
2\text{CaO}\cdot\text{SiO}_2 + \text{CaO} = 3\text{CaO}\cdot\text{SiO}_2 \quad (\text{C}_3\text{S})
\]

Four main mineral types: 3CaO·SiO$_2$ (C$_3$S); 2CaO·SiO$_2$ (C$_2$S); 3CaO·Al$_2$O$_3$ (C3A); 4CaO·Al$_2$O$_3$·Fe$_2$O$_3$ (C$_4$AF).

Units Used as followed in Table A1:

| No. | Unit         | Meanings                                      |
|-----|--------------|-----------------------------------------------|
| 1   | Sej          | Solar emjoules                                |
| 2   | sej/yr       | Average annual emergy                         |
| 3   | m$^2$        | Cement plant area                             |
| 4   | J/m$^2$/yr   | Annual average energy per unit area           |
| 5   | J/yr         | Annual mean energy                            |
| 6   | m/yr         | Average annual rainfall                       |
| 7   | sej/j        | Unit emergy value                             |
| 8   | kg/m$^3$     | Density unit                                  |
| 9   | J/kg         | Water Gibbs free energy unit                  |
| 10  | m/s          | Wind velocity unit                            |
| 11  | Kj/Kg-cl     | Energy consumed per kilogram of clinker       |
| 12  | g/g-cl       | Energy consumed per gram of clinker           |
| 13  | Kj/Kg        | Energy of 1 kg substance                      |
| 14  | t/day        | Daily production of cement                    |
| 15  | t/a          | The cement produced every year                |
| 16  | t/h          | Hourly cement output                          |
| 17  | t/(t-h)      | Production of selected kiln                   |
| 18  | CNY/t        | RMB per ton of cement                         |
| 19  | kWh/t        | Electricity consumption per ton of cement     |
| 20  | sej/kg       | Emergy value per kilogram                     |

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