

## Article

# A Sustainability Analysis Based on the LCA–Emergy–Carbon Emission Approach in the Building System

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**Abstract:** Ecologically sustainable buildings and their carbon emissions are two popular ideas for building life cycle systems. It is a challenge to comprehensively assess the sustainability of building cases using two different methods. Based on over a decade of research, this paper attempts to explore the possibility of quantitatively integrating both approaches. In this study, we adopted the emergy method and carbon emission approach to assess and analyze a building system. In particular, similarities and differences have been identified through emergy and carbon emissions at each stage of the building's whole life cycle. The results demonstrate that the building operation phase is the critical contributor (Approximately 79.6% of the total emergy and 97.9% of the entire carbon emission), which occupies the most emergy and carbon emission amounts of the whole building system. In order to improve the ecological sustainability of the building system, renewable energy subsystems are considered and explored. While the overall sustainability of the building system is enhanced, the new systems will aggrandize the carbon emissions. Therefore, the ecological sustainability of building systems and carbon emissions should be considered comprehensively, and the relationship between the two views needs to be balanced.

**Keywords:** sustainability; LCA–Emergy; LCA–Carbon emission; update strategy; building system



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## 1. Introduction

Increasingly affected by environmental degradation, the building system's sustainability, as a gathering place for humans, is under scrutiny [1,2]. From the ecological field, ecological architecture is a professional term that defines that a building system is sustainable and can achieve long-term development, in a sustainable way [3,4]. However, in order to maintain the ecologically sustainable state of a building system, it needs the continuous support of continuous resources, energy and a service system, which objectively leads to the increase in carbon emissions. At the same time, global warming is caused by excess carbon emissions, and it is also a growing threat to the world's living environment [5,6]. One obvious fact reveals the level of carbon emissions in the building system, which accounts for more than a third of total carbon emissions [7,8]. Therefore, an ecological sustainability study and the carbon emissions of building systems should be focused on simultaneously by scholars.

From the field of ecological economics, the emergy concept is a new viewpoint for the sustainability evaluation of several systems, including agriculture [9,10], urban systems [11–14], water treatment processes [15,16], industrial products [17–19], material production systems [20,21], health systems [22], plant ecology [23], regional analysis [24,25], building systems analysis [26,27], economic subsystem [28], etc.

Therein, the building system is an important focus based on emergy analysis. Simultaneously, a series of scholars conducted emergy calculations and assessments to explore the sustainability of building systems. For instance, Suman et al. (2021) integrated the emergy

method and BIM to realize their union [29]. So as to confirm the environmental building design change, the emergy approach has been used to define a net zero energy building system [30]. By replacing disparate energy sources in green buildings, their sustainable evaluations have been revealed on the basis of an emergy view [31]. Taking the net-zero energy building system as an example, a sustainable assessment has been executed from the view of emergy considerations [32]. Because it involves a lot of data analysis, the sensitivity analysis of building systems has been investigated [33]. Through the integration of the emergy method and sensing system analysis, the effectiveness of smart building has been of concern [34]. Since a building system consists of multiple devices, to verify the utility, emergy analysis has been adopted to confirm the effect of the heating and cooling subsystem integrated with the air source heat pump subsystem [35]. At the same time, the evaluation and selection of construction equipment systems can also be confirmed using the emergy method [36]. Building material systems are also a key field of emergy analysis [37]. The emergy method can also be applied to the updating of the building system to guide the updating design [38].

In addition to the above studies, it is a very popular idea to study the whole life cycle of a building system. Many scholars have studied the building system by leveraging the LCA method [39–45]. However, there are few comprehensive studies integrating the LCA method and the emergy method. As an unusual combination, LCA–Emergy can conduct a sustainable exploration of building systems. After reviewing the literature in the last five years, several articles were discussed using the LCA–Emergy framework. For example, a residential building was selected for sustainability investigation in view of emergy analysis [46]. As a necessary part of the building system, the building cement material system was of concern and was analyzed using an emergy view [47]. As a special form of architecture, highway engineering has also been surveyed through emergy evaluation [48]. By relying on an LCA–Emergy approach, different renewal strategies for building systems are demonstrated, so as to select a better renewal strategy [49].

From the perspective of the carbon emission of building systems, a lot of investigations have been explored by scholars for reducing the carbon emission of building systems, so as to mitigate the impact of climate change. Several different ideas have been tried to analyze, such as carbon emissions from the building sector [50], a low-carbon cities view [51,52], public building type [53], system dynamics carbon emission analysis [54], building supply chain [55], architectural renewal perspective [56], green space [57], passive architectural design [58], building operations [59], carbon emission quotas [60], zero-carbon analysis [61], etc. The details are as follows: Through the carbon emission model and data analysis, the challenges and opportunities of the building sector have been surveyed [50]. Models of carbon emissions up to 2060 are designed to predict the overall trajectory of carbon emissions [51]. From the perspective of a low-carbon city, the carbon emission of the building system was calculated and designed [52]. Taking public buildings as an example, the unbalanced state of carbon emissions is studied [53]. As an effective model, the carbon emission of urban buildings is analyzed and predicted using system dynamics [54]. On account of building supply chain consideration, the carbon emission reduction effect was focused on [55]. In order to improve living conditions, the renovation design of the building is combined with carbon emissions [56]. By integrating natural landscapes and building carbon emissions, green space and water bodies have been proposed due to their carbon reduction effects [57]. By focusing on passive house-certified measures, their carbon emissions and applications are taken into account [58]. The building operation stage has always been the most important aspect of the carbon emissions of a building system, which needs continuous attention [59]. Carbon emission quotas acting as a starting point, their fairness and balance are analyzed and explored [60]. Zero-carbon buildings, as the ultimate goal of building carbon emissions, are currently the research hotspot of building systems [61].

Similarly, besides the above research on carbon emissions, the LCA–Carbon emission estimation of building systems is also a hot topic. Typical studies are as follows. Using

BIM and LCA methodologies, the carbon emission intensity and cost have been studied recently [62]. Based on the carbon emission and driving factor perspective, a specific building case was selected and evaluated [63]. In terms of energy conservation, the LCA–Carbon emissions and economic effects of building systems have been investigated [64]. A large-scale national carbon emission study was carried out on the basis of the LCA approach [65]. Through ecological climate mitigation challenge analysis, the greenhouse gas of a building system was evaluated and displayed [66]. The life-cycle carbon emissions of zero-carbon building renewal design were followed with interest by several researchers [67]. In Sweden, a typical family house was selected for a life cycle cost study [68]. The carbon emissions of prefabricated building systems have been the focus recently, especially based on the integration of BIM and LCA [69]. Four types of rural houses were chosen for carbon reduction exploration by utilizing the LCA method [70].

Up to now, the relationship between ecological sustainability and the carbon emissions of building systems has not been discussed in relation to each other under LCA assessments, which is limited by two completely different methodologies. In this study, it has been considered and preliminarily verified. The innovation of this article lies in the comprehensive evaluation of the sustainability of building systems using emergy methodology and carbon emissions calculation methods. The emergy methodology considers the relationship between building systems and the environment, while the carbon emissions methodology focuses on the carbon emissions of the entire building system, thereby assessing the impact of building systems on the environment. By focusing on the building systems, it compares the advantages and disadvantages of these two approaches, thereby providing valuable insights for sustainable architects and designers.

## 2. Material and Methods

### 2.1. Research Framework

In order to achieve the research objective, two methods have been considered and utilized in this paper. The specific implementation path is displayed in Figure 1. For a building system, to explore the sustainability status, LCA–Emergy and LCA–Carbon emissions have been conducted and compared to evaluate and analyze the sustainable state. From the view of ecology, based on an emergy approach, their emergy quantity calculated to support sustainability indicators for the building system; meanwhile, carbon emission was another breakthrough from the point of view of sustainability. To ensure the integrity of the study, five stages of the whole life cycle of the building were divided and designed, including the building material production stage, building transportation stage, building operation stage, building construction and renewal phase and building demolition stage.

### 2.2. LCA–Emergy Introduction

#### 2.2.1. Emergy Method

The core concept of Emergy (energy with an “m”) method, originated in the US by H.T. Odum [71], is based on the notion that it represents the total sum of energy and resources involved in a specific process within an ecosystem. This includes both direct and indirect energy usage, as well as the energy gained through material and energy transformations. By aggregating all emergy values, the Emergy method allows for comprehensive evaluation and comparison of building systems, revealing their reliance on the environment and assessing their sustainability.

As a systems assessment approach, the Emergy method is used to measure and compare the value and contribution of different resources and energy sources within a building system. It is based on the concept of energy and converts all inputs and outputs of resources and energy into a unified unit of measure called emergy. By considering different resource types, qualities and energy efficiencies, the Emergy method quantitatively evaluates the performance of building systems regarding resource use and energy efficiency.

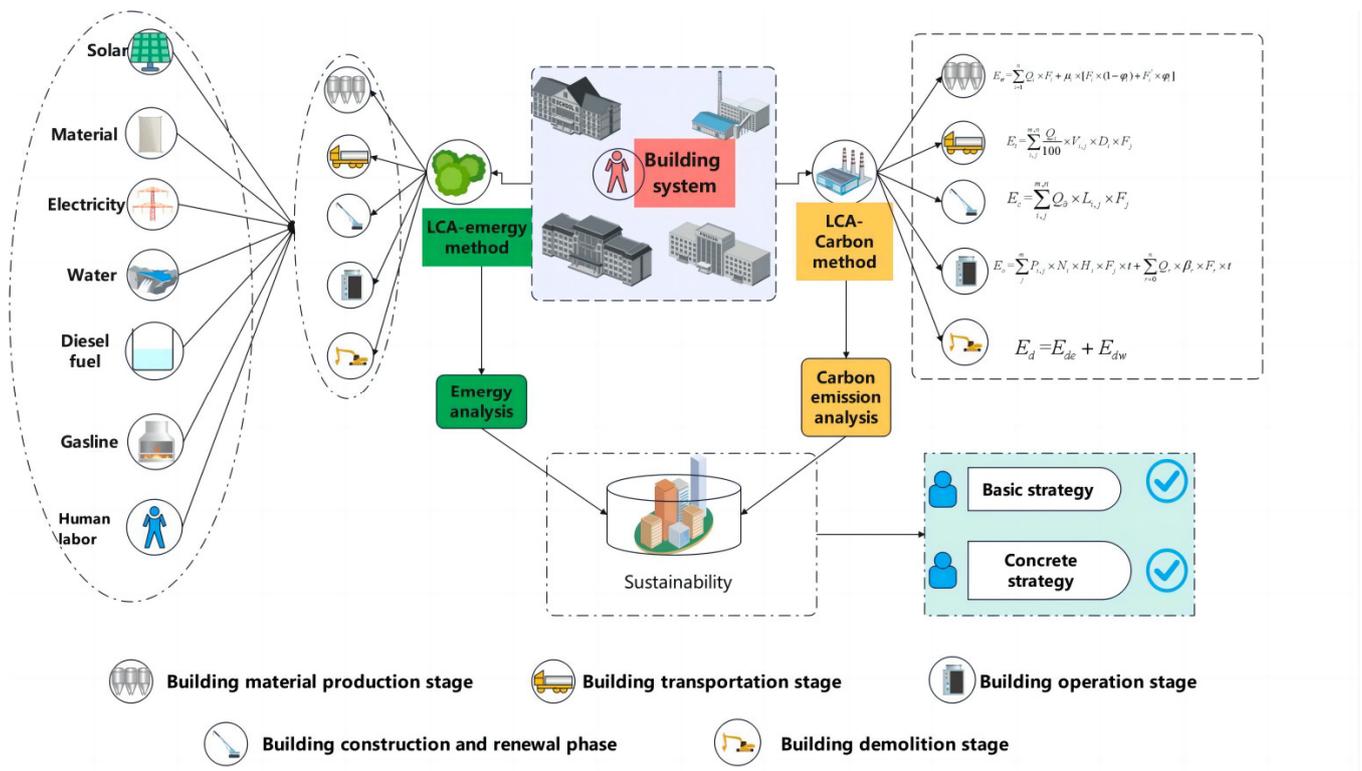


Figure 1. Basic study framework and implementation path.

Compared with other sustainability methods, the Energy method has several advantages. It comprehensively considers the quality and renewability of various resources and provides a unified metric to assess the contributions of diverse resources. Additionally, the Energy method unveils external costs and environmental impacts that are often overlooked in traditional economic analyses, resulting in a more holistic evaluation of the true value and sustainability of building systems.

The Transformity/UEV refers to the amount of energy required to produce a unit of specific output or service at a given scale. In this study, the benchmark for energy calculations is  $12 \times 10^{24}$  sej/year [71].

In Figure 2, the LCA–Energy diagram has been designed and is displayed. There are four main subsections, including renewable energy input (right side), resource and service inputs (upper side), major building system (intermediate position) and external output (left side). Taking renewable energy inputs as an example, this section has five components, which are sunlight, rain-chemical, rain-geopotential, wind and geothermal heat. As the five stages of the building’s life cycle, they have been presented; simultaneously, three renewal strategies have been identified in Figure 2 [71].

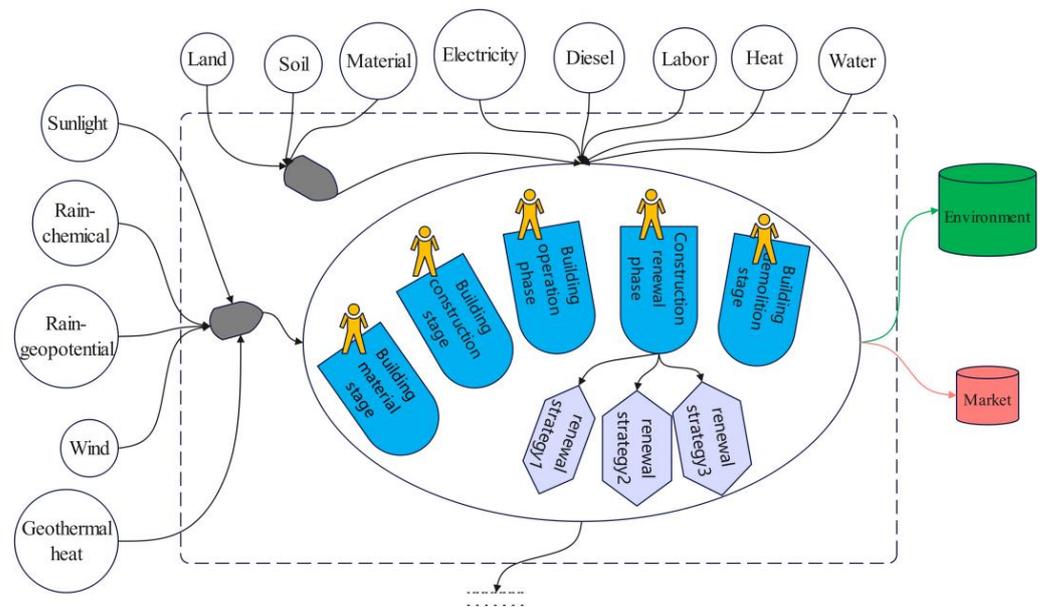
### 2.2.2. LCA–Energy Model

#### (1) Solar irradiation calculation model

The solar energy can be obtained from Equation (1), as follows:

$$E_S = A \times J \times (1 - \beta) \times T_C \times T_{UEVs} \quad (1)$$

where  $E_S$  represents the solar energy in the construction process;  $A$  is the site surface;  $J$  is the solar radiation amount ( $3.5 \times 10^9$  J/m<sup>2</sup>) [72];  $\beta$  is the surface albedo (0.7);  $T_C$  is the construction time;  $T_{UEVs}$  is the unit energy values.



**Figure 2.** LCA–Emergy diagram of the building system.

(2) Mass calculation model

The mass represents the materials in the construction system and the emergy calculation model equation is calculated as follows [34,64]:

$$E_{\text{mass}} = \sum_{i=1}^n Q_i \times T_{U1} \tag{2}$$

where  $E_{\text{mass}}$  is the emergy value of mass;  $Q_i$  is mass amount;  $T_{U1}$  represents the unit emergy value.

(3) Electricity calculation model

The electricity calculation equation can be obtained, as follows:

$$E_e = L \times T_{Ue} \tag{3}$$

where  $E_e$  is the emergy of electricity in the building system;  $L$  is the electricity quantity;  $T_{Ue}$  is the unit emergy value of electricity.

(4) Water

The water emergy has two aspects. On the one hand, the emergy should be calculated in the building demolition and construction stage. The specific Equation (4) can be used, as follows:

$$E_{\text{water}} = V \times \rho \times G \times UEV_w \tag{4}$$

where  $E_{\text{water}}$  is the water emergy;  $V$  is the water volume;  $\rho$  is the water density;  $G$  is the Gibbs energy of water (4.92 J/g);  $UEV_w$  is the water transformity.

On the other hand, the water emergy should also be considered in the operation phase and the equation can be utilized as (5).

$$F_{\text{water}} = V_o \times N_o \times T_o \times \rho \times G \times UEV_w \tag{5}$$

where  $F_{\text{water}}$  is the water emergy in the building operation stage;  $V_o$  is the water volume per day for one person (25 L/d/p);  $N_o$  is the employee number (the number is 200);  $T_o$  is the working time (280 days in this study).

(5) Diesel fuel emergy calculation model

Because of the machinery used, diesel fuel is necessary for the building system. The equation can be obtained as follows:

$$E_{\text{diesel}} = \mu \times \chi \times UEV_d \quad (6)$$

where  $E_{\text{diesel}}$  is the energy of the diesel fuel;  $\mu$  is the amount of diesel oil used in the buildings system;  $\chi$  is the calorific value of diesel fuel;  $UEV_d$  is the unit energy value of diesel fuel.

(6) Gasline energy calculation model

The energy value can be calculated as follows:

$$E_{\text{gasoline}} = \phi \times \varphi \times UEV_g \quad (7)$$

where  $E_{\text{gasoline}}$  is the gasoline energy;  $\phi$  is the gasoline quantity;  $\varphi$  is the calorific value of gasoline;  $UEV_g$  is the unit energy value of gasoline.

(7) Human labor energy calculation model

The energy of human labor can be obtained, as follows:

$$E_H = L_T \times N_p \times T_d \times UEV_H \quad (8)$$

where  $E_H$  is the energy of human labor;  $L_T$  is the working time (8 h);  $N_p$  is the number of employed workers;  $T_d$  is the working day;  $UEV_H$  is the unit energy value of human labor.

(8) Energy indexes

Several indicators have been adopted to evaluate the ecological status in this paper. For example:

- (1) Renewable input ( $R_i$ ) represents the energy input of renewable resources, which has a positive effect on the sustainability in the building system. The calculation formula is as follows: Renewable input ( $R_i$ ) = Renewable energy/Total energy.
- (2) Nonrenewable resource ( $N_s$ ) is energy input proportion of non-renewable resources. A higher proportion demonstrates a less sustainable role. The calculation formula is as follows: Nonrenewable resource ( $N_s$ ) = Non-renewable energy/Total energy.
- (3) Energy feedback input ( $E_f$ ) is the energy feedback based on the total energy output. The calculation formula is as follows: Energy feedback input ( $E_f$ ) = Feedback energy/Total energy
- (4) Energy yield ratio (EYR) can be obtained based on the total energy and energy feedback input, showing the ability to generate energy. It uncovers the system structure and energy distribution. The calculation formula is as follows: EYR = Comprehensive output energy/Comprehensive input energy.
- (5) The environmental loading ratio (ELR) reveals the ecological stress for the system. When the system has a higher number, it means that the system has a higher pressure. The calculation formula is as follows: ELR = Environmental resource consumption energy/Comprehensive output energy.
- (6) Energy sustainability indicator (ESI) states the final ecological situation for a system from an energy perspective. A value below 1 indicates that the entire system is unsustainable in the long run. The calculation formula is as follows: ESI = EYR/ELR.

### 2.3. LCA–Carbon Emission Calculation Model

The calculation formula of the carbon emission calculation model for the whole life cycle of buildings is as follows [73]:

$$E_W = E_\sigma + E_t + E_c + E_o + E_d \quad (9)$$

where  $E_W$  is the total carbon emission in the building system;  $E_\sigma$  is the carbon emission in the building material production stage;  $E_t$  is the carbon emission in the construction

material transport stage;  $E_c$  is the carbon emission in the construction phase;  $E_o$  is the carbon emission in the operational use and maintenance phase;  $E_d$  is the carbon emission in the abandoned and dismantled stage.

(1) Carbon emission calculation of building material production stage

The building materials production stage includes the carbon emissions generated by mining, production and processing. The calculation equation is as follows:

$$E_{\sigma} = \sum_{i=1}^n Q_i \times F_i + \mu_i \times [F_i \times (1 - \varphi_i) + F'_i \times \varphi_i] \tag{10}$$

where  $E_{\sigma}$  is the carbon emission calculation of the building material production stage;  $n$  is the quantity of building materials;  $Q_i$  is the consumption of building material  $i$ ;  $F_i$  is the carbon emission factor in the initial state;  $\varphi_i$  is the carbon emission factor in the recycling state;  $\mu_i$  is the rate of attrition;  $F'_i$  is the recovery utilization rate.

(2) Carbon emission calculation of construction transport stage

The construction process needs a large number of vehicles, resulting in a mass of carbon emissions, which need to be counted and calculated. The transportation process includes two parts, one is the carbon emission calculation of building materials and mechanical equipment transported to the construction site; the other is the carbon emissions from construction waste and earthmoving. The specific calculation formula is as follows:

$$E_t = \sum_{i,j}^{m,n} \frac{Q_i}{100} \times V_{i,j} \times D_i \times F_j \tag{11}$$

where  $E_t$  is the carbon emission calculation of the construction transport stage;  $n$  is the quantity of building materials;  $Q_i$  is the consumption of building material  $i$ ;  $V_{i,j}$  is the amount of energy used to transport materials ( $t/100$  t·km);  $D_i$  is the transportation distance of materials or equipment (km);  $F_j$  is the carbon emission factor.

(3) Carbon emission calculation of building construction and renewal stage

The carbon emissions of the construction phase is mainly the use of machinery and the electricity in the factory, which can be calculated by gasoline, diesel and electricity usage. The specific calculation equation is as follows:

$$E_c = \sum_{i,j}^{m,n} Q_{\partial} \times L_{i,j} \times F_j \tag{12}$$

where  $E_c$  is the carbon emission calculation of the building construction stage;  $n$  is the quantity of equipment;  $m$  is the number of energy types;  $Q_{\partial}$  is the total number of machines;  $L_{i,j}$  is the energy consumed by machinery;  $F_j$  is the carbon emission factor.

(4) Carbon emission calculation of operational use stage

There are two aspects of carbon emissions in this stage. On the one hand, it is the carbon emissions generated by the lighting load, air conditioning system load, refrigeration equipment, water supply and drainage load in the operation stage. On the other hand, the carbon emissions are generated by the upgrading and maintenance of building materials and facilities.

The specific calculation equation is as follows:

$$E_o = \sum_j^m P_{i,j} \times N_i \times H_i \times F_j \times t + \sum_{r=0}^n Q_r \times \beta_r \times F_r \times t \tag{13}$$

where  $E_o$  is the carbon emission calculation of operational use stage;  $m$  is the total types of energy;  $n$  is the material renewal quantity;  $t$  is the life of the building (year);  $P_{i,j}$  is the

energy expended per hour;  $N_i$  is the total number of equipment;  $H_i$  is the average operating hours of the device;  $F_j$  is the carbon emission factor of equipment;  $Q_r$  is the maintenance update consumption;  $\beta_r$  is the annual renewal rate;  $F_r$  is the carbon emission factor of alternate material.

#### (5) Carbon emission calculation of building demolition stage

The carbon emission at the stage of building demolition consists of two parts: the carbon emission of mechanical equipment and the carbon emission of waste transportation. The specific equation is shown in (14).

$$E_d = E_{de} + E_{dw} \quad (14)$$

where  $E_d$  is the carbon emission at the stage of building demolition;  $E_{de}$  is the carbon emission of mechanical equipment;  $E_{dw}$  is the carbon emission of waste transportation.

#### (6) Carbon dioxide emissions

In the whole life cycle of the building, the most carbon dioxide is emitted in the building material production stage, at approximately 85%. In this paper, the carbon dioxide can be computed by Equation (15).

$$A_{CO_2} = \sum_{j=1}^n S_{CO_2} \times L_{CO_2} \quad (15)$$

where  $A_{CO_2}$  is the amount of carbon dioxide emissions;  $S_{CO_2}$  is the mass amount;  $L_{CO_2}$  is the emission factors of different building materials.

### 3. Case Study

#### 3.1. Update Policy

Because the building needs to be updated, the basic renewal strategy should take functional and aesthetic aspects into consideration. There are two aspects of the renovation design. On the one hand, the interior decoration design of the building is carried out. On the other hand, the facade of the building also needs to be updated. The list of required architectural design details and materials can be obtained from the architect.

#### 3.2. Case Introduction

A type of commercial complex was selected for the updated design, which is located in Nanjing, China. The buildings are more than 20 years old, and the poor indoor and outdoor conditions need to be improved, such as being renovated internally and updated externally.

A commercial complex is revealed in Figure 3. A five-story commercial center and a twelve-story hotel make up the commercial complex, covering an area of over 51,000 square meters. The whole building complex adopts the classical design strategy and the facade is decorated with a roof component form. In addition to the commonly used building materials, the whole building materials are made of white mortar walls, decorative wood and black metal.

The renovation design strategy for this building is based on low-energy building standards, with the following specific parameters:

- (1) The annual heating demand per unit area of the building,  $Q_h$ , is  $\leq 15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ .
- (2) The heating load per unit area of the building,  $q_h$ , is  $\leq 10 \text{ W}/\text{m}^2$ .
- (3) The annual cooling demand per unit area of the building,  $Q_c$ , is  $\leq 15 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ .
- (4) The maximum cooling load per unit area of the building,  $q_c$ , max, is  $\leq 20 \text{ W}/\text{m}^2$ .
- (5) The total primary energy demand per unit area of the building,  $E_{PT}$ , is  $\leq 120 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ .

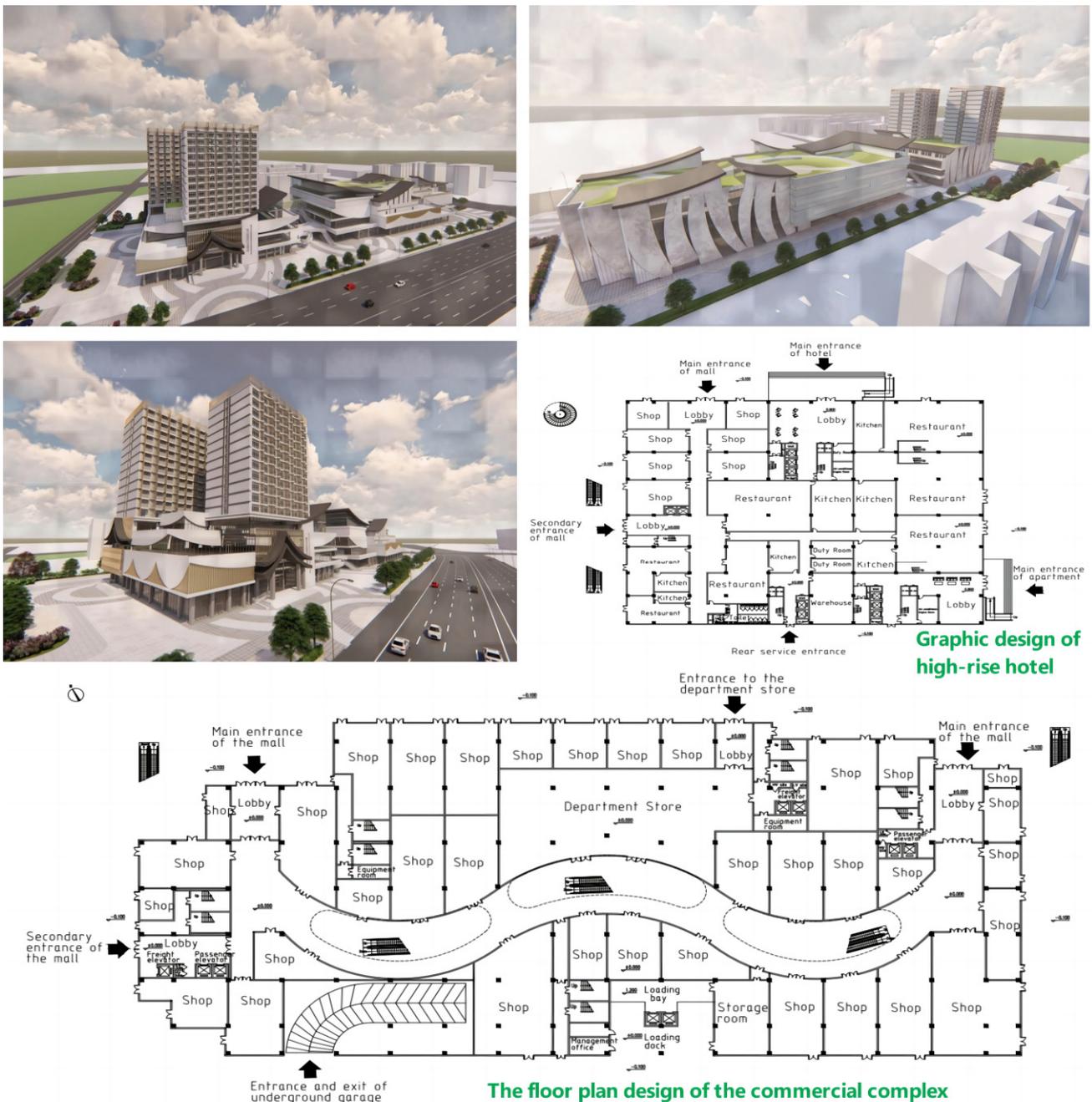


Figure 3. A commercial complex building case.

### 3.3. Data Collection

The basic building data can be obtained from the design and construction documents. Updated design data can be obtained from design and construction units. The specific data include a building material data list, a building energy use data list and a labor data list. In addition, carbon emission factor data and energy conversion rates need to be collected.

The carbon emission factor is derived from the emission coefficient method, which is one of the most widely used carbon emission accounting methods. The carbon emission factor is defined as the production of greenhouse gases associated with the consumption per unit of substance. For the construction field, the most commonly used carbon emission factors include three types: the fossil energy carbon emission factor, the electric power carbon emission factor and the building material carbon emission factor.

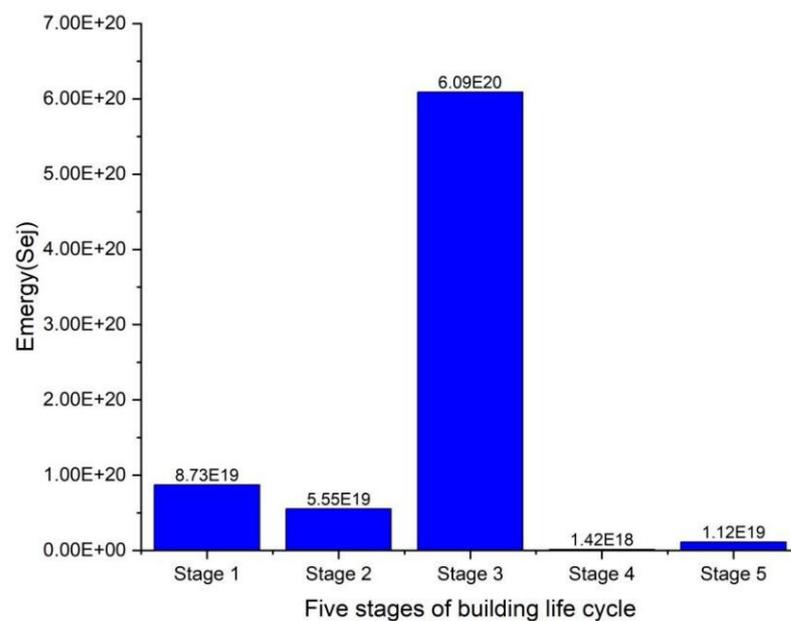
IPCC (Intergovernmental Panel on Climate Change), as an authoritative international institution, has conducted sufficient research on the carbon emission factors of fossil energy. In this paper, energy carbon emission factors are selected based on the IPCC Guidelines for the Preparation of National Greenhouse Gas Inventories. There are various types of building materials in this study, and carbon emission measurement data from authoritative institutions are adopted. The details are shown in Appendix A.

## 4. Results and Discussion

### 4.1. LCA–Emergy Analysis

#### 4.1.1. Dominated Contributor

The five stages of the whole life cycle of the building are studied and discussed. Firstly, the largest emergy contribution is the building run phase because the running emergy of 20 years is calculated in this paper ( $6.09 \times 10^{20}$  sej). The secondary contributor is the emergy in the stage of building materials ( $8.73 \times 10^{19}$  sej), followed by the building construction stage ( $5.55 \times 10^{19}$  sej), building demolition stage ( $1.12 \times 10^{19}$  sej) and building renewal stage ( $1.42 \times 10^{18}$  sej) in Figure 4.



**Figure 4.** Comparative analysis of each stage. (stage 1—building material production stage; stage 2—building construction stage; stage 3—building operation stage; stage 4—building renewal stage; stage 5—building demolition stage).

As the primary impact element, the building operation stage contains four types of inputs, which are Solar, Electricity, Heat and Water. Therein, electricity plays a major role from an emergy point of view to analyze (98.3% of the entire operation’s emergy in the building).

There are 19 categories of materials for the building materials stage (in Figure 3). Among them, steel, cement and brick are the key inputs, which account for 60.14%, 15.83% and 12.14% of the total building material emergy.

During the building construction phase, there are six subsystems that need to be designed and analyzed, involving environmental inputs, water supply and sewage system treatment facilities, heating and cooling systems, electricity installations, telecommunications systems, the elevator system, etc. Their emergy ratio is shown in Figure 5.

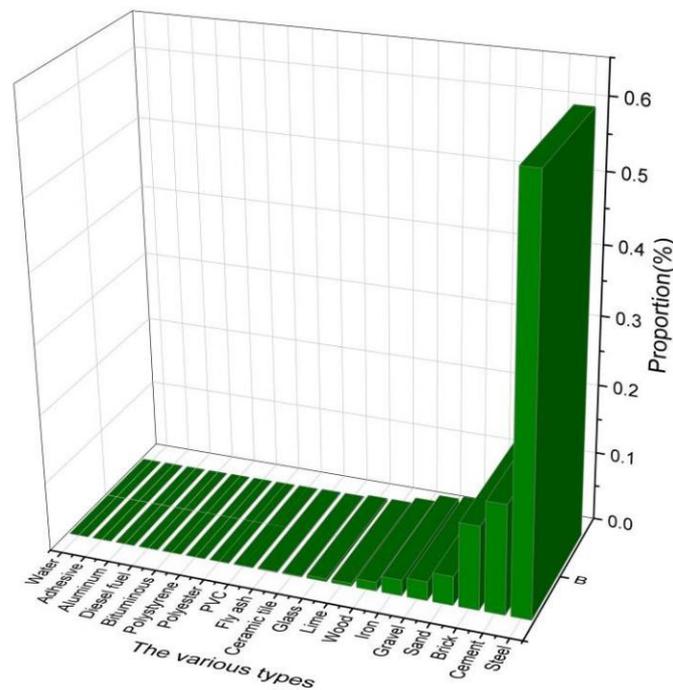


Figure 5. The order of all kinds of materials.

Figure 6 demonstrates that water supply and sewage system treatment facilities are critical subsystems, accounting for roughly 73% of the total energy in the building construction stage, followed by environmental inputs (14%), electricity installations (7%), the telecommunications system (3%), heating and cooling systems (2%) and the elevator system (1%).

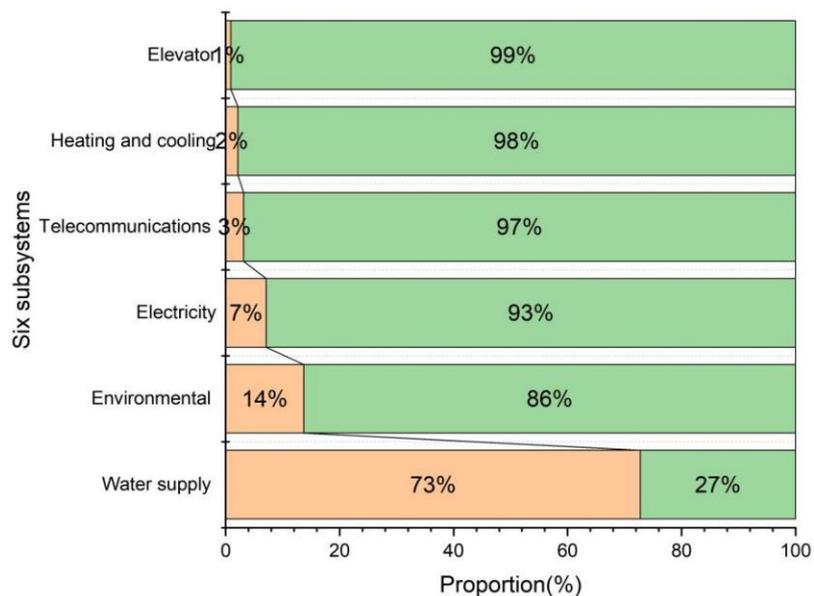


Figure 6. Six subsystems on the stage of building construction.

In order to better update building types, there are three renewal strategies, respectively, and the specific details can be obtained in Table 1. The unit energy value reference can be found in the literature [46].

**Table 1.** Emergy of building renewal stage.

Item	Data	Unit	UEVs	UEVs Unit	UEVs Ref.	Emergy (sej)
Updated Scenario 1						
PVC	$1.14 \times 10^4$	Kg	$2.22 \times 10^{11}$	Sej/kg	[71]	$2.53 \times 10^{15}$
Cement	$4.72 \times 10^5$	Kg	$2.94 \times 10^{12}$	Sej/kg	[46]	$1.39 \times 10^{18}$
Water	$9.52 \times 10^6$	Kg	$2.67 \times 10^9$	Sej/kg	[46]	$2.54 \times 10^{16}$
Diesel fuel	$6.76 \times 10^6$	Kg	$1.36 \times 10^5$	Sej/kg	[46]	$9.19 \times 10^{11}$
Updated Scenario 2						
Bricks	$5.67 \times 10^4$	Kg	$2.03 \times 10^{11}$	Sej/kg	[46]	$1.15 \times 10^{16}$
Concrete	$3.71 \times 10^5$	kg	$1.19 \times 10^{12}$	Sej/kg	[46]	$4.41 \times 10^{17}$
Diesel fuel	$4.48 \times 10^6$	Kg	$1.36 \times 10^5$	Sej/kg	[46]	$6.09 \times 10^{11}$
Updated Scenario 3						
Glass	$6.15 \times 10^4$	Kg	$1.69 \times 10^{12}$	Sej/kg	[71]	$1.04 \times 10^{17}$
Aluminum	$2.36 \times 10^1$	Kg	$9.65 \times 10^{11}$	Sej/kg	[46]	$2.28 \times 10^{13}$
Copper	$1.73 \times 10^1$	Kg	$1.52 \times 10^{12}$	Sej/kg	[46]	$2.63 \times 10^{13}$
Diesel fuel	$9.24 \times 10^6$	J	$1.36 \times 10^5$	Sej/J	[46]	$1.26 \times 10^{12}$

According to Table 1, in the three kinds of updating strategies, emergy accounted for 71.86%, 22.99% and 5.3%, respectively. However, for the building as a whole, they did not display the major roles.

The stage of building demolition is distinguished in two ways. On the one hand, some materials will be recycled, such as glass, PVC, iron, diesel fuel, concrete, bricks and aluminum, which account for about 84% of the total demolition emergy. On the other hand, approximately 16% of the entire emergy will be lost because of the landfill style.

#### 4.1.2. Emergy Indexes Analysis

In Table 2, six primary indexes have been shown for the sustainable state. Compared with renewable input and emergy feedback input, the nonrenewable resource input occupies a dominant position. Based on the  $R_i$ ,  $N_s$  and  $E_f$ , EYR and ELR have been calculated as 69.1 and 81.4. Then, the Emergy sustainability indicator (ESI) is computed and the value is 0.849. According to the sustainable standard (the eligibility standard is 1), the ESI is close to 1, which illustrates that the whole building system needs continuous improvement in order to improve its sustainability.

**Table 2.** Emergy indexes list.

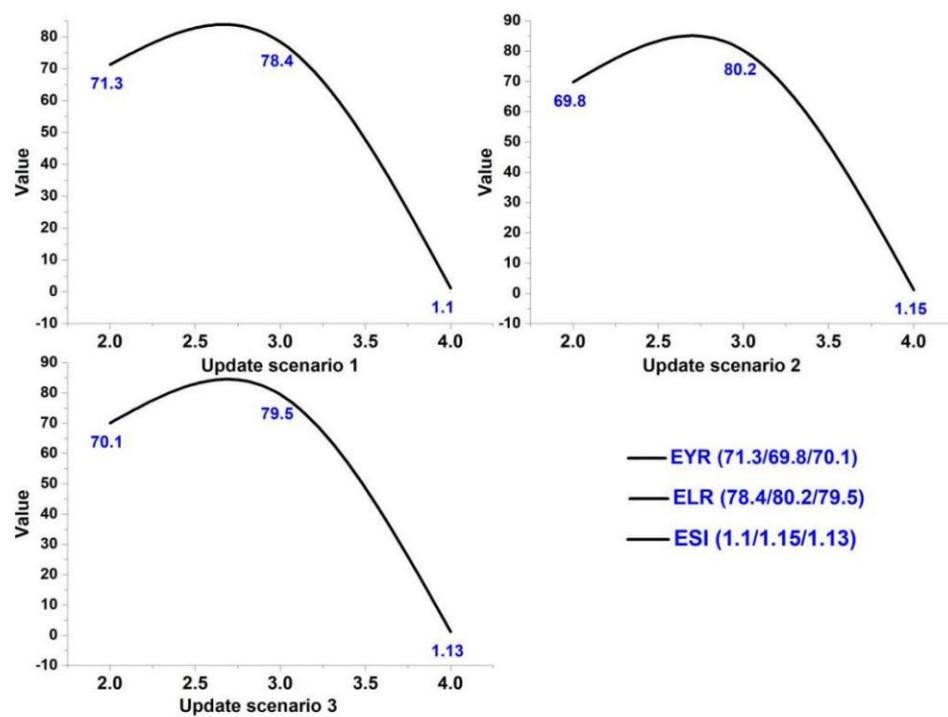
No.	Indicators	Values	Unit
1	Renewable input ( $R_i$ )	$9.38 \times 10^{18}$	Sej
2	Nonrenewable resource ( $N_s$ )	$7.64 \times 10^{20}$	Sej
3	Emergy feedback input ( $E_f$ )	$1.14 \times 10^{19}$	Sej
4	Emergy yield ratio (EYR)	69.1	-
5	Environmental loading ratio (ELR)	81.4	-
6	Emergy sustainability indicator (ESI)	0.849	-

### 4.1.3. The Sustainability Impact of Different Update Strategies

In Table 3 and Figure 7, the sustainability of the three renewal strategies has been shown. Compared with the original version, the total energy of the three renewal versions has been supplemented. Due to the use of renewable materials in the renewal phase, the environmental load decreased in the three stages, and the overall sustainability index improved significantly. In Figure 8, to compare and analyze three kinds of indicators, it is obvious that ESI has made significant changes (Red cloud map).

**Table 3.** Sustainability effects of three renewal strategies.

Item	Indexes	Value	Unit
Update scenario 1			
Emergy yield ratio	EYR	71.3	-
Environmental loading ratio	ELR	78.4	-
Emergy sustainable indicator	ESI	1.10	-
Update scenario 2			
Emergy yield ratio	EYR	69.8	-
Environmental loading ratio	ELR	80.2	-
Emergy sustainable indicator	ESI	1.15	-
Update scenario 3			
Emergy yield ratio	EYR	70.1	-
Environmental loading ratio	ELR	79.5	-
Emergy sustainable indicator	ESI	1.13	-



**Figure 7.** Sustainability comparison trend of three renewal strategies.

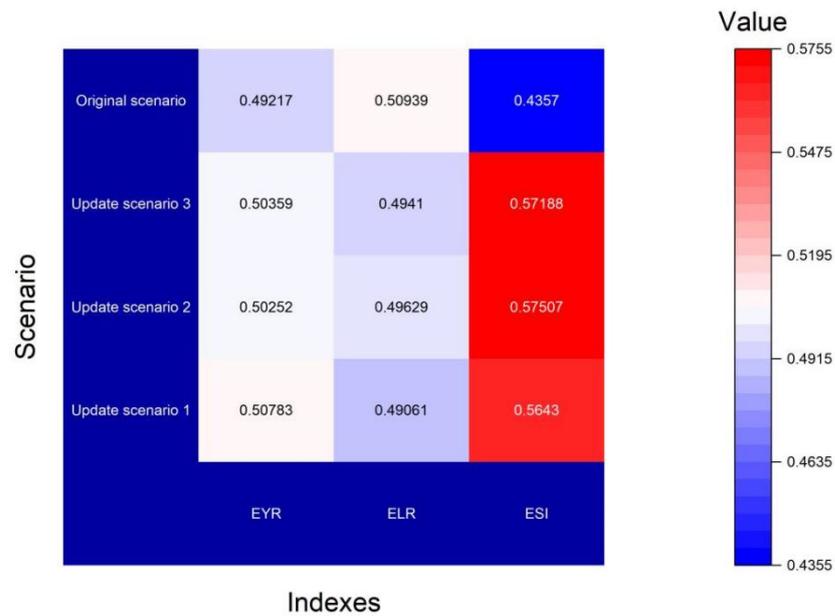


Figure 8. Sustainability changes of three renewal strategies.

In Figure 9, the change ranges of sustainability indicators have been visualized. Therein, the ESI indexes proportion of the renewal stage displays evident improvements from the original scenario (from 0.56/0.58/0.57 to 0.44).

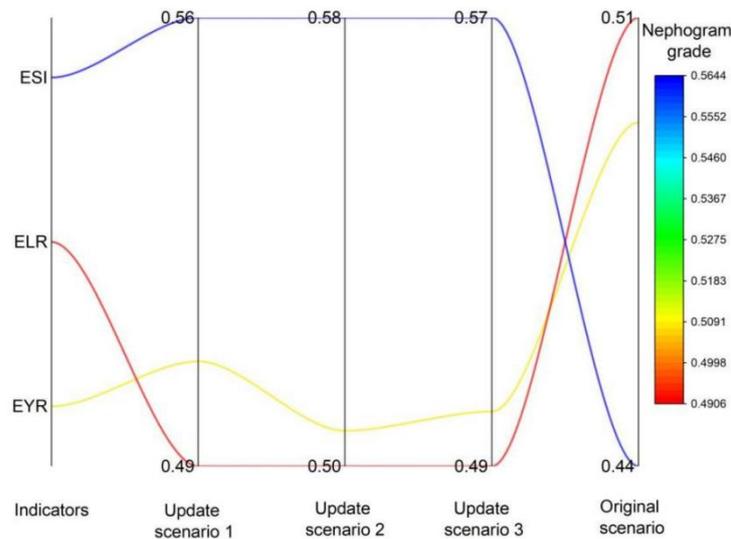


Figure 9. Sustainability index variation.

#### 4.1.4. Sensitivity Analysis of LCA–Emergy View

According to the main contributors, the building operation stage and building material stage have the primary impact on the total emergy amount for the entire building. Therefore, their sensitivity analysis needs to be considered for accuracy.

The specific assumptions are as follows:

**Hypothesis 1 (H1) (Table 4).** At the stage of building operation, six subsystems should be investigated, including environmental inputs, water supply and sewage system treatment facilities, heating and cooling systems, electricity installations, telecommunications system, elevator system, etc. The emergy of each subsystem varies by 5% and 10%, and then the amplitude of the final sustainability indicator change will be verified.

**Table 4.** Sensitivity analysis of sustainable indicators under Hypothesis 1.

Indicators	Former	Latter (10%)	Latter (5%)	Range of Variation		Unit
				10%	5%	
EYR	69.1	61.97	64.61	10.32%	6.50%	-
ELR	81.4	75.05	76.12	7.80%	6.49%	-
ESI	0.849	0.83	0.86	2.24%	1.30%	-

**Hypothesis 2 (H2) (Table 5).** At the stage of building material, seven main types of building materials are selected, involving steel, cement, brick, sand, gravel, iron, and wood, etc. (accounting for about 98.7% of the total emergy on the stage of building material). Similarly, under the changes of 5% and 10% for each material value, the magnitude of changes in sustainability indicators needs to be displayed.

**Table 5.** Sensitivity analysis of sustainable indicators under Hypothesis 2.

Indicators	Values	Latter (10%)	Latter (5%)	Range of Variation		Unit
				10%	5%	
EYR	69.1	64.61	66.55	6.50%	3.69%	-
ELR	81.4	81.02	80.60	0.47%	0.98%	-
ESI	0.849	0.80	0.83	5.77%	2.24%	-

Figure 10A shows the sensitivity analysis under hypothesis 1. Based on a 10% change, three sustainable indexes have a consistent float and it is close to a linear trend, which demonstrates the validity of the calculation results. Under the 10% change, EYR (10.32%) has a more distinct difference than ELR (7.8%) and ESI (2.24%). Similar results at a 5% alteration can be obtained from Figure 10B. The difference is that a 5% linearity is worse than a 10% linearity, which illustrates that a 5% variation is more sensitive to the impact of sustainability indicators under Hypothesis 1. For Hypothesis 2, the data validity is also verified at 10% and 5% changes. However, a clear distinction is that a 10% change in the data has a large impact on sustainable indexes, which can be found in Figure 10C,D. It can be concluded that the building operation phase is more sensitive to small changes in data (5% variation), whereas the building materials phase is more sensitive to large changes in data (10% variation). The reason for this result is that the subsystems of the building operation stage are multiple mechanical systems, whose sensitivity to data is significantly higher than that of the building material stage.

#### 4.1.5. Unit Emergy Values (UEVs)

Generally speaking, unit emergy value is the core concept of LCA–Emergy analysis. However, in the field of architectural research, not many people calculate and evaluate it, resulting in a lack of sustainability assessment based on the emergy method. In this paper, the UEV has been computed ( $1.49 \times 10^{16}$  sej/m<sup>2</sup>), which has a relatively high value.

To compare and analyze the latest article [46], the UEV is  $2.14 \times 10^{18}$  sej/m<sup>2</sup>, which is higher than that studied in this article ( $1.49 \times 10^{16}$  sej/m<sup>2</sup>). It indicates that the whole building system needs more emergy input, which will consume a lot of resources and energy. The UEV of the entire building system studied in this paper is smaller, elucidating that the design of building renewal in this paper is feasible.

#### 4.2. LCA–Carbon Emission Analysis

In this section, the life-cycle carbon emissions of the building system are calculated and demonstrated. Among them, the carbon emission factor can be obtained from reference [74,75].

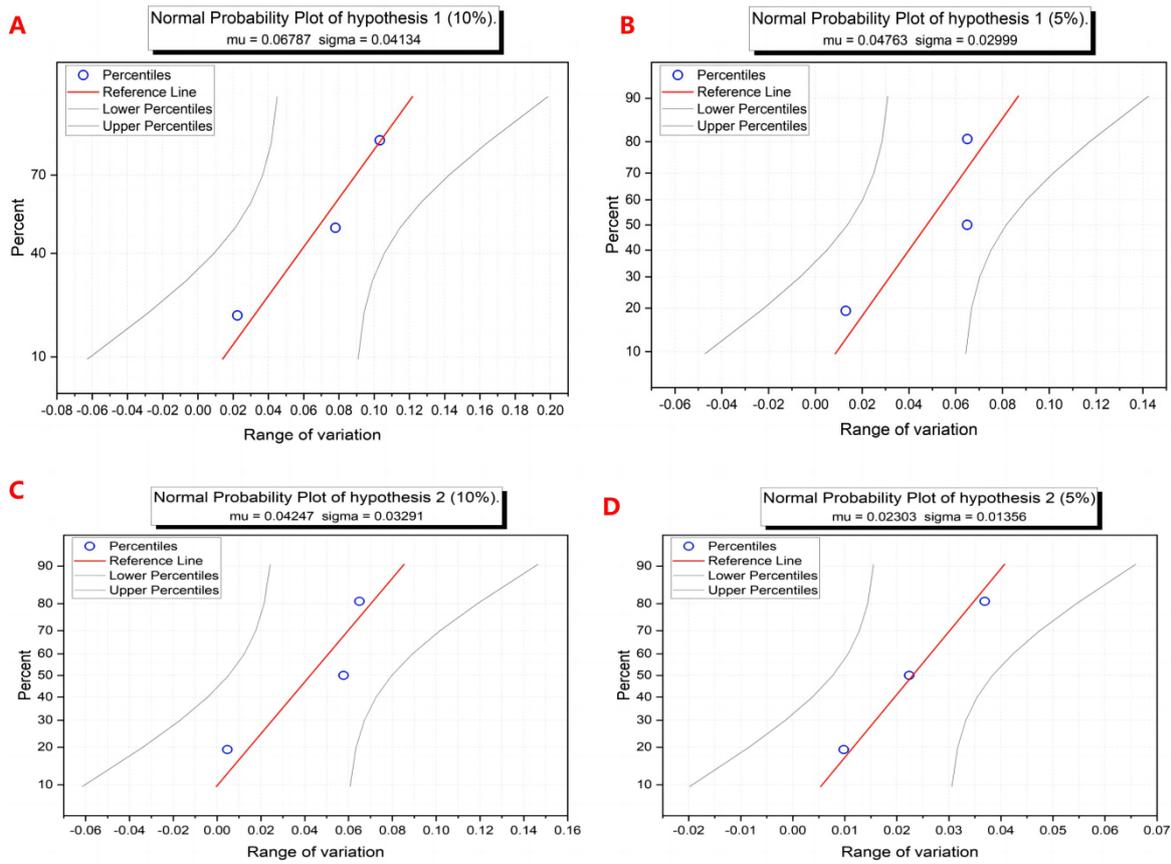


Figure 10. Sensitivity analysis under Hypothesis 1 and 2.

#### 4.2.1. The Carbon Emission of the Building Material Stage

In the building materials stage, there are 19 types of material inputs, of which the largest carbon emission output is steel, followed by gravel and iron, which are 66,750 tCO<sub>2</sub>, 30,400 tCO<sub>2</sub> and 1312 tCO<sub>2</sub> (as shown in Table 6 and Figure 11). Depending on the carbon emissions of individual materials, carbon reduction measures need to target the major materials (steel, gravel and iron).

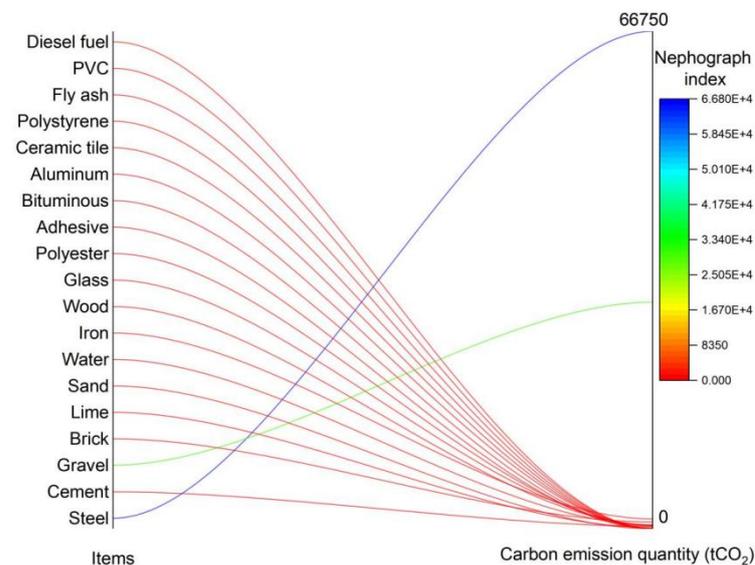


Figure 11. Dominated carbon emission differentiation.

**Table 6.** The carbon emission in the building material production stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Steel	$2.5 \times 10^7$	Kg	2.67 tCO <sub>2</sub> /t	66,750	tCO <sub>2</sub>
Cement	$4.7 \times 10^6$	Kg	0.07 tCO <sub>2</sub> /t	329	tCO <sub>2</sub>
Gravel	$1.9 \times 10^6$	Kg	16 kgCO <sub>2</sub> /kg	30,400	tCO <sub>2</sub>
Brick	$3.8 \times 10^6$	Kg	0.24 kgCO <sub>2</sub> /kg	912	tCO <sub>2</sub>
Lime	$3.1 \times 10^5$	Kg	0.44 tCO <sub>2</sub> /t	136.4	tCO <sub>2</sub>
Sand	$2.9 \times 10^6$	Kg	2.51 kgCO <sub>2</sub> /t	7.279	tCO <sub>2</sub>
Water	$5.9 \times 10^5$	M <sup>3</sup>	0.82 kgCO <sub>2</sub> /m <sup>3</sup>	483.8	tCO <sub>2</sub>
Iron	$6.4 \times 10^5$	Kg	2.05 tCO <sub>2</sub> /t	1312	tCO <sub>2</sub>
Wood	$1.7 \times 10^6$	Kg	0.31 kgCO <sub>2</sub> /kg	527	tCO <sub>2</sub>
Glass	$3.5 \times 10^5$	Kg	1.4 kgCO <sub>2</sub> /kg	490	tCO <sub>2</sub>
Polyester	$4.6 \times 10^3$	Kg	72.65 tCO <sub>2</sub> /t	334.19	tCO <sub>2</sub>
Adhesive	$7.8 \times 10^3$	Kg	1.1 kgCO <sub>2</sub> /kg	8.58	tCO <sub>2</sub>
Bituminous	$9.1 \times 10^3$	Kg	0.04 kgCO <sub>2</sub> /kg	0.364	tCO <sub>2</sub>
Aluminum	$6.3 \times 10^3$	Kg	15.8 tCO <sub>2</sub> /t	99.54	tCO <sub>2</sub>
Ceramic tile	$4.7 \times 10^4$	Kg	0.74 tCO <sub>2</sub> /t	34.78	tCO <sub>2</sub>
Polystyrene	$5.1 \times 10^3$	Kg	3.78 kgCO <sub>2</sub> /kg	19.278	tCO <sub>2</sub>
Fly ash	$5.9 \times 10^3$	Kg	0.18 tCO <sub>2</sub> /t	1.062	tCO <sub>2</sub>
PVC	$7.4 \times 10^3$	Kg	4.79 kgCO <sub>2</sub> /kg	35.446	tCO <sub>2</sub>
Diesel fuel	1244	Kg	3.797 tCO <sub>2</sub> /t	4.723468	tCO <sub>2</sub>

#### 4.2.2. The Carbon Emission of Building Construction Stage

During the construction phase, the specific carbon emissions of six subsystems are shown in Table 7. Therein, water supply and sewage system treatment facilities emit the most carbon dioxide, at approximately 22,640 tCO<sub>2</sub>, accounting for 38.55% of the total construction carbon emission, followed by the telecommunications system (18,370.3 tCO<sub>2</sub>, roughly 31.28%); labor and service (6341 tCO<sub>2</sub>, roughly 10.79%); heating and cooling systems (5125.2 tCO<sub>2</sub>, roughly 8.73%); the elevator system (4102.8 tCO<sub>2</sub>, roughly 6.98%) and electricity installations (2151.1 tCO<sub>2</sub>, roughly 3.66%), etc. In Figure 12A, the trend of fluctuation can be clearly identified.

**Table 7.** The carbon emission in the building construction stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
<b>Labor and service</b>					
Diesel fuel	$6.00 \times 10^2$	t	3.797 tCO <sub>2</sub> /t	2278.2	tCO <sub>2</sub>
Machinery diesel	$9.00 \times 10^2$	t	3.797 tCO <sub>2</sub> /t	3417.3	tCO <sub>2</sub>
Transport diesel	$1.70 \times 10^2$	t	3.797 tCO <sub>2</sub> /t	645.49	tCO <sub>2</sub>
<b>Water supply and sewage system treatment facilities</b>					
Steel	$5.21 \times 10^6$	Kg	2.67 tCO <sub>2</sub> /t	13,910.7	tCO <sub>2</sub>
PVC	$8.41 \times 10^3$	Kg	4.79 kgCO <sub>2</sub> /kg	40.2839	tCO <sub>2</sub>
Polystyrene	$2.67 \times 10^3$	Kg	3.78 kgCO <sub>2</sub> /kg	10.0926	tCO <sub>2</sub>
Brass	$7.40 \times 10^3$	Kg	3.73 tCO <sub>2</sub> /t	27.602	tCO <sub>2</sub>

Table 7. Cont.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Polypropylene	$7.99 \times 10^3$	Kg	5.98 tCO <sub>2</sub> /t	47.7802	tCO <sub>2</sub>
Glass fiber	$8.41 \times 10^3$	Kg	1.4 kgCO <sub>2</sub> /kg	11.774	tCO <sub>2</sub>
Iron	$2.93 \times 10^4$	Kg	2.05 tCO <sub>2</sub> /t	60.065	tCO <sub>2</sub>
Ceramic	$5.82 \times 10^5$	Kg	0.74 tCO <sub>2</sub> /t	430.68	tCO <sub>2</sub>
Glass	$4.21 \times 10^6$	Kg	1.4 kgCO <sub>2</sub> /kg	5894	tCO <sub>2</sub>
Cement	$5.33 \times 10^6$	Kg	0.07 tCO <sub>2</sub> /t	373.1	tCO <sub>2</sub>
Water	$4.81 \times 10^4$	m <sup>3</sup>	0.82 kgCO <sub>2</sub> /m <sup>3</sup>	39.442	tCO <sub>2</sub>
Gravel	$6.02 \times 10^4$	Kg	16 kgCO <sub>2</sub> /kg	963.2	tCO <sub>2</sub>
Diesel fuel	$2.19 \times 10^2$	t	3.797 tCO <sub>2</sub> /t	831.543	tCO <sub>2</sub>
<b>Heating and cooling systems</b>					
Steel	$4.61 \times 10^5$	Kg	2.67 tCO <sub>2</sub> /t	1230.87	tCO <sub>2</sub>
Polypropylene	$4.78 \times 10^3$	Kg	5.98 tCO <sub>2</sub> /t	28.5844	tCO <sub>2</sub>
Aluminum	$5.92 \times 10^3$	Kg	15.8 tCO <sub>2</sub> /t	93.536	tCO <sub>2</sub>
Glass wool	$9.03 \times 10^3$	Kg	1.4 kgCO <sub>2</sub> /kg	12.642	tCO <sub>2</sub>
Brass	$8.51 \times 10^3$	Kg	3.73 tCO <sub>2</sub> /t	31.7423	tCO <sub>2</sub>
Copper	$8.66 \times 10^3$	Kg	3.73 tCO <sub>2</sub> /t	32.3018	tCO <sub>2</sub>
Diesel fuel	$1.90 \times 10^2$	t	3.797 tCO <sub>2</sub> /t	721.43	tCO <sub>2</sub>
<b>Electricity installations</b>					
Copper	$1.34 \times 10^4$	Kg	3.73 tCO <sub>2</sub> /t	49.982	tCO <sub>2</sub>
Aluminum sheet	$4.82 \times 10^4$	Kg	15.8 tCO <sub>2</sub> /t	761.56	tCO <sub>2</sub>
Galvanized steel	$5.72 \times 10^4$	Kg	15.8 tCO <sub>2</sub> /t	903.76	tCO <sub>2</sub>
Steel	$9.04 \times 10^5$	Kg	15.8 tCO <sub>2</sub> /t	14,283.2	tCO <sub>2</sub>
Rubber	$6.99 \times 10^4$	Kg	2.4 tCO <sub>2</sub> /t	167.76	tCO <sub>2</sub>
Polyester	$7.83 \times 10^3$	Kg	72.65 tCO <sub>2</sub> /t	568.8495	tCO <sub>2</sub>
Iron	$5.44 \times 10^4$	Kg	2.05 tCO <sub>2</sub> /t	111.52	tCO <sub>2</sub>
Ceramics	$6.78 \times 10^4$	Kg	0.74 tCO <sub>2</sub> /t	50.172	tCO <sub>2</sub>
Plastic	$9.94 \times 10^4$	Kg	7.83 kgCO <sub>2</sub> /kg	778.302	tCO <sub>2</sub>
Glass	$3.82 \times 10^4$	Kg	1.4 kgCO <sub>2</sub> /kg	53.48	tCO <sub>2</sub>
Diesel fuel	$1.69 \times 10^0$	t	3.797 tCO <sub>2</sub> /t	641.693	tCO <sub>2</sub>
<b>Telecommunications system</b>					
Copper	$5.63 \times 10^4$	Kg	3.73 tCO <sub>2</sub> /t	209.999	tCO <sub>2</sub>
PVC	$6.67 \times 10^4$	Kg	4.79 kgCO <sub>2</sub> /kg	319.493	tCO <sub>2</sub>
Aluminum sheet	$7.98 \times 10^4$	Kg	15.8 tCO <sub>2</sub> /t	1260.84	tCO <sub>2</sub>
Plastic	$2.33 \times 10^4$	Kg	7.83 kgCO <sub>2</sub> /kg	182.439	tCO <sub>2</sub>
Brass	$4.53 \times 10^4$	Kg	3.73 tCO <sub>2</sub> /t	168.969	tCO <sub>2</sub>
Aluminum	$6.74 \times 10^4$	Kg	15.8 tCO <sub>2</sub> /t	1064.92	tCO <sub>2</sub>
Glass	$8.88 \times 10^4$	Kg	1.4 kgCO <sub>2</sub> /kg	124.32	tCO <sub>2</sub>
Steel	$6.79 \times 10^4$	Kg	15.8 tCO <sub>2</sub> /t	1072.82	tCO <sub>2</sub>
Diesel fuel	$1.90 \times 10^0$	t	3.797 tCO <sub>2</sub> /t	721.43	tCO <sub>2</sub>

Table 7. Cont.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
<b>Elevator system</b>					
Steel	$2.11 \times 10^5$	Kg	15.8 tCO <sub>2</sub> /t	3333.8	tCO <sub>2</sub>
Rubber	$5.32 \times 10^3$	Kg	2.4 tCO <sub>2</sub> /t	12.768	tCO <sub>2</sub>
Iron	$8.93 \times 10^3$	Kg	2.05 tCO <sub>2</sub> /t	18.3065	tCO <sub>2</sub>
Glass	$9.06 \times 10^3$	Kg	1.4 kgCO <sub>2</sub> /kg	12.684	tCO <sub>2</sub>
Diesel fuel	$1.91 \times 10^1$	t	3.797 tCO <sub>2</sub> /t	725.227	tCO <sub>2</sub>

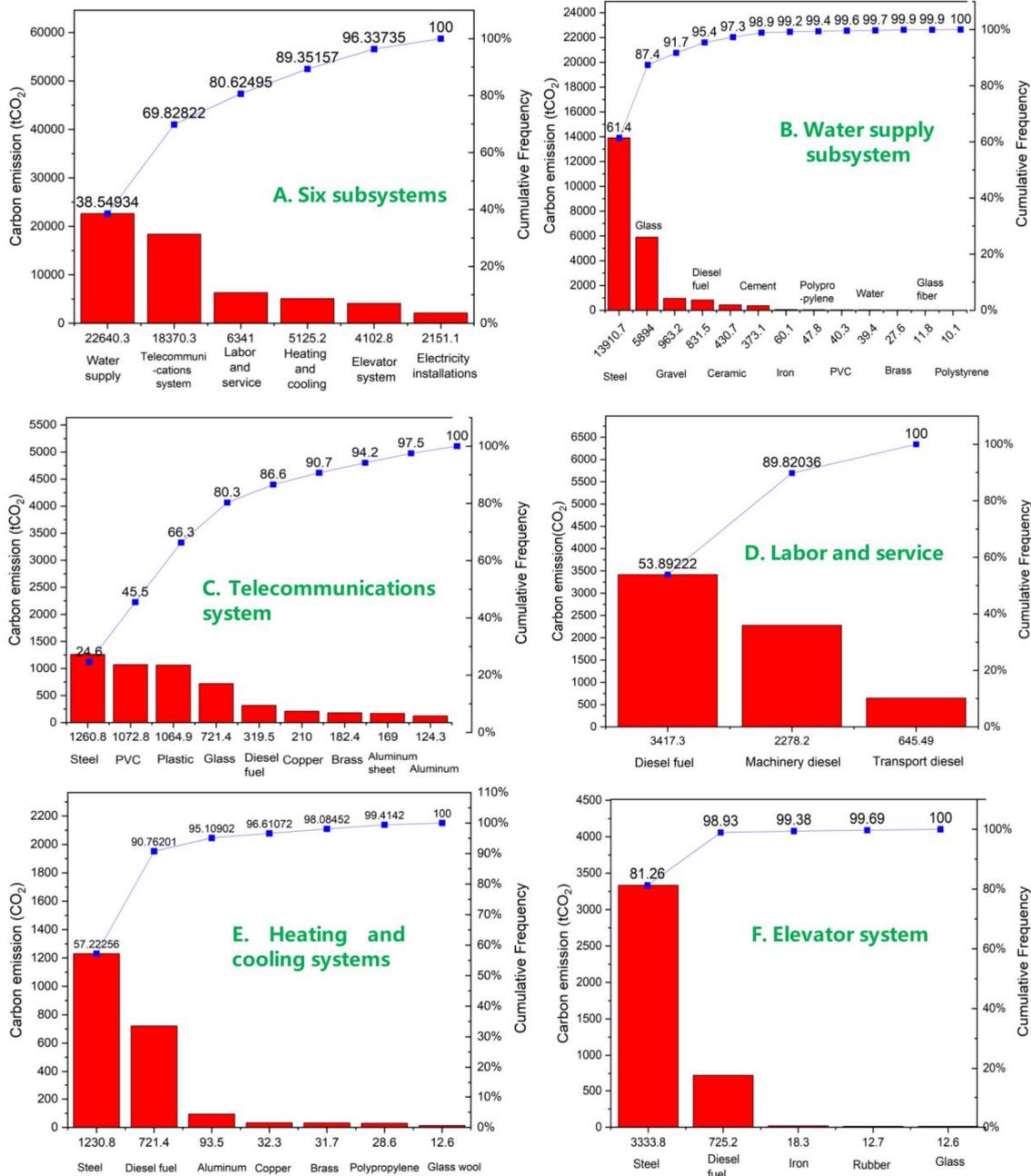


Figure 12. Cont.

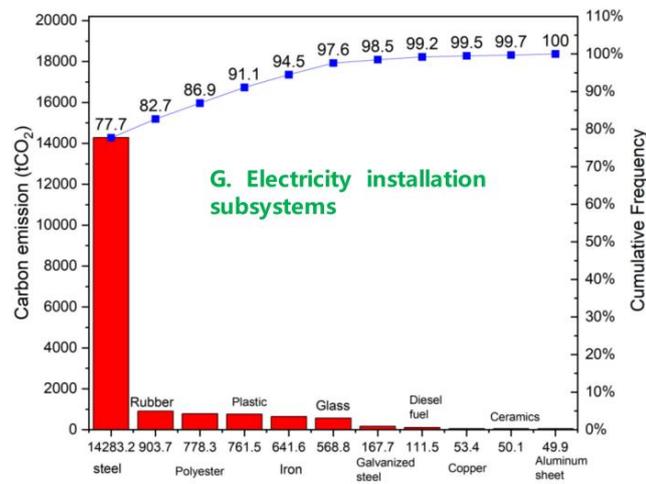


Figure 12. The carbon emission trend of six subsystems.

Taking the water supply subsystem as an example, it has thirteen components (shown in Figure 10B), including steel, glass, gravel, diesel fuel, ceramic, cement, iron, polypropylene, PVC, water, brass, glass fiber and polystyrene, accounting for about 61.4% of entire water supply subsystem, at 26%, 4.3%, 3.7%, 1.9%, 1.6%, 0.3%, 0.2%, 0.2%, 0.1%, 0.1%, 0.1%, 0.1% and 0.1%, respectively.

For the same reason, telecommunications systems, labor and service, heating and cooling systems and electricity installations have been analyzed according to carbon emission trends. Specific changes are referred to in Figure 12C–G. For the telecommunications system, the top six inputs account for 90.7% of total carbon emissions (which are steel, PVC, plastic, glass, diesel fuel and copper). For labor and service, diesel fuel incurs a main effect for the subsystem. For heating and cooling systems, steel and diesel fuel are the primary contributors, which account for 57.2% and 23.5% of the total carbon emission amounts, respectively. For the elevator system, similar results can be obtained. Steel and diesel fuel are the dominant inputs, accounting for about 81.26% and 17.67%. For electricity installations, steel, rubber, polyester, plastic, iron, and glass, are leading elements (97.6% of carbon emission).

#### 4.2.3. The Carbon Emission in the Building Operation Stage

Because the operational phase takes into account a 20-year period, the amount of carbon emissions is huge, amounting to  $1.14 \times 10^7$  tons. In total, heat carbon emission has  $9.62 \times 10^6$  tCO<sub>2</sub>, electricity ( $1.78 \times 10^6$  tCO<sub>2</sub>) and water ( $2.71 \times 10^2$  tCO<sub>2</sub>), as seen in Table 8 and Figure 13. Through the overall study of this paper, the building operation stage has the most carbon emissions in the whole building system, which needs to be paid more attention.

Table 8. The carbon emission of the building operation stage (tCO<sub>2</sub>).

Item	Data	Unit	Carbon Emission Factors	Carbon Emission
Electricity	$2.53 \times 10^9$	kWh	0.7025 kgCO <sub>2</sub> /kWh	$1.78 \times 10^6$
Heat	$4.81 \times 10^9$	J	0.002 tCO <sub>2</sub> /J	$9.62 \times 10^6$
Water	$3.31 \times 10^5$	m <sup>3</sup>	0.82 kgCO <sub>2</sub> /m <sup>3</sup>	$2.71 \times 10^2$

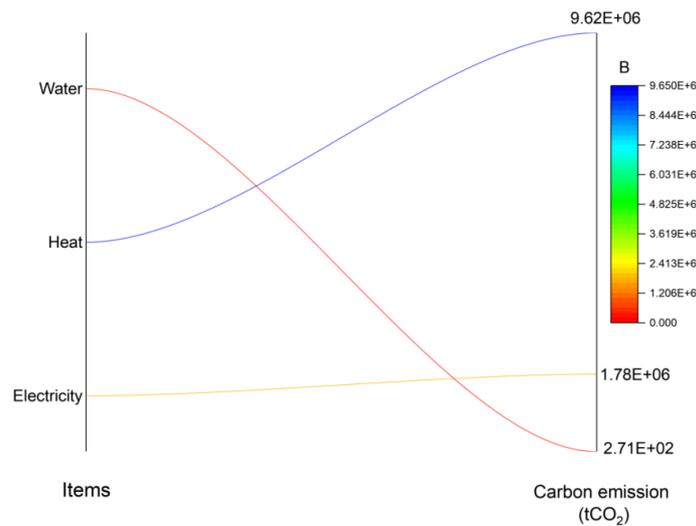


Figure 13. The carbon emission in the building operation stage.

#### 4.2.4. The Carbon Emission in the Building Renewal Stage

There are three categories of upgrading strategies that focus on sustainable goals. Design strategy 1 revolves around green vegetation, including measures such as vertical landscape walls, rooftop gardens and sunken plaza gardens. Design strategy 2 emphasizes equipment upgrades, such as adding solar photovoltaic power generation devices, rainwater collection systems, heat pump technology utilization and updating the fresh air system. Design strategy 3 aims to improve the spatial performance of the building complex, involving the replacement of energy-saving walls and the use of phase change storage walls, etc.

From the view of a renewal operation, three scenarios have been executed. The specific data and calculation processes are displayed in Table 9. In Figure 14, the change trend is clear. Updated scenario 3 discharged 2584 tCO<sub>2</sub>, more than updated scenario 1 (1650.3 tCO<sub>2</sub>) and updated scenario 2 (1092.2 tCO<sub>2</sub>). This update process is designed for a usage of 20 years.

Table 9. The carbon emission of the building renewal stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Updated Scenario 1					
PVC	$1.14 \times 10^4$	Kg	4.79 kgCO <sub>2</sub> /kg	54.606	tCO <sub>2</sub>
Cement	$4.72 \times 10^5$	Kg	0.07 tCO <sub>2</sub> /t	33.04	tCO <sub>2</sub>
Water	$9.52 \times 10^3$	Kg	0.82 kgCO <sub>2</sub> /m <sup>3</sup>	7.8064	tCO <sub>2</sub>
Diesel fuel	$6.76 \times 10^6$	Kg	0.23 tCO <sub>2</sub> /t	1554.8	tCO <sub>2</sub>
Updated Scenario 2					
Bricks	$5.67 \times 10^4$	Kg	0.24 kgCO <sub>2</sub> /kg	13.608	tCO <sub>2</sub>
Concrete	$3.71 \times 10^5$	Kg	0.13 kgCO <sub>2</sub> /kg	48.23	tCO <sub>2</sub>
Diesel fuel	$4.48 \times 10^6$	Kg	0.23 tCO <sub>2</sub> /t	1030.4	tCO <sub>2</sub>
Updated Scenario 3					
Glass	$6.15 \times 10^4$	Kg	1.4 kgCO <sub>2</sub> /kg	86.1	tCO <sub>2</sub>
Aluminum	$2.36 \times 10^1$	Kg	15.8 tCO <sub>2</sub> /t	372.88	tCO <sub>2</sub>
Copper	$1.73 \times 10^1$	Kg	3.73 tCO <sub>2</sub> /t	0.065	tCO <sub>2</sub>
Diesel fuel	$9.24 \times 10^6$	kg	0.23 tCO <sub>2</sub> /t	2125.2	tCO <sub>2</sub>

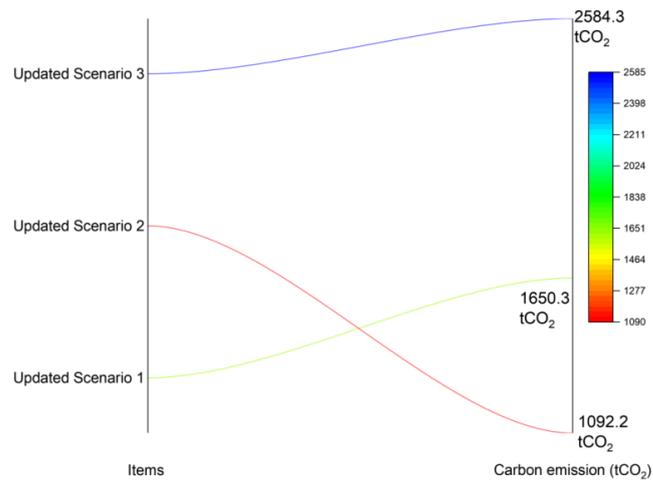


Figure 14. The carbon emission in the building renewal stage.

#### 4.2.5. The Carbon Emission in the Building Demolition Stage

For the building demolition stage, there are seven major categories, as seen in Table 10. Figure 15 reveals the changes in each input. Depending on 59,860 tCO<sub>2</sub>, iron played a pivotal role, producing far more carbon than any other term. Then, glass was the second most important factor on the basis of 7630 tCO<sub>2</sub>. The carbon emissions of the other inputs performed a subordinate function, such as Aluminum (538.78 tCO<sub>2</sub>), Concrete (153.4 tCO<sub>2</sub>), PVC (106.82 tCO<sub>2</sub>), Bricks (13.75 tCO<sub>2</sub>) and Diesel fuel (0.85 tCO<sub>2</sub>).

Table 10. The carbon emission of the building demolition stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Glass	$5.45 \times 10^6$	Kg	1.4 kgCO <sub>2</sub> /kg	7630	tCO <sub>2</sub>
Iron	$2.92 \times 10^7$	Kg	2.05 tCO <sub>2</sub> /t	59,860	tCO <sub>2</sub>
PVC	$2.23 \times 10^4$	Kg	4.79 kgCO <sub>2</sub> /kg	106.82	tCO <sub>2</sub>
Aluminum	$3.41 \times 10^4$	Kg	15.8 tCO <sub>2</sub> /t	538.78	tCO <sub>2</sub>
Bricks	$5.73 \times 10^4$	Kg	0.24 kgCO <sub>2</sub> /kg	13.75	tCO <sub>2</sub>
Concrete	$1.18 \times 10^6$	Kg	0.13 kgCO <sub>2</sub> /kg	153.4	tCO <sub>2</sub>
Diesel fuel	$2.25 \times 10^2$	Kg	3.797 tCO <sub>2</sub> /t	0.85	tCO <sub>2</sub>

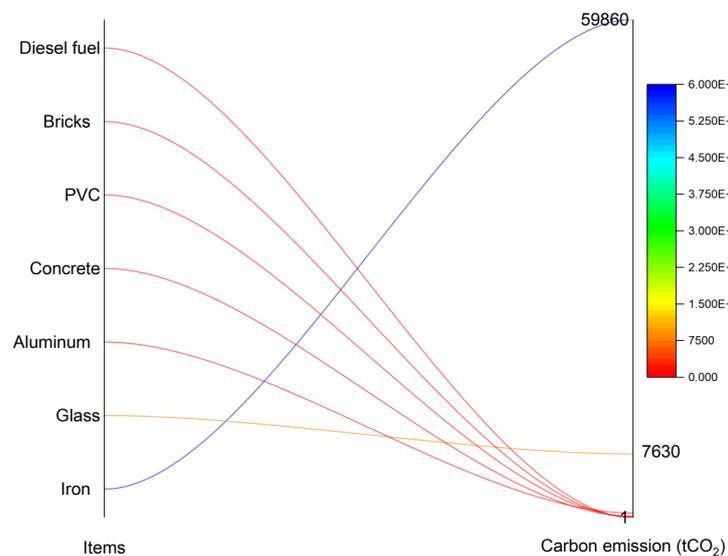


Figure 15. The carbon emission in the building demolition stage.

### 4.2.6. LCA–Carbon Emissions Analysis

Table 11 presents the carbon emission situations of the five stages. In accordance with the 20-year service life, the operating phase has the largest carbon footprint ( $1.14 \times 10^7$  tCO<sub>2</sub>), followed by the building material production stage ( $1.02 \times 10^5$  tCO<sub>2</sub>), the building demolition stage ( $6.83 \times 10^4$  tCO<sub>2</sub>), the building construction stage ( $5.87 \times 10^4$  tCO<sub>2</sub>) and the building renewal stage ( $5.33 \times 10^3$  tCO<sub>2</sub>). Figure 16 explains the changing trend by comparing it with five stages. The carbon emissions of the operational phase are much higher than those of the other four phases (accounting for 97.9%, roughly; shown in Figure 17).

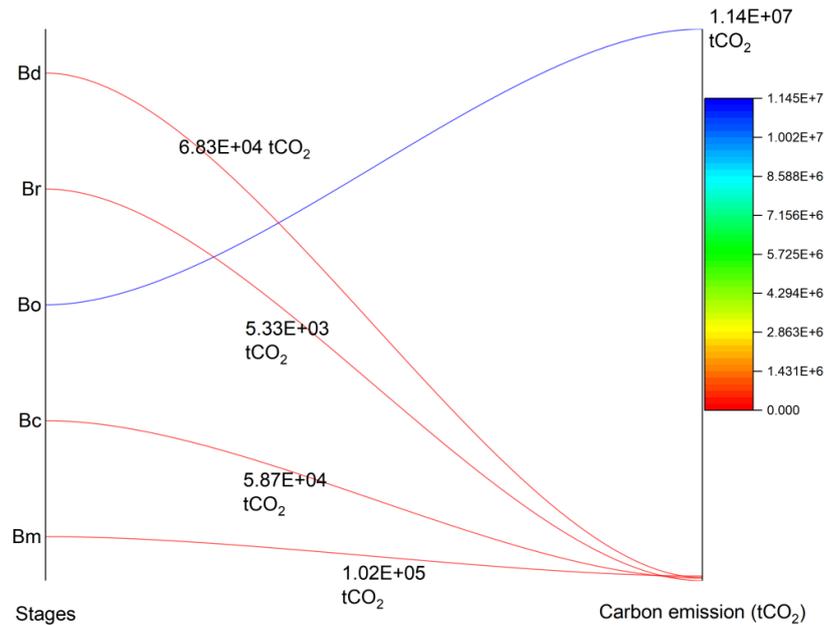


Figure 16. The carbon emission of LCA–Carbon emission stage.

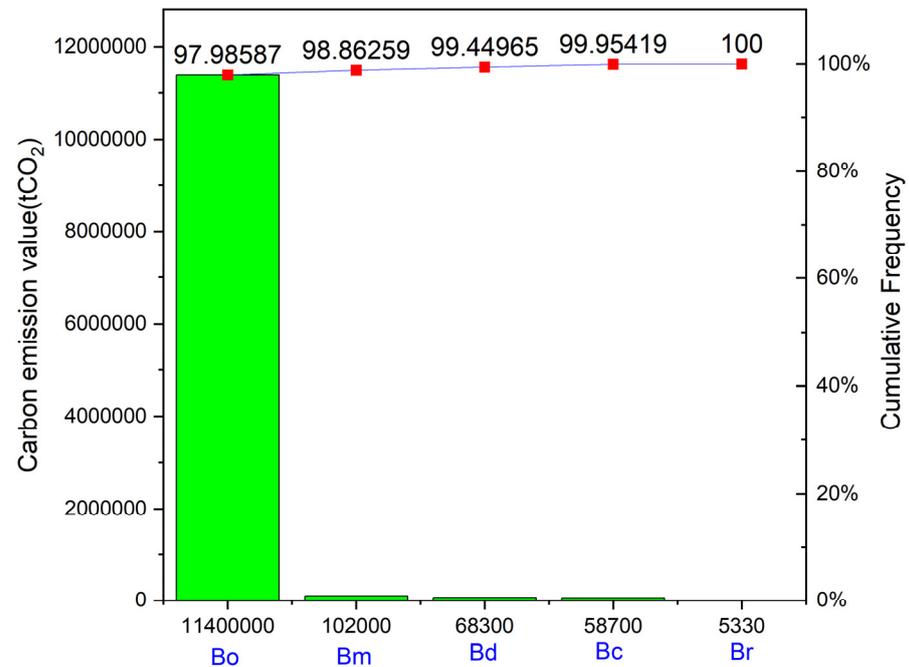


Figure 17. The carbon emission comparison of the five stages.

**Table 11.** The carbon emission calculation of the LCA–Carbon method.

Stages	Abbreviation	Carbon Emission	Unit
Building material production stage	Bm	$1.02 \times 10^5$	tCO <sub>2</sub>
Building construction stage	Bc	$5.87 \times 10^4$	tCO <sub>2</sub>
Building operation stage	Bo	$1.14 \times 10^7$	tCO <sub>2</sub>
Building renewal stage	Br	$5.33 \times 10^3$	tCO <sub>2</sub>
Building demolition stage	Bd	$6.83 \times 10^4$	tCO <sub>2</sub>

4.2.7. Sensitivity Analysis of LCA–Carbon Emissions View

On account of carbon emission amount, the building operation stage plays a critical role. Because it has a decisive effect on the overall carbon output, its sensitivity should be selected and analyzed to ensure the accuracy of this study.

From Section 4.2.3, a fact can be found that electricity and heating consumption are the primary influence factors. To confirm the accuracy of this, four hypotheses were set out and tested.

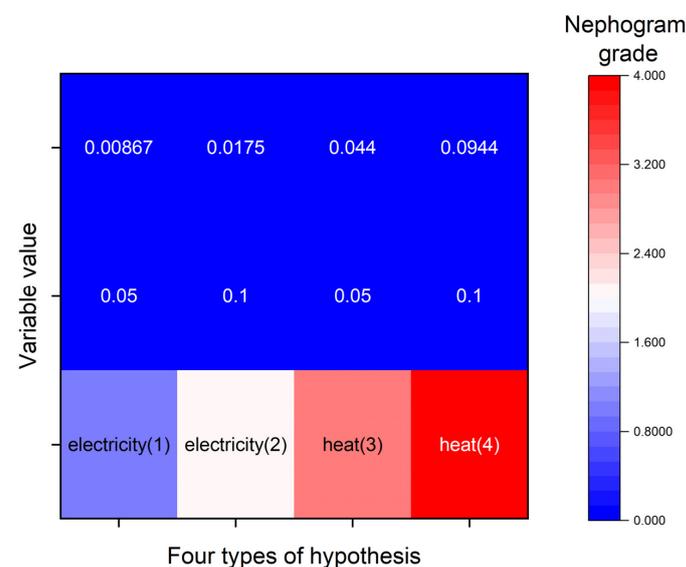
Hypothesis 1—A 5% change in electricity will be carried out to verify the impact on total carbon emission amount.

Hypothesis 2—A 10% change in electricity will be considered to explore the impact on total carbon emission amount.

**Hypothesis 3 (H3).** A 5% change in heat will be conducted to test the impact on total carbon emission amount.

**Hypothesis 4 (H4).** A 10% change in heat will be performed to confirm the impact on the total carbon emission amount.

According to the calculation results, Figure 18 has been manufactured. In Figure 18, two distinct features can be obtained. On the one hand, Hypothesis 3 and Hypothesis 4 have a larger float than Hypothesis 1 and Hypothesis 2 (to distinguish size based on the cloud color), which illustrates that the sensitivity of heat input is higher than that of electricity. On the other hand, the larger the data of the operation stage, the greater the change in the carbon emissions of the whole building. Hence, to ensure the study accuracy, heat input sensitivity is the first consideration, followed by electrical input sensitivity.



**Figure 18.** The sensitivity analysis based on the variation of the operation stage.

## 5. A New Type of Energy System Reuse Analysis

According to the research in this paper, the building operation stage is the main influencing factor, no matter whether this is from the energy perspective or the carbon emission perspective. Among them, the building operation stage is mainly composed of the thermal subsystem and the electrical subsystem. Therefore, the strategy improvement in this paper will focus on the thermal subsystem and the electrical subsystem.

To verify the influence of heat and electric energy on the whole building system, a new power and heat supply subsystem has been designed and is displayed in Figure 19. The most obvious highlight of the system is that the energy comes from the waste heat recycling of the glass manufacturing system, which belongs to the reuse of surplus energy. It provides new energy supplies while reducing waste.

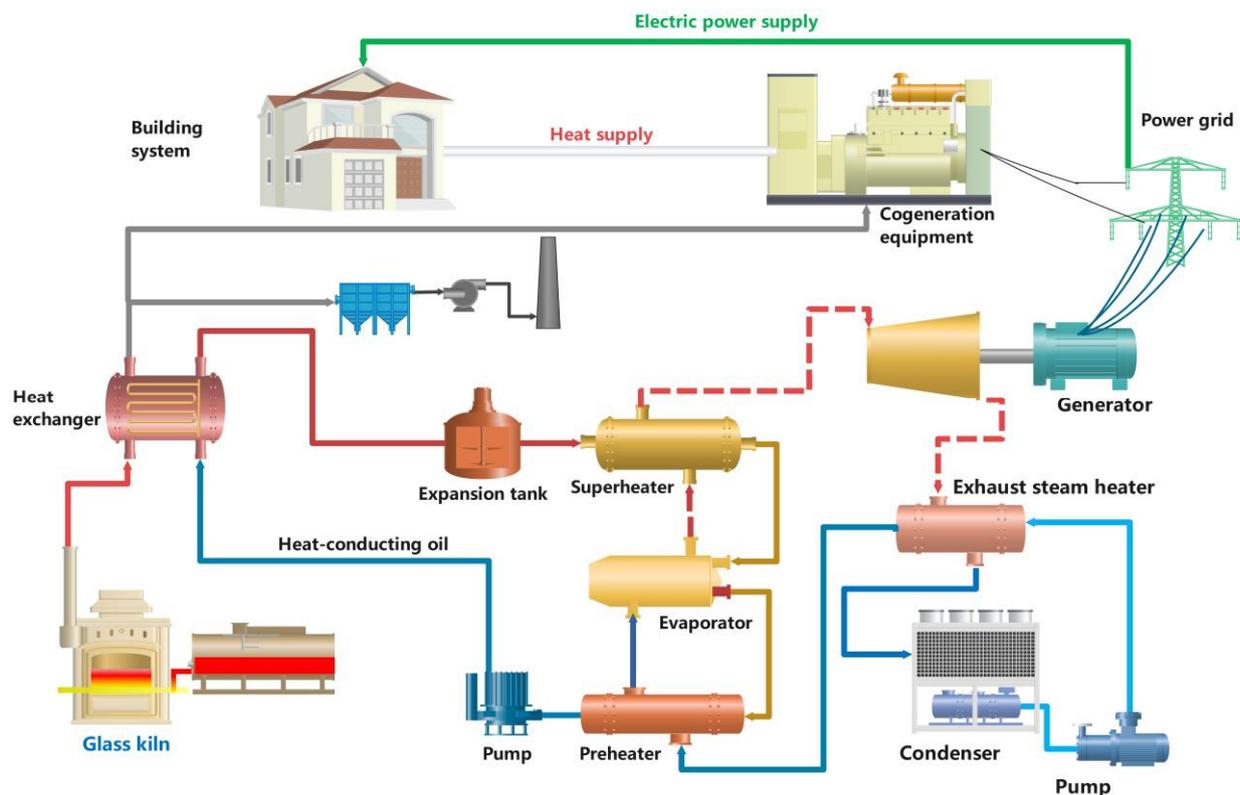


Figure 19. A new power and heat supply subsystem.

In Figure 19, a glass kiln is the energy source used to provide heat energy through a range of mechanical devices to convert it into electricity, including a heat exchanger, heat-conducting oil, pump, preheater, evaporator, super-heater, expansion tank, exhaust steam heater, condenser, pump, generator, etc. Finally, electricity is produced by the new power generation subsystem, some of which goes to the grid, and some of which goes to the cogeneration machine, where it is used to generate heat for the building system.

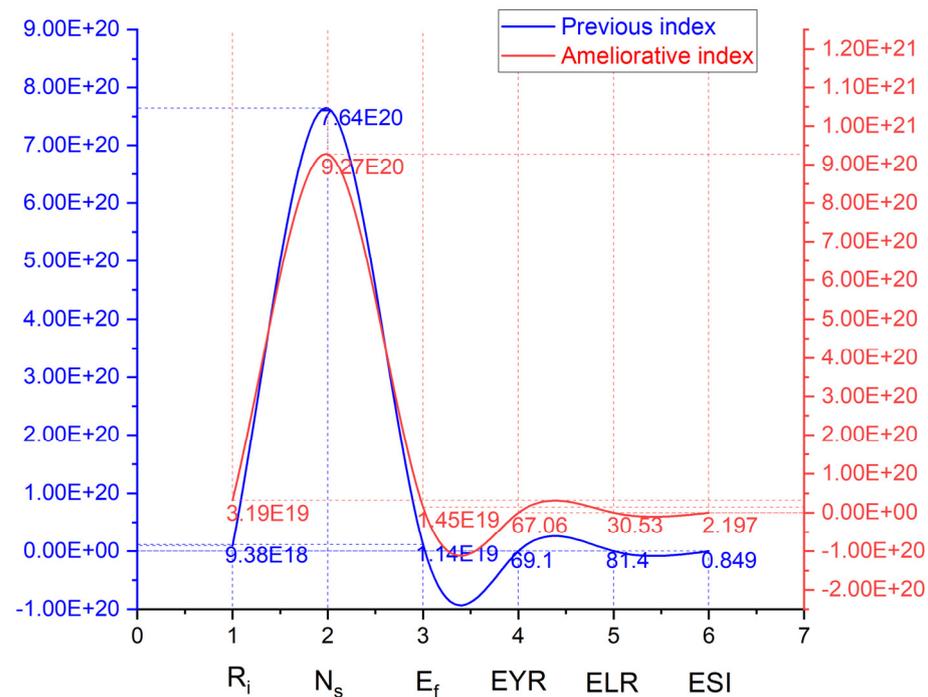
### (1) From the energy point of view

Through the data collection, the total energy of the new power and heat supply subsystem has been calculated. Thus, it provides support for the completion of the calculation of sustainability indicators in Table 12.

**Table 12.** Sustainable energy index progress.

No.	Indicators	Previous Index	Ameliorative Index	Unit
1	Renewable input ( $R_i$ )	$9.38 \times 10^{18}$	$3.19 \times 10^{19}$	Sej
2	Nonrenewable resource ( $N_s$ )	$7.64 \times 10^{20}$	$9.27 \times 10^{20}$	Sej
3	Emergy feedback input ( $E_f$ )	$1.14 \times 10^{19}$	$1.45 \times 10^{19}$	Sej
4	Emergy yield ratio (EYR)	69.1	67.06	-
5	Environmental loading ratio (ELR)	81.4	30.53	-
6	Emergy sustainability indicator (ESI)	0.849	2.197	-

Table 12 and Figure 20 clearly show the change differences between the previous index and the improved indicator. As a whole, with the new system connected, four indexes are increased, including Renewable input ( $R_i$ ), Nonrenewable resource ( $N_s$ ), Emergy feedback input ( $E_f$ ) and the Emergy sustainability indicator (ESI). The remaining two indicators are decreased (Emergy yield ratio (EYR) and Environmental loading ratio (ELR)). Although the emergy of the whole system is increased, the addition of a renewable energy system leads to an environmental pressure reduction, which enhances the sustainability effect of the whole building system. Taking the ESI as an example, the sustainability effect was significantly boosted (from 0.849 to 2.197), with an increment of 1.58 times.



**Figure 20.** Index improvement range based on the new power and heat supply subsystem.

(2) From the carbon emission point of view consider

As this subsystem is embedded in the daily operation of the building system, the carbon emission of the whole building system in the operation stage is greatly incremental, increasing carbon emissions by about 13.45%. This phenomenon explains that no matter what kind of system is embedded, carbon emissions are raised. However, from the ecosystem perspective, sustainability is improved, which is an evident distinction between the two views.

### 6. Improvement Strategies

In addition to embedding new systems, two other categories of improvement are also being explored, in terms of renewable energy reuse and alternative resource utilization.

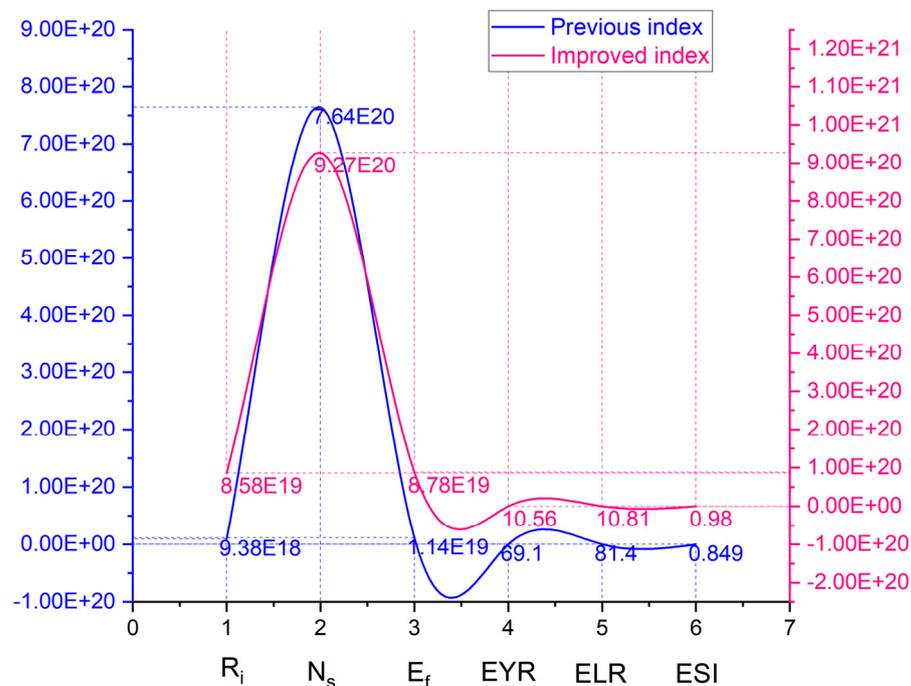
#### 6.1. Clean Energy Reuse

At present, the Chinese government is vigorously developing clean energy utilization. If a building system can adopt clean energy, it will greatly promote the sustainable level of the building system. In China, there are three main types of clean energy, which are solar energy [76,77], wind energy [78,79] and hydroelectric power energy [80,81], respectively. Among them, the use of solar energy is the most popular method.

Taking solar energy as an example to assess, if the entire building system increases energy by 10%, the related indexes will change significantly. Table 13 exhibits the changing situation. Figure 21 explains the comparison between the previous indicator and the improved index. The most meaningful change is the increase in the sustainability parameter (0.849 to 0.98 of ESI), which was enhanced by 15.43% than before. It is a clear and positive trend to illustrate that solar energy replacement is positive for the building system.

**Table 13.** Sustainable energy index progress.

No.	Indicators	Previous Index	Improved Index	Unit
1	Renewable input ( $R_i$ )	$9.38 \times 10^{18}$	$8.58 \times 10^{19}$	Sej
2	Nonrenewable resource ( $N_s$ )	$7.64 \times 10^{20}$	$9.27 \times 10^{20}$	Sej
3	Emergy feedback input ( $E_f$ )	$1.14 \times 10^{19}$	$8.78 \times 10^{19}$	Sej
4	Emergy yield ratio (EYR)	69.1	10.56	-
5	Environmental loading ratio (ELR)	81.4	10.81	-
6	Emergy sustainability indicator (ESI)	0.849	0.98	-



**Figure 21.** Index improvement range based on solar energy replacement.

In terms of a carbon emissions viewpoint, assuming that solar power emits one-tenth as much carbon as fossil fuels, it could save  $1.6 \times 10^6$  tCO<sub>2</sub> in building systems, roughly.

It accounts for about 14.05% of the total carbon emissions in the building system, with a good performance.

6.2. Alternative Resource Utilization

As the second factor for energy analysis and carbon emission evaluation in this paper, the influence of the building material phase cannot be ignored. According to the data in Appendix A, steel, cement and brick lead the role in the building material phase. Hence, the hypothesis was carried out according to their substitution. In this paper, we designed and implemented a hypothesis, as follows: how do the sustainability and carbon emissions of the entire building system change if the steel and cement materials are replaced with new renewable materials?

Table 14 lists the calculation results and Figure 22 reveals the change after the assumption. From the point of view of renewable parameters (ESI), it has a noticeable improvement, from 0.849 to 1.487, with a 42.9% advancement.

Table 14. Sustainable energy index change based on reuse material replacement.

No.	Indicators	Previous Index	Improved Index	Unit
1	Renewable input ( $R_i$ )	$9.38 \times 10^{18}$	$5.25 \times 10^{19}$	Sej
2	Nonrenewable resource ( $N_s$ )	$7.64 \times 10^{20}$	$8.75 \times 10^{20}$	Sej
3	Emergy feedback input ( $E_f$ )	$1.14 \times 10^{19}$	$3.53 \times 10^{19}$	Sej
4	Emergy yield ratio (EYR)	69.1	27.275	-
5	Environmental loading ratio (ELR)	81.4	18.339	-
6	Emergy sustainability indicator (ESI)	0.849	1.487	-

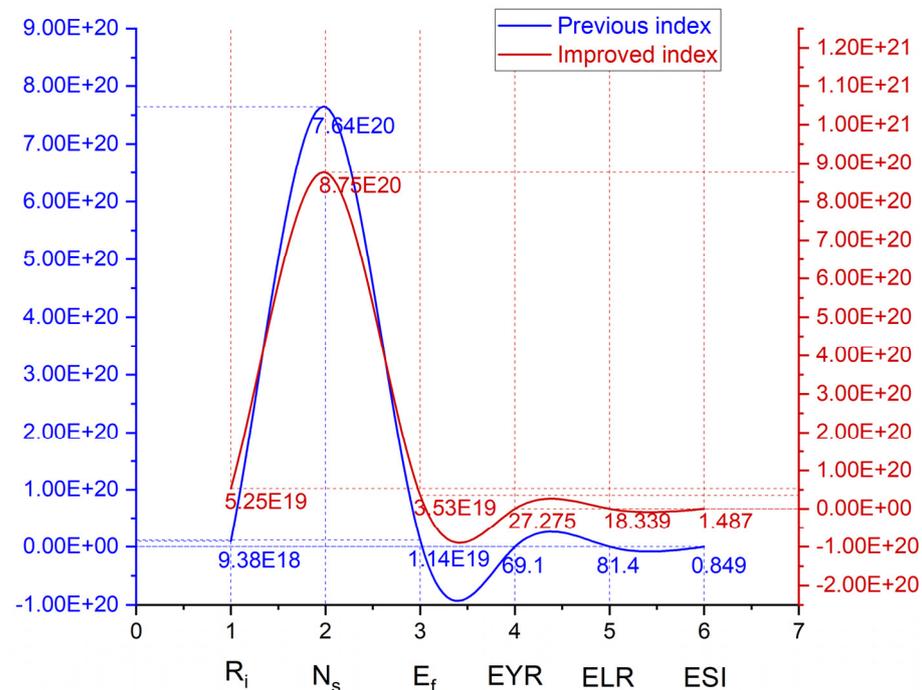


Figure 22. Index improvement range based on alternative material replacement.

In addition, many researchers have investigated alternative materials for building sustainability enhancement and carbon reduction effects. For instance, for enhancing the performance of fibers reinforced cementitious composites, a steel–basalt hybrid substitution has been considered [82]. Cement substitution has also been widely investigated and explored for cement production and cementitious composites [83,84].

## 7. The Final Discussion

From an LCA–Emergy point of view, the dominant impact element is the building operation stage, followed by the building material production stage, which is similar to study result based on the LCA–Carbon emission perspective. This clarifies that, in the long run, both the building operation stage and the building material stage are factors that cannot be ignored from the perspective of ecology or carbon emission. Meanwhile, the building renewal stage plays a subordinate effect on the basis of the LCA–Emergy and LCA–Carbon emission methods. This stage verifies the consistency of emergy and carbon emission results based on the whole life cycle consideration in the building system.

The difference is that there are a series of sustainable indicators that can display the sustainability status based on LCA–Emergy. However, in accordance with the LCA–Carbon emission view, carbon emissions at each stage can be calculated and analyzed, which cannot be used to assess a sustainable situation in view of the indicators.

At present, there is a lack of scholarly research that combines energy valuation studies with carbon emission calculations. For instance, a study conducted in Spain focused on carbon reduction in building systems from an energy renovation perspective. The analysis highlighted economic factors, inadequate owner awareness and construction sound insulation as barriers to implementing energy renovation [85]. In Romania, researchers extensively discussed the transformation of inefficient buildings into smart buildings to achieve low-carbon and high-efficiency structures [86]. A comparative analysis of energy consumption before and after the use of novel insulation materials has been conducted, contributing to the exploration of innovative energy-saving systems for buildings [87]. Utilizing the Web of Science core collection database, research related to energy and buildings has been analyzed, indicating significant interest and recognition among scholars [88].

To summarize the above study, through the LCA–Emergy–Carbon emission methodology, an integrated analysis can be realized. Ecological sustainability is considered, while carbon emissions are analyzed simultaneously. In this way, the study of the building system can be more accurate and comprehensive, so as to provide corresponding improvement strategies.

In the context of this study, the research focuses on the analysis from two perspectives: emergy valuation and carbon emissions. This provides a comprehensive assessment of sustainability for building systems, which is more advantageous compared with single-method analyses of building system sustainability. Additionally, the framework of LCA–Emergy–Carbon emission can serve as a reference for the design of building renovations. However, there are limitations to this study as well. Further research is needed to investigate the cross-research mechanisms and models of these two approaches in order to obtain more accurate sustainability results for building systems.

## 8. Conclusions

This study is aimed at the whole life cycle of building systems, using calculation and evaluation based on the emergy method and the carbon emission method, which has been shown and analyzed from the sustainability point of view.

LCA–Emergy analysis reveals the sustainable state of the building system. The building operation stage is the main emergy input item; as the primary contributor, it should be much accounted for. Meanwhile, its emergy sustainability index needs to be perfected, which can be verified using unit emergy values.

An LCA–Carbon emission exploration yields a number of similar results; for instance, the operating phase of the building system emits the most carbon, which displays an analogous outcome, and is consistent with the LCA–Emergy analysis results. However, there are also differences: although the coupling of the new energy subsystem can reduce the level of sustainability in the building system, its carbon emissions are increasing, which is contradictory from an environmental sustainability perspective.

To sum up, the LCA–Emergy–Carbon emission methodology is available, and it provides a positive reference for architects and designers. In addition to focusing on emergy

input and carbon emissions during the building operation phase, a higher level of sustainable systems does not mean a reduction in carbon emissions and requires comprehensive and adequate consideration. This provides new insights for future researchers, indicating that the assessment of sustainable building systems can go beyond the use of a single energy-based method or carbon emission approach. The integration of both approaches proves to be a viable alternative. Further research can focus on exploring the long-term sustainability indicators of building systems and utilizing machine learning techniques to predict their changing trends. This will realize the comprehensive monitoring and validation of buildings throughout their life cycle.

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### Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
BIM	Building Information Modeling
UEV	Unit Emergy Value
R <sub>i</sub>	Renewable Input
N <sub>s</sub>	Nonrenewable Resource
E <sub>f</sub>	Emergy Feedback Input
EYR	Emergy Yield Ratio
ELR	Environmental Loading Ratio
ESI	Emergy Sustainability Indicator
IPCC	Intergovernmental Panel on Climate Change

### Appendix A

**Table A1.** The emergy in the building material production stage.

Item	Data	Unit	UEVs	Emergy (sej)
Steel	$2.5 \times 10^7$	Kg	$2.1 \times 10^{12}$	$5.25 \times 10^{18}$
Cement	$4.7 \times 10^6$	Kg	$2.94 \times 10^{12}$	$1.38 \times 10^{19}$
Gravel	$1.9 \times 10^6$	Kg	$1.27 \times 10^{12}$	$2.41 \times 10^{18}$
Brick	$3.8 \times 10^6$	Kg	$2.79 \times 10^{12}$	$1.06 \times 10^{19}$
Lime	$3.1 \times 10^5$	Kg	$1.28 \times 10^{12}$	$3.97 \times 10^{17}$
Sand	$2.9 \times 10^6$	Kg	$1.27 \times 10^{12}$	$3.68 \times 10^{18}$
Water	$5.9 \times 10^5$	Kg	$2.67 \times 10^9$	$1.58 \times 10^{15}$
Iron	$6.4 \times 10^5$	Kg	$3.15 \times 10^{12}$	$2.02 \times 10^{18}$
Wood	$1.7 \times 10^6$	Kg	$6.68 \times 10^{11}$	$1.14 \times 10^{18}$
Glass	$3.5 \times 10^5$	Kg	$1.07 \times 10^{12}$	$3.75 \times 10^{17}$
Polyester	$4.6 \times 10^3$	Kg	$7.34 \times 10^{12}$	$3.38 \times 10^{16}$

**Table A1.** *Cont.*

Item	Data	Unit	UEVs	Emergy (sej)
Adhesive	$7.8 \times 10^3$	Kg	$7.25 \times 10^{11}$	$5.66 \times 10^{15}$
Bituminous	$9.1 \times 10^3$	Kg	$2.4 \times 10^{12}$	$2.18 \times 10^{16}$
Aluminum	$6.3 \times 10^3$	Kg	$9.65 \times 10^{11}$	$6.08 \times 10^{15}$
Ceramic tile	$4.7 \times 10^4$	Kg	$2.43 \times 10^{12}$	$1.14 \times 10^{17}$
Polystyrene	$5.1 \times 10^3$	Kg	$5.23 \times 10^{12}$	$2.67 \times 10^{16}$
Fly ash	$5.9 \times 10^3$	Kg	$1.78 \times 10^{13}$	$1.05 \times 10^{17}$
PVC	$7.4 \times 10^3$	Kg	$7.49 \times 10^{12}$	$5.54 \times 10^{16}$
Diesel fuel	$5.1 \times 10^{10}$	J	$1.36 \times 10^5$	$6.94 \times 10^{15}$

**Table A2.** The emergy in the building construction stage.

Item	Data	Unit	UEVs	Emergy (sej)
Environmental inputs				
Land use	$5.73 \times 10^{10}$	J	$9.42 \times 10^4$	$5.40 \times 10^{15}$
Solar	$4.31 \times 10^9$	J	$1.00 \times 10^0$	$4.31 \times 10^9$
Labor and service				
Diesel fuel	$2.35 \times 10^6$	J	$1.28 \times 10^{12}$	$3.01 \times 10^{18}$
Machinery diesel	$3.61 \times 10^6$	J	$1.27 \times 10^{12}$	$4.58 \times 10^{18}$
Transport diesel	$6.99 \times 10^6$	J	$2.67 \times 10^9$	$1.87 \times 10^{16}$
Water supply and sewage system treatment facilities				
Steel	$5.21 \times 10^6$	Kg	$3.53 \times 10^{12}$	$1.84 \times 10^{19}$
PVC	$8.41 \times 10^3$	Kg	$7.49 \times 10^{12}$	$6.30 \times 10^{16}$
Polystyrene	$2.67 \times 10^3$	Kg	$6.7 \times 10^{12}$	$1.79 \times 10^{16}$
Brass	$7.40 \times 10^3$	Kg	$1.33 \times 10^{12}$	$9.84 \times 10^{15}$
Polypropylene	$7.99 \times 10^3$	Kg	$7.49 \times 10^{12}$	$5.98 \times 10^{16}$
Glass fiber	$8.41 \times 10^3$	Kg	$2.28 \times 10^{12}$	$1.92 \times 10^{16}$
Iron	$2.93 \times 10^4$	Kg	$3.15 \times 10^{12}$	$9.23 \times 10^{16}$
Ceramic	$5.82 \times 10^5$	Kg	$2.43 \times 10^{12}$	$1.41 \times 10^{18}$
Glass	$4.21 \times 10^6$	Kg	$1.07 \times 10^{12}$	$4.50 \times 10^{18}$
Cement	$5.33 \times 10^6$	Kg	$2.94 \times 10^{12}$	$1.57 \times 10^{19}$
Water	$4.81 \times 10^4$	Kg	$2.67 \times 10^{12}$	$1.28 \times 10^{17}$
Gravel	$6.02 \times 10^4$	Kg	$1.27 \times 10^{12}$	$7.65 \times 10^{16}$
Diesel fuel	$8.98 \times 10^7$	J	$1.36 \times 10^5$	$1.22 \times 10^{13}$
Heating and cooling systems				
Steel	$4.61 \times 10^5$	Kg	$2.1 \times 10^{12}$	$9.68 \times 10^{17}$
Polypropylene	$4.78 \times 10^3$	Kg	$6.7 \times 10^{12}$	$3.20 \times 10^{16}$
Aluminum	$5.92 \times 10^3$	Kg	$9.65 \times 10^{11}$	$5.71 \times 10^{15}$
Glass wool	$9.03 \times 10^3$	Kg	$7.28 \times 10^{12}$	$6.57 \times 10^{16}$
Brass	$8.51 \times 10^3$	Kg	$1.33 \times 10^{13}$	$1.13 \times 10^{17}$

**Table A2.** *Cont.*

Item	Data	Unit	UEVs	Emergy (sej)
Copper	$8.66 \times 10^3$	Kg	$1.52 \times 10^{12}$	$1.32 \times 10^{16}$
Diesel fuel	$7.72 \times 10^6$	J	$1.36 \times 10^5$	$1.05 \times 10^{12}$
Electricity installations				
Copper	$1.34 \times 10^4$	Kg	$1.52 \times 10^{12}$	$2.04 \times 10^{16}$
Aluminum sheet	$4.82 \times 10^4$	Kg	$1.25 \times 10^{12}$	$6.03 \times 10^{16}$
Galvanized steel	$5.72 \times 10^4$	Kg	$3.53 \times 10^{12}$	$2.02 \times 10^{17}$
Steel	$9.04 \times 10^5$	Kg	$2.1 \times 10^{12}$	$1.90 \times 10^{18}$
Rubber	$6.99 \times 10^4$	Kg	$5.48 \times 10^{12}$	$3.83 \times 10^{17}$
Polyester	$7.83 \times 10^4$	Kg	$7.34 \times 10^{12}$	$5.75 \times 10^{17}$
Iron	$5.44 \times 10^4$	Kg	$3.15 \times 10^{12}$	$1.71 \times 10^{17}$
Ceramics	$6.78 \times 10^4$	Kg	$2.43 \times 10^{12}$	$1.65 \times 10^{17}$
Plastic	$9.94 \times 10^4$	Kg	$4.37 \times 10^{12}$	$4.34 \times 10^{17}$
Glass	$3.82 \times 10^4$	Kg	$1.07 \times 10^{12}$	$4.09 \times 10^{16}$
Diesel fuel	$6.91 \times 10^7$	J	$1.36 \times 10^5$	$9.40 \times 10^{12}$
Telecommunications system				
Copper	$5.63 \times 10^4$	Kg	$1.52 \times 10^{12}$	$8.56 \times 10^{16}$
PVC	$6.67 \times 10^4$	Kg	$7.49 \times 10^{12}$	$5.00 \times 10^{17}$
Aluminum sheet	$7.98 \times 10^4$	Kg	$1.25 \times 10^{12}$	$9.98 \times 10^{16}$
Plastic	$2.33 \times 10^4$	Kg	$4.37 \times 10^{12}$	$1.02 \times 10^{17}$
Brass	$4.53 \times 10^4$	Kg	$1.33 \times 10^{12}$	$6.02 \times 10^{16}$
Aluminum	$6.74 \times 10^4$	Kg	$9.65 \times 10^{12}$	$6.50 \times 10^{17}$
Glass	$8.88 \times 10^4$	Kg	$1.07 \times 10^{12}$	$9.50 \times 10^{16}$
Steel	$6.79 \times 10^4$	Kg	$2.1 \times 10^{12}$	$1.43 \times 10^{17}$
Diesel fuel	$7.78 \times 10^7$	J	$1.36 \times 10^5$	$1.06 \times 10^{13}$
Elevator system				
Steel	$2.11 \times 10^5$	Kg	$2.1 \times 10^{12}$	$4.43 \times 10^{17}$
Rubber	$5.32 \times 10^3$	Kg	$5.48 \times 10^{12}$	$2.92 \times 10^{16}$
Iron	$8.93 \times 10^3$	Kg	$3.15 \times 10^{12}$	$2.81 \times 10^{16}$
Glass	$9.06 \times 10^3$	Kg	$1.07 \times 10^{12}$	$9.69 \times 10^{15}$
Diesel fuel	$7.82 \times 10^8$	J	$1.36 \times 10^5$	$1.06 \times 10^{14}$

**Table A3.** The emergy of building operation stage.

Item	Data	Unit	UEVs	Emergy (sej)
Solar	$6.52 \times 10^{12}$	J	$1.00 \times 10^0$	$6.52 \times 10^{12}$
Electricity	$9.36 \times 10^{15}$	J	$6.39 \times 10^4$	$5.98 \times 10^{20}$
Heat	$4.81 \times 10^{12}$	J	$2.01 \times 10^6$	$9.67 \times 10^{18}$
Water	$3.31 \times 10^8$	kg	$2.67 \times 10^9$	$8.84 \times 10^{17}$

**Table A4.** The emergy of building renewal stage.

Item	Data	Unit	UEVs	Emergy (sej)
Updated Scenario 1				
PVC	$1.14 \times 10^4$	Kg	$2.22 \times 10^{11}$	$2.53 \times 10^{15}$
Cement	$4.72 \times 10^5$	Kg	$2.94 \times 10^{12}$	$1.39 \times 10^{18}$
Water	$9.52 \times 10^6$	Kg	$2.67 \times 10^9$	$2.54 \times 10^{16}$
Diesel fuel	$6.76 \times 10^6$	Kg	$1.36 \times 10^5$	$9.19 \times 10^{11}$
Updated Scenario 2				
Bricks	$5.67 \times 10^4$	Kg	$2.03 \times 10^{11}$	$1.15 \times 10^{16}$
Concrete	$3.71 \times 10^5$	Kg	$1.19 \times 10^{12}$	$4.41 \times 10^{17}$
Diesel fuel	$4.48 \times 10^6$	Kg	$1.36 \times 10^5$	$6.09 \times 10^{11}$
Updated Scenario 3				
Glass	$6.15 \times 10^4$	Kg	$1.69 \times 10^{12}$	$1.04 \times 10^{17}$
Aluminum	$2.36 \times 10^1$	Kg	$9.65 \times 10^{11}$	$2.28 \times 10^{13}$
Copper	$1.73 \times 10^1$	Kg	$1.52 \times 10^{12}$	$2.63 \times 10^{13}$
Diesel fuel	$9.24 \times 10^6$	J	$1.36 \times 10^5$	$1.26 \times 10^{12}$

**Table A5.** The emergy of building demolition stage.

Item	Data	Unit	UEVs	Emergy (sej)
Recycling section				
Glass	$5.45 \times 10^6$	Kg	$2.21 \times 10^{11}$	$1.20 \times 10^{18}$
Iron	$2.92 \times 10^7$	Kg	$2.31 \times 10^{11}$	$6.75 \times 10^{18}$
PVC	$2.23 \times 10^4$	Kg	$2.22 \times 10^{11}$	$4.95 \times 10^{15}$
Aluminum	$3.41 \times 10^4$	Kg	$2.21 \times 10^{11}$	$7.54 \times 10^{15}$
Bricks	$5.73 \times 10^4$	Kg	$2.03 \times 10^{11}$	$1.16 \times 10^{16}$
Concrete	$1.18 \times 10^6$	Kg	$1.19 \times 10^{12}$	$1.40 \times 10^{18}$
Diesel fuel	$9.21 \times 10^9$	J	$1.36 \times 10^5$	$1.25 \times 10^{15}$
Landfill emergy				
Non-recycled materials	$8.53 \times 10^6$	Kg	$2.1 \times 10^{11}$	$1.79 \times 10^{18}$
Diesel fuel	$6.75 \times 10^9$	J	$1.36 \times 10^5$	$9.18 \times 10^{14}$

**Table A6.** Various input categories based on emergy analysis viewpoint.

Renewable Part	Solar Irradiation
Non-renewable part	Materials
	Electricity
Purchased part	Water
	Gasoline and Diesel fuel
	Labor services

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