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Analysis of CarbonEmissions of HVAC Systems for Public Buildings in China based on LCA

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Abstract
With the background of global warming, the public shift towards carbon reduction in the building sector has indicated the need for a detailed analysis of carbon emissions across the whole life cycle of buildings. HVAC system is a large contributor to energy consumption and carbon emissions in public buildings, the focus of carbon emissions research about systems has been on the operational stage. To have a more comprehensive analysis of the carbon emissions of HVAC systems in public buildings, based on the theory of life cycle assessment (LCA), this paper establishes a carbon emission accounting model for HVAC system. Three typical office buildings in Guangzhou are selected as engineering cases for calculation. Result shows that the total carbon emissions of the equipment operation stage are the largest with an average share of 89.71%. The carbon emissions of the equipment disposal stage are the largest in unit time with an average share of 69.13%. The carbon emissions of the equipment production and disposal stage are analyzed, the result shows that improving the refrigerant recovery rate is helpful to alleviate short term carbon emission pressure. The establishment of the model improves the transparency of the carbon emissions of public building HVAC systems, and provides a new idea and theoretical support for the energy saving and carbon reduction of HVAC systems.

Keywords: *Life cycle assessment, Carbon emissions,Publicbuildings, HVAC systems*

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I. INTRODUCTION

The impact of climate warming is increasing[1], how to effectively reduce carbon emissions has become a global research hotspot. According to statistics, the building sector consumes 36% of global energy and produces 39% of carbon emissions[2]. In China, air conditioning and heating account for about 65% of total building energy consumption[3]. As the world's largest country of carbon emissions, China is committed to energy saving and carbon reduction and proposed a "double carbon" strategy in 2020. Under this background, the energy saving standards of public buildings have been rising and carbon emission accounting is the first step to energy saving and carbon reduction. In 2019, the Ministry of Housing and Urban-Rural Development (MOHURD) introduced for the first time *the Carbon Emission Calculation Standard for Buildings* (GB/T51366-2019), which regulated the carbon emission calculation standard for buildings. And *the General Specification for Energy Efficiency and Renewable Energy Utilization in Buildings* (GB55015-2021), which has been implemented from April 1, 2022, made building carbon emission accounting become a mandatory rule. The HVAC system is one of the key targets for energy saving and carbon reduction.

To reduce carbon emissions of HVAC systems, it is essential to analysis the entire life cycle. A well-established method to evaluate the environmental impact of a building's life cycle is life cycle assessment (LCA). LCA is considered a promising tool for gaining a comprehensive understanding of potential energy consumption, carbon emissions and environmental impact by defining the scope of analysis of an object over its life cycle. With the standardization of LCA theory by ISO in 2006, LCA has been developing in the construction industry[4]. In general, there are two types of LCA studies for HVAC systems. The first type of study compares between two or more systems to determine which system has a lower environmental impact, or to assess the influences of parameters such as energy mix and climatic conditions on the environmental impact[5]. These studies focus on stages with a large share of energy consumption, such as equipment operation stage, a detailed assessment is not needed. The second type of study is the detailed assessment of systems[6]. One of the main objectives of these studies is to improve the transparency of the environmental impact of HVAC systems and to avoid errors caused by the neglect and simplification of data, this type of study is few because of high demand of data.

For public buildings, carbon emissions during the operation stage account for more than 70% of the whole life cycle carbon emissions[7]. Of which, the vast majority of the carbon emissions are contributed by building energy systems such as HVAC systems, lighting and elevator systems. However, due to the wide variety of system equipment, it is not easy to count the equipment material data. So very few LCA studies include detailed calculation. The existing studies mostly regard the building HVAC systems as part of the building to calculate carbon emissions. Compared to the building envelope, the material consumption of building HVAC systems is small, in addition to the equipment operation stage, carbon emissions of the other stages are not considered[8]. But from a whole life cycle perspective, if only part of the life cycle is considered, there is a risk that the focus to carbon emission reduction is shifted to another part of the life cycle. Meanwhile, it also leads to the lack of scientific basis for building energy saving design and renovation. In order to have a more comprehensive analysis of the carbon emissions of building HVAC systems, this paper calculates carbon emissions quantitatively based on the LCA theory for a complete life cycle from material production to waste disposal, providing a new perspective to analyze the energy saving and carbon reduction of building HVAC systems.

II. METHODOLOGY

2.1 Goal and scope

The goal of the study was to quantify the life cycle carbon emissions of building HVAC systems and identify the influencing factors. The research boundary for the study is shown in Fig.1, including the equipment production stage, the equipment transportation stage, the equipment construction stage, the equipment operation stage, and the equipment disposal stage. In this study, the greenhouse gases consist of CO_2, CH_4, N_2O and refrigerant gases. The calculation results are converted by 100-year Global Warming Potential (GWP) to CO_2. Using the carbon emission factor as a functional unit, the carbon emission factor characterizes the carbon emissions from the production or use of a unit material or energy at a certain life cycle stage.

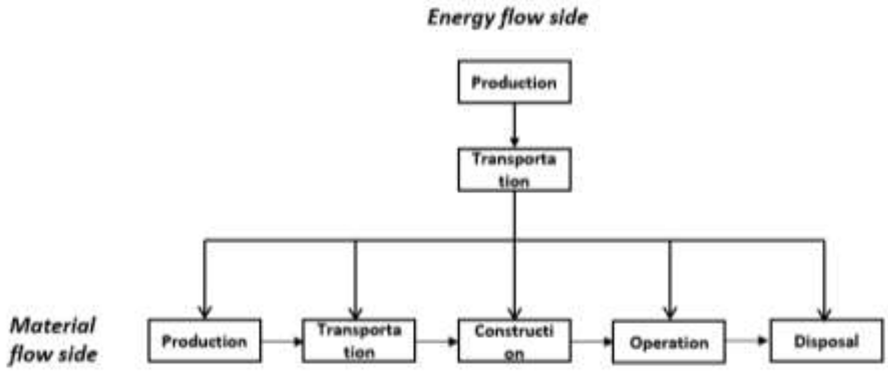

Figure 1.Life cycle research boundary

2.2 Life cycle carbon emission accounting model

2.2.1 Equipment production stage

The equipment production stage carbon emissions consist of carbon emissions from the energy and material consumed, which are based on the following equation:

$$C_P = \sum_n \sum_j G_{n,j} \cdot C_j + \sum_n \sum_k G_{n,k} \cdot C_k (1)$$

Where C_P is the carbon emissions of the equipment production stage ($kgCO_2$). $G_{n,j}$ is the is amount of the material j consumed to produce the equipment n (kg). C_j is the carbon emission factor of material j ($kgCO_2$/kg), $G_{n,k}$ is the amount of the energy k consumed to produce the equipment n (unit). C_k is the carbon emission factor of energy k($kgCO_2$/unit).

2.2.2 Equipment transportation stage

Carbon emissions of the equipment transportation are from the energy consumption, which can be calculated as follows:

$$C_T = \sum_n \sum_l G_n \cdot \sigma_{n,l} \cdot \varphi_{n,l} \cdot D_l \cdot \mu_l (2)$$

Where C_T is the carbon emissions of the equipment transportation stage ($kgCO_2$), G_n is the weight of the equipment n (kg).$\sigma_{n,l}$is the percentage of equipment n by the mode l of transportation, $\sum \sigma_{n,l} = 1$. $\varphi_{n,l}$is the transport intensity per unit mass of equipment n by the mode l of transport ($kgCO_2$/(km·kg)). D_l is the transport distance of equipment n by mode l (km). $\mu_l$is the idle rate of the mode l of transport.

2.2.3 Equipment construction stage

The carbon emissions of the equipment construction stage consist of the carbon emissions form the material consumption, energy consumption and workers, which can be calculated as the follows:

$$C_c = \sum_j S_j \cdot C_j + \sum_i \sum_t N_{i,\ t} \sum_k G_{t,\ k} \cdot C_k + n_{wo} \cdot C_{wo} \quad (3)$$

Where C_c represents carbon emissions during the equipment construction stage ($kgCO_2$). S_j is the amount of the material j consumed to construct the equipment (kg). $N_{i,\ t}$ is the amount of the type i machinery table consumed to install and disposal the equipment n. $G_{t,\ k}$ is the amount of the energy k consumed of unit type j machinery table (kg or kwh). n_{wo} is total construction days (day). C_{wo} is the carbon emissions of unit worker living ($kgCO_2$/day). Others are above.

2.2.4 Equipment operation stage

The carbon emissions during equipment operation stage produced by the energy consumption of equipment operating, refrigerant leakage, which can be calculated as follows：

$$C_o = \sum_n \sum_k t \cdot W_{n,\ k} \cdot C_k + G_r \cdot \alpha \cdot \omega \cdot \tau \quad (4)$$

Where C_o represents carbon emissions during the equipment operation stage ($kgCO_2$). t is the full load operation time (h). $W_{n,\ k}$ is the amount of the energy k consumed to operate the equipment n (unit/h). G_r is the refrigerant charge quantity (kg). α is the annual refrigerant leakage rate. ω is the GWP value of refrigerant. τ is the operation time of refrigeration equipment (year). Others are above.

2.2.5 Equipment disposal stage

The carbon emissions during the equipment disposal stage are produced by the leakage of uncollected refrigerant, the energy consumption of transportation and solid waste landfill and the production of energy,which can be calculated as follows:

$$C_D = \sum_n \sum_j G_{n,j} \cdot \gamma_j \cdot D \cdot \beta \cdot \mu + \sum_n \sum_j G_{n,j} \cdot \left(1 - \gamma_j\right) \cdot \varphi_j / \rho_j + G_r \cdot \omega \cdot (1 - \varepsilon) \quad (5)$$

Where C_D represents carbon emissions during the equipment disposal stage ($kgCO_2$). γ_j is the recovery rate of the material j. D is the transport distance of the recycle materials (km). β is the transport intensity per unit mass ($kgCO_2$/(km·kg)). μ is the idling rate of transportation. φ_j is is the carbon emissions from solid waste landfills per unit volume ($kgCO_2/m^3$). ρ_j is the density of material j (kg/m^3). ε is the refrigerant recovery rate. Others are above.

III. CASE STUDY

3.1 Basic information for cases

The methodology described above was applied for the carbon emissions of inventory analysis of 3 office building cases in Guangzhou, China. The design life of HVAC system is 20 years. Maintenance and replacement of equipment is neglected. The basic information is presented in Table 1.

Table 1.Basic information for the three office building cases

Item	Case1	Case2	Case3
Story number	7	11	5
Gross floor area (m^2)	14753	13260	4524
Total height (m)	19.1	35.8	12.8
Building structure	Reinforced concrete	Steel	Brick concrete
Window to wall ratio	0.4	0.5	0.3
Building design life (a)	70	70	50
Form of air-conditioning	Fan coil	Fan coil	Fan coil
Cold source	Water-cooled chiller	Underground pipe heat pump	Wind-cooled chiller
Cop of the cold source	5.36	6.28	3.89

3.2 Data collection

Data collection is a difficult part of the study, for the equipment production stage, data are collected by literature and standard researching, telephone and visiting. For the equipment transportation stage, the underlying data origin from China Traffic Statistics Yearbook in 2014. The energy consumption during the equipment operation can be calculated by the simulation results from Energy plus based on Design Code for Heating, Ventilation and Air Conditioning of Civil Buildings (GB50736-2012) and Code for Green Design of Civil Buildings (JGJ/T229-2010). The data of equipment construction stage and equipment disposal stage are obtained through the engineering projects in China. In this study, the annual leakage rate of refrigerant is set to 6%[9], the recovery rates of metal material, plastic material and refrigerant are 90%, 30% and 30% [10]. The carbon emissions factor of the material and energy are form the official data.

IV. RESULTS AND DISCUSSION

4.1 Unit selection

Because of the difference in gross floor area, unit floor area carbon emissions is used as unit ($kgCO_2/m^2$).

4.2 Carbon emissions of the life cycle stage

The calculation result shows that the total life cycle carbon emissions of case 1, case2, case3 are 478.2 $kgCO_2/m^2$, 558.9 $kgCO_2/m^2$ and 572.4 $kgCO_2/m^2$. The carbon emissions of each life cycle stage are illustrated in Fig.2. It is obvious that the carbon emissions during the equipment operation stage are much higher than others.

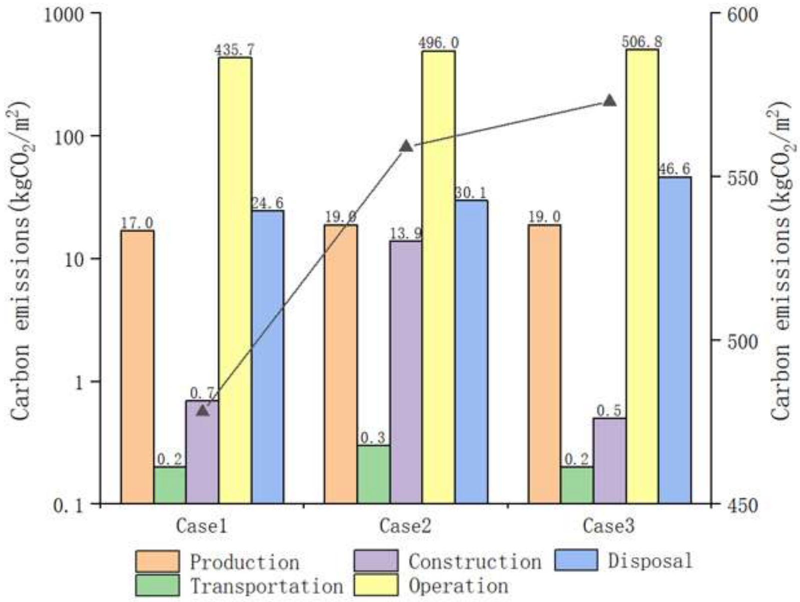

Figure 2. Carbon emissions of each life cycle stage and total life cycle

Fig.3 shows the proportions of 3 cases' life cycle carbon emissions, it can be seen that carbon emissions during the equipment operation stage account for 89.71% of the total life cycle carbon emissions while the proportions of the equipment disposal and the equipment production are 5.70% and 3.39%.Of which the high carbon emissions of the equipment construction stage in Case 2 illustrate that the huge material and energy consumption of the construction of the underground pipe system. The key direction of energy saving and carbon reduction of building HVAC systems is in the equipment operation stage. There are two general directions of energy saving and carbon reduction for the equipment operation, one is improving building maintenance structure to reduce the load [11]. The other one is improving equipment energy efficiency to reduce energy consumption [12].

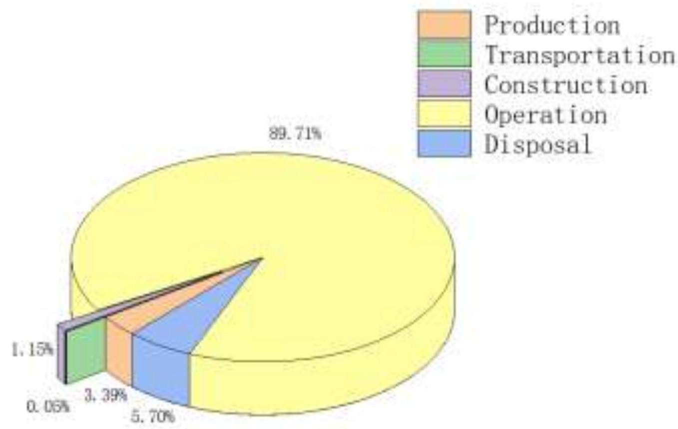

Figure 3. Proportions of 3 cases' life cycle carbon emission

4.3 Carbon emissions per unit time of the life cycle stage

The duration of each life cycle stage of building HVAC systems varies greatly. Take the example of an energy system with a design life of 20 years, it takes 6 months and 4 months to complete the production and construction of the equipment, and the time spent to transport and disposal the equipment is 1 month and 2 months. Hence, there is a limitation to reduce carbon emissions by studying total carbon emissions of each stage. For a more scientific comparative analysis, the total carbon emissions of each life cycle stage are divided by the time spent, carbon emissions per unit time of the life cycle stage are calculated, the result shows in Fig.4 and Fig.5.

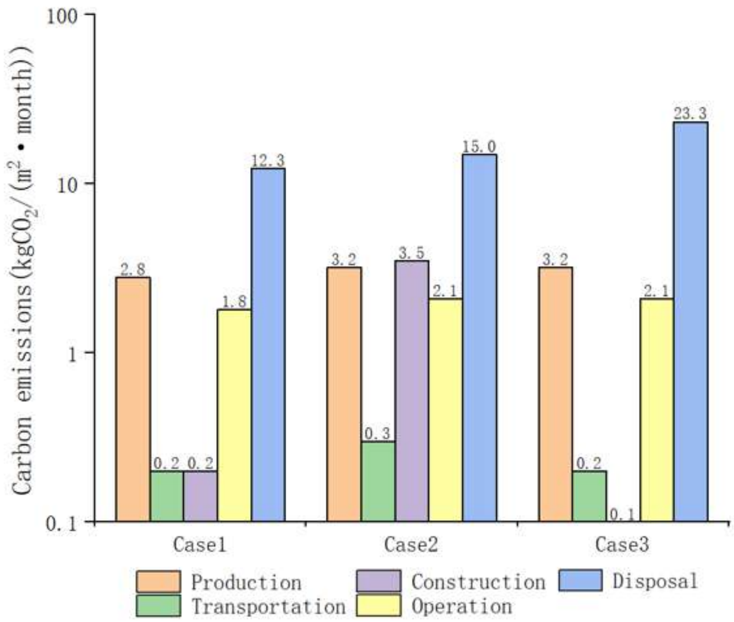

Figure 4. Carbon emissions per unit time of each life cycle stage

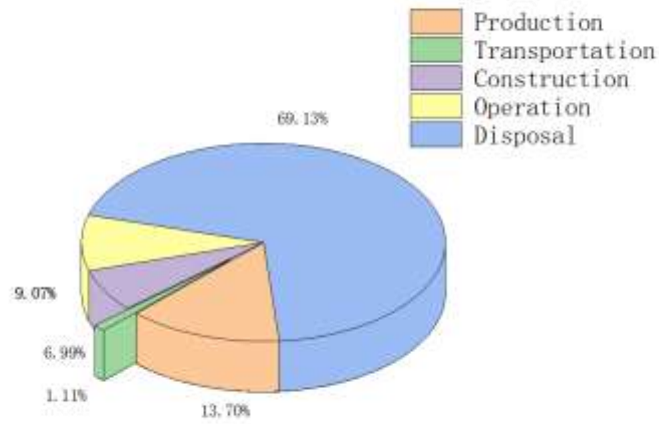

Figure 5. Proportions of 3 cases' life cycle carbon emission per unit time

The result shows that the life cycle stage with highest carbon emissions within a month is the equipment disposal stage, which accounts for 69.13%. The equipment production stage ranks second with 13.70%. Yet, the equipment operation stage with the highest total carbon emissions in the whole life cycle only accounts for 9.07%. The proportions of the equipment transportation and construction are 6.99% and 1.11%. There is a need to analyze carbon emissions during the equipment production stage and equipment disposal stage.

4.4 Analysis of Carbon emissions during the equipment production stage

To analysis the detailed carbon emissions of the equipment production stage, Fig.6 shows the carbon emissions of the production of each material and the processing of equipment. It can be seen that the production of metal materials produces nearly 90% of the carbon emissions in the equipment production stage. Of which, various steel materials account for more than 60% carbon emissions while copper and aluminum account for about 14% and 6%. Therefore, improving the production technology to reduce the metal material carbon emission factor will be helpful to decrease the carbon emission in the equipment production. Metal smelting has a long history, the current carbon reduction measures for metal material production include increasing the proportion of steel slag recycling, improving energy efficiency and product yield[13].

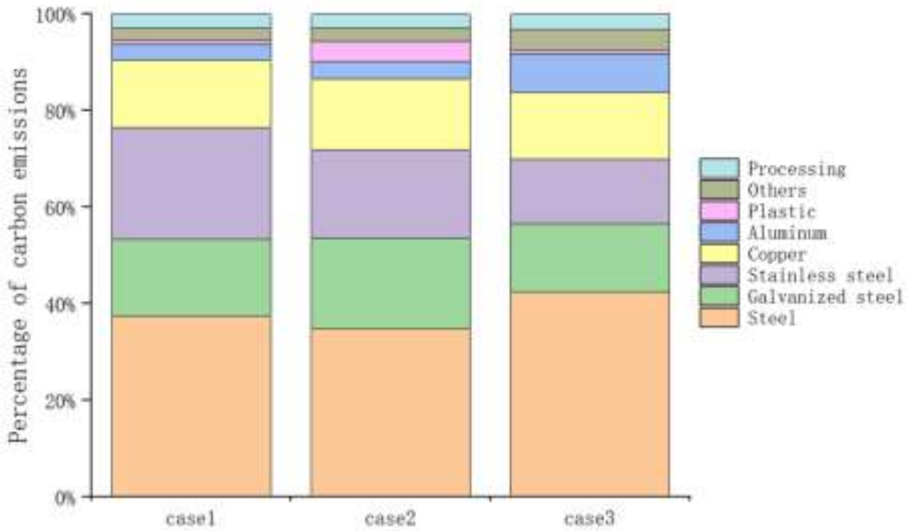

Figure6. Proportions of carbon emissions during the equipment production stage

4.5 Analysis of Carbon emissions during the equipment production stage

According to Eq.(5), transportation and landfill, refrigerant leakage are two sources of carbon emissions during the equipment disposal stage. Table 2 shows the detailed carbon emissions of the equipment disposal stage, it can be got that almost all carbon emissions origin from the refrigerant leakage, and they are positively correlated with the amount of refrigerant. Refrigerant with high GWP value leaks into the atmosphere in a short time, this caused the equipment disposal stage carbon emissions in per unit time are much higher than other stages. To reduce the carbon emissions during the equipment disposal stage, the key is to decrease the refrigerant leakage.

Table 2.Carbon emissions of the equipment disposal stage

Item	Case1	Case2	Case3
Transportation＆landfill ($kgCO_2/m^2$)	0.14	0.15	0.17
Refrigerant leakage ($kgCO_2/m^2$)	24.48	29.90	46.42

Fig.7 shows the carbon emissions of the equipment disposal stage with different refrigerant recovery rates, the dashed line represents the average carbon emissions of 3 cases' equipment operation stage. It can be seen that when the refrigerant recovery rate is 30%, the carbon emissions of the equipment disposal within a month is much higher than that of the equipment operation stage. If the refrigerant recovery rate is increased to 90%, the carbon emissions of both stages will be almost equal. Therefore, the recovery rate of refrigerant has great influence on alleviating short-term carbon emission pressure. However, compared with developed countries such as Japan and America, there is a big gap in the volume and proportion of refrigerant recovery in China[10]. The main reasons include imperfect top-level design of the system, unsound technical standards for recovery and reuse, and weak awareness of the main responsibility of recovery enterprises, which make it difficult to establish a sustainable refrigerant recovery industry chain. These are the problems that the Chinese government needs to solve on the way to achieve the goal of carbon neutrality and carbon peaking.

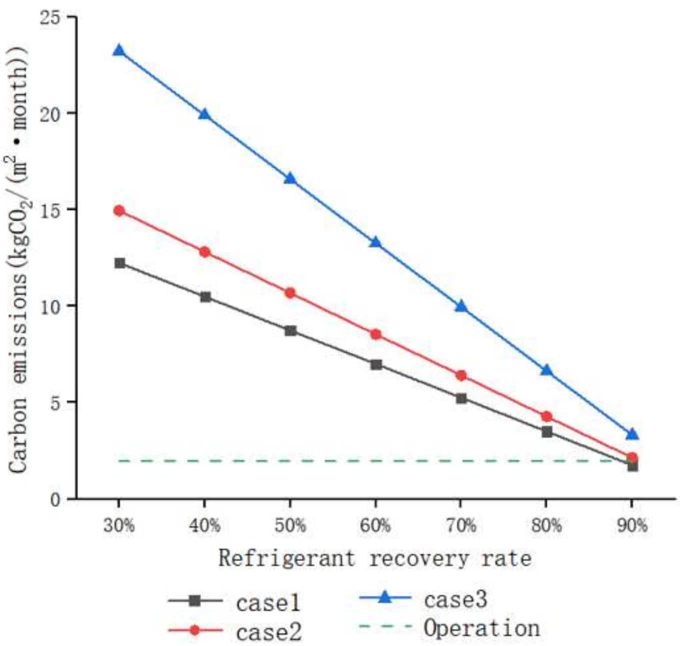

Figure 7.Carbon emissions of the equipment disposal stage with different refrigerant recovery rates

V. CONCLUSION

In an effort to have a more comprehensive analysis of the carbon emissions of HVAC systems in public buildings, based on the life cycle assessment (LCA) method, this paper established a carbon emission accounting model for the HVAC systems of public building. Three office buildings in Guangzhou, China, were selected as case studies for validating the model. The following conclusions were drawn:

(1)The life cycle of the HVAC systems was divided into the equipment production stage, the equipment transportation stage, the equipment construction stage, the equipment operation stage, and the equipment disposal stage.

(2)The total life cycle carbon emissions of 3 case are 478.2 $kgCO_2/m^2$, 558.9 $kgCO_2/m^2$ and 572.4 $kgCO_2/m^2$, of which carbon emissions during the equipment operation stage account for the most part, with an average proportion of 89.71%. The equipment disposal stage (5.70%) and equipment production stage (3.39%) are the second and third largest contributors to carbon emissions. Thus sufficient attention will still be paid on the equipment operation stage, reducing load and improving energy efficiency are two effective ways to reduce the carbon emissions of HVAC systems in public building.

(3)The different duration of each life cycle stage was considered, the calculation result shows that within a month, the carbon emissions during the equipment disposal stage are much higher than other stages with an average proportion of 69.13%. The equipment production stage ranks second with 13.70% while the equipment operation stage with the highest total carbon emissions only accounts for 9.07%.

(4)For the carbon emissions during the equipment production stage, more than 90% of which are produced by the production of metal materials. The production of steel, galvanized steel and stainless steel are three largest carbon sources.

(5)For the carbon emissions during the equipment disposal stage, more than 99% of which were produced by the refrigerant leakage. Increasing the recovery rate of refrigerant is a good method of alleviating short-term carbon emission pressure.

In summary, the establishment of the model and case study provide a clear quantitative analysis of the carbon emissions of HVAC systems in public buildings and make building energy retrofits more purposeful and directional, so to build a more sustainable living environment.

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