Analysis of Carbon Emission Characteristics Over the Entire Life Cycle of Indoor Substation Structures

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Abstract. As a key infrastructure in the power industry, substations play an important role in achieving the strategic goal of "dual carbon", and their sustainable development concept radiates to the entire field of structural buildings and ecological buildings. Based on a systematic review and in-depth analysis of carbon emissions across the entire life cycle of substations, this paper, in combination with the characteristics of substation projects, analyzed the boundaries for carbon emission calculations and carbon emission accounting methods. It calculates the carbon emissions over the entire life cycle and compares and analyzes the carbon emissions under different structural forms. The study finds that the carbon emissions during the operation phase dominate, accounting for as much as 54% in the entire life cycle of substation. Furthermore, steel-structured substations reduce carbon emissions by approximately 10% compared to concrete structure substations. Considering energy conservation and emission reduction comprehensively, steel structure substations are superior to concrete structure substations. The research results not only provided strong data support and theoretical basis for the low-carbon design, construction and operation of substation, but also contributed to the energy conservation and emission reduction in the construction industry, civil engineering and hydraulic engineering field.

1 Introduction

In recent years, scholars have made a lot of achievements in the study of key issues related to the carbon emission management of the substation and the power industry throughout the life cycle. These achievements not only promote the green development of the power industry, but also are closely linked to the concepts of ecological architecture, sustainable development and structural construction [1-2]. In terms of life cycle management, Jin et al. [3] used sensitivity analysis to study the life cycle cost of offshore wind power projects, and their research methods and results provided useful references for the field of ecological construction and sustainable development. Zeng et al. [4], aiming at the goal of green and low-carbon construction and operation of substation, proposed to promote green and low-carbon transformation in the aspects of substation building system, auxiliary energy supply and energy-saving equipment, which not only helps to reduce the carbon emissions of traditional substation (which can be reduced by 19.3%), but also promotes the development of structural buildings in a more environmentally friendly and sustainable direction.

Based on the life-cycle cost of electrochemical energy storage, Wang et al. [5] studied the economy of energy storage participating in auxiliary service of power frequency regulation, providing a reference for the construction of frequency modulation energy storage projects and a new idea for the energy management of ecological buildings. Yuan et al. [6] Based on the LCC theory, combined with the actual situation of substation equipment, and based on the life-cycle cost of equipment operation, the decision analysis of equipment updating and upgrading was made, and the economic transformation plan of substation was proposed. In terms of carbon emission management and countermeasures to adapt to the requirements of "dual carbon", scholars' research has more deeply integrated the concept of ecological architecture and sustainable development. He et al. [7] designed the carbon emission calculation framework for the whole life cycle of the substation by using Monte Carlo simulation method, and measured the carbon emissions in the four stages of materialization, construction, operation and demolition of the substation. This framework provided a scientific basis for carbon emission management in the field of ecological building. In view of the high proportion of renewable energy equipment and power electronic equipment in the power system, Ding et al. [8] put forward technical paths to meet the needs of low-carbon development from the aspects of research and development, design, manufacturing and application of new equipment. These technical paths not only contribute to the low-carbon transformation of the power system, but also provide technical support for the green upgrade of structural buildings. Zhu et al. [9] proposed an assessment method for substation carbon emissions based on the green concept, starting from the four stages of substation materialization, transportation, construction and operation and maintenance. Wang et al. [10] identified the factors affecting carbon emissions during the whole life cycle of

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substation buildings, analyzed the energy saving and emission reduction potential of each stage, and proposed corresponding low-carbon strategies. These strategies not only contributed to the low-carbon development of substation, but also provided beneficial references for energy saving and emission reduction of ecological buildings and structural buildings.

Based on the background of the implementation of the "dual-carbon" strategic goal and the requirements of The Times of low-carbon transformation of substations, this paper analyzes the carbon emissions of substations with different structural forms under the "dual-carbon" goal from the perspective of the whole life cycle of substations, and puts forward suggestions for the low-carbon development of substations in combination with the concept of ecological architecture and sustainable development. These proposals aim to promote the realization of the "dual carbon" goal of the power industry, while promoting the sustainable and collaborative development of substation structural buildings in the direction of ecological buildings.

2 Calculation method for carbon emissions of substations

2.1 Boundary conditions

The bottom-up model [11] based on carbon emission analysis is commonly used for carbon emission estimation. Lifecycle assessment (LCA) is a comprehensive environmental impact assessment technique and methodology system, known as the "cradle-to-grave" approach. The study divided the life cycle into seven stages, namely building materials production, building materials transportation, construction, operation stage and demolition stage, all of which involved resource and energy consumption, waste gas and waste water discharge and solid waste.

2.2 Calculation model

Carbon footprint is a comprehensive analysis method for accounting carbon emission sources and quantities throughout the lifecycle of the study object [12]. The carbon footprint of a substation refers to the accounting of carbon sources and carbon emissions throughout its lifecycle [13]. Emission factor method is used to construct the calculation model. The carbon emission factor data mainly refer to GB/T51366-2019 [14], and the specific calculation formula was shown in Eq. (1):

$$E = \sum Q \times EF \tag{1}$$

where E is the CO2 emissions; Q is the activity level, which quantifies the activities that cause greenhouse gas emissions; and EF is the emission factor, which is the amount of CO2 emitted per unit of activity level.

The calculation model for the full lifecycle of a building includes the material production stage, material transportation stage, construction stage, operation stage, maintenance stage, demolition stage, and waste recovery stage. The calculation formula for this is shown in Eq. (2):

$$C_{\mathrm{lc}} = C_{\mathrm{mp}} + C_{\mathrm{mt}} + C_{\mathrm{co}} + C_{\mathrm{op}} + C_{\mathrm{de}} \tag{2}$$

where Clc is the total carbon emissions over the full lifecycle of the building (kgCO2); Cmp is the carbon emissions during the material production stage (kgCO2); Cmt is the carbon emissions during the material transportation stage (kgCO2); Cco is the carbon emissions during the construction stage (kgCO2); Cop is the carbon emissions during the operation stage (kgCO2); and Cde is the carbon emissions during the demolition stage (kgCO2).

3 Calculation method for carbon emissions of concrete structure substation

3.1 Project overview

The 220kV Chunxi Substation is located in Nanjing City, Jiangsu Province. The substation has two floors above ground and one floor underground, with a total building area of 4209m^2 and a design service life of 50 years. The Chunxi Substation adopts an indoor layout, with main buildings including the power distribution equipment building, fire pump room, and auxiliary rooms. The power distribution equipment building has one floor above ground and is of concrete frame structure, including 110kV GIS room, 220kV GIS room, 10kV power distribution and assembly room, secondary equipment room, battery room, capacitor room, reactor room, etc. The auxiliary rooms are also of concrete frame structure, housing a guard room, fire control room, etc.

3.2 Carbon emission characteristics of concrete structure substation

3.2.1 Carbon emission in the material production and transportation stage

Carbon emissions during these stages were calculated based on the consumption of building materials, with corresponding emission factors taken from GB/T51366-2019 [14]. The consumption of building materials is set according to the substation design plan, material procurement list, etc. Carbon emissions during the transportation stage were obtained by multiplying the quantity of building materials, transportation distance, and carbon emission factor per unit distance. The main building materials used and their carbon emissions were shown in Table 1.

Based on the above consumption and corresponding production carbon emission factors, the total carbon emissions from production and transportation were approximately 8407 tCO_2, with production carbon emissions accounting for 97% of this stage and transportation carbon emissions accounting for 3%.

Table 1. Carbon Emissions from Building Material Production and Transportation**.**

Materials	Consumption	Unit	Carbon emissions in the Production /tCO_2	Carbon emissions in the transportation /tCO_2
Steel	1640	t	3905	27
Concrete	10389	m^3	3584	168
Cement mortar	321	t	236	6
Iron pieces	24	t	55	0.4
Rubble	785	t	4	13
Window	203	m^2	52	0.02
Bricks	80	m^3	28	3
The door	213	m^2	37	0.01
Sand	877	t	6	14
Water Pipes	22	t	181	0.4
Paint	24	t	85	0.4
Plaster	0.97	t	3	0.01
Asbestos	0.14	t	1	0.002

3.2.2 Carbon emission in the construction stage

The energy consumption method for construction processes is adopted to estimate energy consumption during this stage [15], combined with the substation construction engineering plan [16], to obtain the energy consumption for this stage. The consumption of gasoline, diesel, and electricity was 0.087t, 1.263t, and 4766kW·h, respectively, resulting in carbon emissions of 804tCO_2 for this stage.

3.2.3 Carbon emission in the operation stage

Carbon emissions during the operation stage are calculated based on electricity consumption, which includes the power used by equipment, lighting, ventilation, air conditioning, etc. Using the power of the substation to calculate the electricity consumption, the electricity consumption includes the equipment, lighting, ventilation and air condition in the substation, the average annual electricity consumption for equipment is 250300kW·h, 30000kW·h, 8700kW·h, and 102800kW·h, respectively. With a design service life of 50 years for the substation, the carbon emissions during the operation stage are approximately 12056.92tCO_2.

3.2.4 Carbon emission in the demolition stage

Carbon emissions during the demolition stage include those from demolition construction, waste transportation, and negative carbon from material recycling. Using a method similar to that of the construction stage, carbon emissions were obtained by multiplying the quantity of each material, transportation distance, and transportation factor coefficient. The carbon emissions during the demolition stage were 1085.43tCO_2.

4 Calculation method for carbon emissions of steel structure substation

4.1 Project overview

The 220kV Torch Substation is located in Suzhou City, Jiangsu Province. The substation has two floors above ground and one floor underground, with a total building area of 3230 m^2 and a design service life of 50 years. The substation adopted an indoor layout, with core buildings including the power distribution equipment building, fire pump room, and auxiliary facilities room. The power distribution equipment building has one floor above ground and adopted a steel structure frame as its structural support. It was subdivided into multiple functional areas such as 110kV and 220kV (GIS) rooms, 10kV power distribution equipment assembly room, secondary equipment monitoring room, battery storage room, capacitor room, reactor room, etc. The auxiliary facilities room was also constructed with a steel structure frame, housing key departments such as the security guard room and fire command center.

4.2 Carbon emission characteristics of steel structure substation

4.2.1 Carbon emission in the material production and transportation stage

During the calculation of carbon emissions, classification was based on the consumption of building materials, with carbon emission factors taken from GB/T51366-2019 [14]. The consumption of building materials was derived from the substation design plan, material procurement list, and other documents. For carbon emissions during the transportation stage, they were obtained by multiplying the usage of building materials, transportation distance, and carbon emission factor per unit distance. The main building materials used and their carbon emissions are shown in Table 2.

Table 2. carbon emissions from production and transportation of building materials.

Materials	Consumption	Unit	Carbon emissions in the Production /tCO_2	Carbon emissions in the transportation /tCO_2
Steel	1765	t	4202	29
Concrete	7041	m^3	2429	114
Cement mortar	991	t	728	16
Iron pieces	27	t	63	0.4
Rubble	9836	t	43	159
Window	141	m^2	36	0.02
Bricks	97	m^3	33	4
The door	189	m^2	32	0.01
Sand	4058	t	27	66
Water pipes	3	t	26	0.05
Paint	5	t	19	0.09
Plaster	0.7	t	2	0.01
Asbestos	1.3	t	3	0.02

Based on the above consumption and corresponding production carbon emission factors, the total carbon emissions from production and transportation were approximately 8032tCO_2. Among them, production carbon emissions account for 95% of this stage, while transportation carbon emissions account for 5%.

4.2.2 Carbon emission in the construction stage

The energy consumption method for construction processes was adopted to estimate energy consumption during this stage, combined with the substation construction engineering plan, to obtain the energy consumption for this stage. The consumption of gasoline, diesel, and electricity is 0.055t, 1.284t, and 3746 kW·h, respectively, resulting in carbon emissions of 919tCO_2 for this stage.

4.2.3 Carbon emission in the operation stage

The carbon emissions during the operation stage of the substation are determined by calculating its electricity consumption, which covers the energy consumption of equipment, lighting, ventilation, and air conditioning systems. According to the design plan, the average annual electricity consumption of the substation's equipment is 200200kW·h, the lighting system is 18000kW·h, the ventilation system is 8700kW·h, and the air conditioning system is 85100kW·h. Considering the design service life of the substation to be 50 years, the total carbon emissions during the operation stage can be calculated to be approximately 10086.14tCO_2.

4.2.4 Carbon emission in the demolition stage

Carbon emissions during the demolition stage include those from demolition construction, waste transportation, and negative carbon from material recycling. Using a method similar to that of the construction stage, carbon emissions are obtained by multiplying the quantity of each material, transportation distance, and transportation factor coefficient. The carbon emissions during the demolition stage were 1007.65tCO2.

5 Comparative analysis of carbon emissions between concrete and steel structure substations

After aggregating and analyzing the data, the carbon emissions for each lifecycle phase of the two structures were shown in Table 3. The total carbon emissions for the full lifecycle of the concrete structure were 22353.35t, while the total carbon emissions for the full lifecycle of the steel structure were 20044.79t, representing 10% reduction in carbon emissions compared to the concrete structure. There was a significant difference in carbon emissions between the concrete and steel structure schemes during the operation stage, reaching 1970.78t (16.3%). This was mainly due to the better thermal insulation performance of the steel structure, which reduced the heat transfer between the indoor and outdoor environments, significantly lowering the indoor air conditioning load. Additionally, there is also a relatively large difference in carbon emissions during the material production stage of the two structures. This is because the steel structure uses less concrete, and concrete production generates a large amount of CO_2.

Table 3. Carbon emission calculation results of concrete and steel structure in each stage.

Stage	Concrete structure		Steel structure	
	carbon emissions/t	carbon emissions per unit area/t	carbon emissions/t	carbon emission per unit area/t
Production	8177	1.94	7643	2.37
Transportation	230	0.05	389	0.12
Construction	804	0.19	919	0.28
Run	12056.92	2.86	10086.14	3.12
Demolition	1085.43	0.26	1007.65	0.31
Total	22353.35	5.31	20044.79	6.21

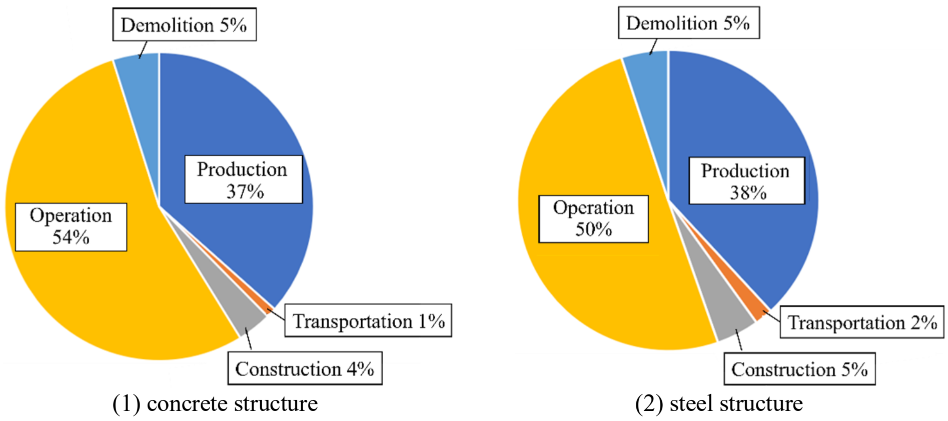

Fig. 1. Proportion of carbon emission in each stage of substation.

The carbon emission proportions for each stage of the concrete and steel structures were shown in Fig. 1.

It can be observed that among the two structural types, the carbon emissions during the building operation stage account for approximately 52%, the carbon emissions during the building materialization stage (production, transportation, and construction) account for about 43%, and the building demolition stage accounts for 5%. Among them, the operation stage was the most significant contributor to carbon emissions. Unlike civil buildings, the primary energy consumption of substation buildings comes from cabinet equipment and air conditioning for cooling. Additionally, due to the excellent thermal insulation performance of steel structures, their carbon emissions during the operation stage account for a relatively lower proportion. Furthermore, the proportions of carbon emissions during the building material production stage were almost identical for both concrete and steel structures, but the actual carbon emissions for concrete structures were slightly higher than those for steel structures.

6 Conclusion

Based on the carbon emission accounting method and the principle of sustainable development in ecological building structure, the carbon emission of substation building materials in production and transportation, construction, operation and demolition were calculated. The results indicated that the carbon emission in substation operation stage is dominant, followed by the construction stage. Therefore, the focus of carbon reduction technological retrofitting for substations should be on the construction and operation stages. Furthermore, steel structures reduce overall carbon emissions by approximately 10% compared to concrete structures. From the perspective of energy conservation and emission reduction, steel structure substations were superior to concrete structure substations. Based on the above research and findings, the following suggestions were proposed:

(1) Reasonably select the structural form of substations to reduce carbon emissions throughout their life cycle.

(2) Research and apply low-energy building technologies for substations, reducing the energy consumption of substations in terms of building material selection, envelope structure design, temperature control, and other aspects.

(3) Explore and develop integrated energy utilization technologies for substations, utilizing photovoltaic and geothermal energy for auxiliary power supply and improving the utilization rate of renewable energy.

(4) Establish economic incentive policies for carbon reduction to promote the clean and efficient development of the energy system.

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