Research on carbon footprint of substation life cycle

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Abstract. With the advancing steadily in the work of “carbon peaking and carbon neutrality” target, the quantification of carbon emissions has become a difficult problem for substation management. Power supply companies in various cities have a large amount of low-carbon investment, but cannot explain the effect and output clearly, which is difficult to meet the purpose of implementing "carbon peaking and carbon neutrality" in the power system. To this end, this paper takes the substation as the object, establishes an abstract carbon model, analyzes the carbon expression and quantification method in various activities of the substation in the construction stage, operation stage, and demolition stage, and defines fixed, continuous and comprehensive carbon emissions to describe the carbon footprint. The research results show that reasonable low-carbon investment can effectively promote the neutralization of the substations carbon footprint. By further adopting long-term energy-saving measures for equipment and sufficient new energy installed capacity, the substation can offset the load consumption in the station through new energy power generation, and achieve carbon neutrality state. In addition, combined with the actual low-carbon design of a substation, this paper introduces the latest design route and actual effect of carbon reduction in substations, which provides ideas for the design and construction of low-carbon substations in the future.

Keywords: substation; carbon footprint; life cycle; low carbon; carbon neutralization.

1. Introduction

The carbon emission of power industry accounts for about 37% of the total carbon emission of national energy activities [1], which is the primary focus under the "carbon peaking and neutrality" goals. In the process of actively promoting low-carbon development, various power departments continue to increase investment, and local power supply bureaus have invested heavily in purchasing environmental protection equipment. However, in terms of quantifying the effect of carbon reduction, there is a lack of statistical data, and it is in the predicament that the extent of carbon reduction of environmental protection equipment is unclear, the carbon emission value of production and operation is unclear, and it is difficult to identify the starting point of carbon reduction measures.

There are many studies on carbon footprint quantification at home and abroad. In 2008, the PAS 2050, “Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services”, was the first carbon footprint measurement standard in the world [2]; Base on this, ISO/TC 207, Environmental Management Committee has formulated the ISO 14067 Carbon footprint of products [3], which is divided into two parts: the quantification of product greenhouse gas emissions and the communication of product greenhouse gas emissions. The carbon footprint of products can be calculated up to 95%;In 2009,Japan published TS Q 0010 "General Principles for Assessment and Labeling of Carbon Footprint of Products" [4], which was updated in 2010, details the greenhouse gas emissions of products including all activities from raw material acquisition to final recycling, and has gradually become the official document of the Japanese industrial standard; In 2006, ISO 14064 Greenhouse Gas Calculation and Verification Standard jointly completed by international experts from 45 countries and 19 organizations was officially promulgated [5], which stipulates the best international model for the management, reporting and verification of greenhouse gas data. The research on carbon footprint in China started relatively late. In 2010, Sun Jianwei et al. calculated China's carbon emissions based on the IPCC input-output method, improved the IOA-EF ecological footprint model, analyzed the composition of my country's carbon footprint sectors, and concluded that the carbon emissions of electricity, heat and manufacturing are most affected by the pull of the national economy[6]; In 2011, Dai Fangzhou et al. proposed industrial carbon footprint, and discussed the accounting of industrial carbon footprint from three levels: product, enterprise, and region[7]; Recently, Liu Junbo et al. proposed the construction of a full-cycle point-flow model to reveal the energy activities in the power industry chain in view of the underestimation of actual emissions caused by the hidden carbon emissions in the power industry, and then clarified the full-cycle carbon footprint based on the consideration of the power consumption side[8].

With the deepening of research, the definition of carbon footprint and general evaluation methods have been relatively unified, but most of the practical applications tend to be macroscopic. The research on carbon footprint at the micro level, especially in the key links of the power industry, is not deep enough. Wang Junzhang et al.[9] classified and estimated the carbon footprint of electricity base on the carbon emission intensity and consumption level of different power sources, combined with the changes in the carbon sequestration capacity of land cover. But the analysis is relatively macro, the specific estimation items in each classification are not deepened. Liu Yun et al. [10] takes power enterprises as an example, and establishes a carbon footprint life cycle accounting technology system according to the specific conditions and processes of the enterprise. It is mainly elaborated on the basis of the evaluation standards of developed countries, and not sufficiently integrated with local reality. Some results may no longer be applicable in the implementation of specific projects, and further practical application research is still required. Another study by Liu Yun et al. [11], based on the carbon footprint assessment and accounting theory, adopts the life cycle method, bottom-up, and specifically analyzes and evaluates the carbon footprint of a coal power plant, obtains relatively detailed carbon footprint data at the power generation side, which has practical guiding significance. However, It needs further research whether the theory is also applicable to the substation. Hua Zhilei et al. [12] proposed a method of using improved sensing technology and optimized network communication to ensure low power consumption and high reliability of carbon footprint data channels. But It lacks research on the specific utilization of carbon monitoring data. Tang Zhongda[13] calculated the life cycle carbon footprint of substations and determined that carbon emissions are mainly from mechanical and electrical equipment, metal structures, concrete and energy consumption in operation and maintenance. However, there is a lack of in-depth development of low-carbon optimization measures and optimization results.

Based on the above analysis, this paper further analyzes and studies the carbon footprint of substation by using the theory of carbon footprint evaluation method and the existing evaluation results of carbon footprint of power industry. Through the identification and analysis of different characteristics of carbon emission sources in substations, it is found that there are three types of carbon emission sources: fixed one-time, continuous and comprehensive. In different stages of the life cycle, the three types of emission sources have their own emphasis. During the construction stage of substations, fixed one-time carbon emissions dominated by cement, metal and other building materials are the main source of carbon footprint, while In the operation and maintenance stage, the carbon footprint is dominated by the power consumption of primary and secondary equipment, which is a continuous carbon emission source. Some important equipment and facilities are comprehensive carbon emission sources, that is, they have both fixed one-time carbon emission and continuous carbon emission. By analyzing the evaluation methods of different carbon emission sources and studying specific carbon reduction measures, differentiated emission reduction strategies will be formulated for different objects and a new perspective will be provided for the truly efficient implementation of carbon peaking and carbon neutrality.

This paper proposes different characteristic types of substation carbon emission sources, introduces the evaluation and analysis method of carbon footprint in the life cycle of substations, refines the carbon footprint model, and proposes a classification calculation method. Through targeted analysis, an effective emission reduction strategy is obtained. Finally, the effectiveness of the evaluation method and emission reduction measures is verified by the actual substation project.

2. Carbon Footprint Depiction

Carbon footprint is derived from the ecological footprint theory, It is used to measure the direct or indirect emission level of CO2 and other greenhouse gases in the life cycle of a human activity or product [14]. Its analysis methods mainly includes input-output method, life cycle assessment method, IPCC method, etc. The input-output method uses the input-output table to calculate the relationship between initial, intermediate, total input, and the intermediate , final , total output through the balance equation. The IPCC method is a guideline for national greenhouse gas inventories, and is an internationally recognized and common carbon emission assessment method. The life cycle method is shown in Fig. 1 below. From the bottom to the top, the carbon emissions are comprehensively assessed from the micro level through the determination of purpose and scope, inventory analysis, impact assessment and result interpretation iteration.

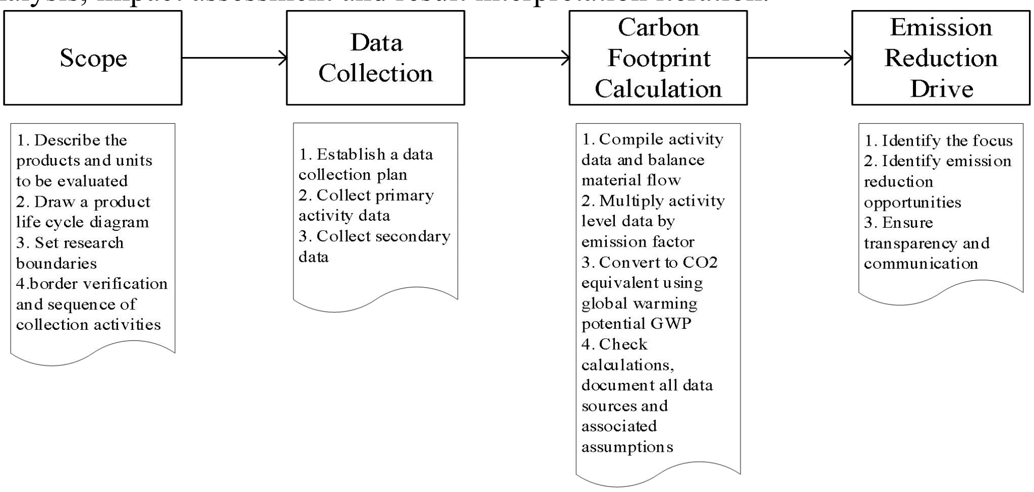

Fig. 1. PAS 2050 life cycle approach

2.1 Carbon Footprint of the Electric Power Industry

The electric power industry is generally divided into four different industrial engineering types: power generation, power transmission, power transformation and distribution. The carbon footprint analysis and research of each type is different, as shown in Fig.2. In the power generation industry, for traditional thermal power plants, the carbon footprint distribution is mainly a large amount of direct or indirect carbon emissions [15]. The direct emission mainly comes from the emission of coal-fired boilers, which is also the largest source of carbon emission in thermal power plants. On the other hand, the desulfurization of coal-fired tail gas is also an important direct carbon emission source. The desulfurization process is the reaction of SO2 and CaCO3 to generate CO2, it needs to be estimated according to a certain desulfurization efficiency. Indirect carbon emissions are mainly from coal mining, processing and transportation, which are generally evaluated indirectly based on the standard coal carbon emission factor and fuel oil carbon emission factor. For new energy power generation methods, the carbon footprint is mainly reflected in the production stage, and the volume is much smaller than traditional thermal power generation methods.

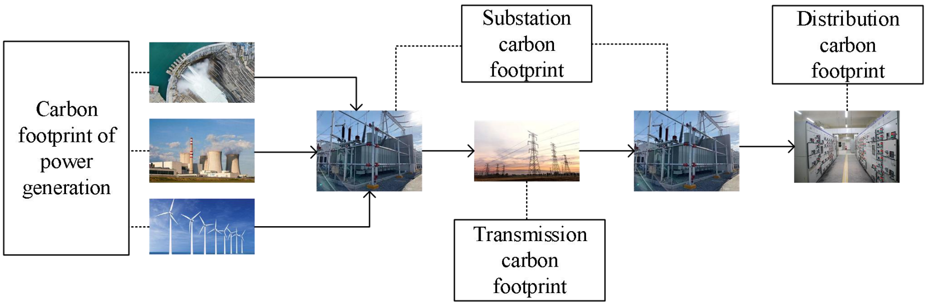

Fig. 2. carbon emission sources of the power industry

The carbon footprint of the transmission industry is mainly distributed in the loss of power grid transmission lines [16]. The calculation steps of its quantitative model include: calculating the theoretical value of transmission loss under the baseline situation, calculating the theoretical value of transmission loss under the project situation, calculating the network loss reduction coefficient, calculating the actual power loss of the grid in the operation process, calculating the grid carbon emission factor, and calculating carbon emissions of the project.

Using life cycle method, the carbon footprint quantification method of distribution industry is divided into four stages: material manufacturing, construction and transportation, operation and maintenance, decommissioning and scrapping. In addition, the influence of power flow needs to be taken into account [17], especially in the context of distributed new energy access. Distributed power generation represented by wind and photovoltaics will be integrated into the distribution network in a clean and negative carbon way. Besides, the load regulation of energy storage power station and the access of irregular electric vehicle charging will cause complex power flow.

The substation also usually uses a bottom-up life cycle approach to assess carbon emissions, which is divided into construction stage, operation stage, and demolition stage [18]. By identifying different carbon emission sources, verifying boundaries, collecting data, and calculating carbon footprints, identifying the emission reduction opportunities and other links, the carbon footprint map of the substation finally can be drawn.

2.2 Depiction of Substation Carbon Footprint

In order to comprehensively study the carbon footprint characteristics of substations, this paper defines three different types of carbon emission sources: fixed carbon emission sources, continuous carbon emission sources and comprehensive carbon emission sources. The carbon footprint model is constructed through the division of different carbon emission sources, the calculations are merged and simplified. And in this way, carbon emission reduction opportunities are easier to be found. This will finally provide guidance for optimizing the carbon footprint and achieving the carbon reduction goal.

What was called fixed carbon emission source refers to the carbon emission generated by the one-time investment or purchase of a certain equipment or product in the life cycle of the substation, and generally will not change again. Continuous carbon emission source, that is the carbon emission generated by a certain emission source during a period of time or the whole time of the substation life cycle, which changes constantly or intermittently. Comprehensive carbon emissions, that is, a certain emission source has both fixed carbon emissions and persistent carbon emissions. It is worth noting that if an emission source is less than 1% of the total carbon footprint, it should not be counted as a fixed carbon emission source, and labor cost cannot be evaluated as a carbon emission source for construction, operation and maintenance.[19].

Based on the above definitions, the substation carbon footprint model as shown in Fig.3 below is established, including two perspective dimensions. One dimension is the life cycle, which is divided into production stage X, operation stage Y, and demolition stage Z. The other is the carbon emission type dimension, which is divided into fixed carbon emission A, continuous carbon emission B, and comprehensive carbon emission C. The two dimensions form coordinates to accurately locate the carbon emissions of the substation.

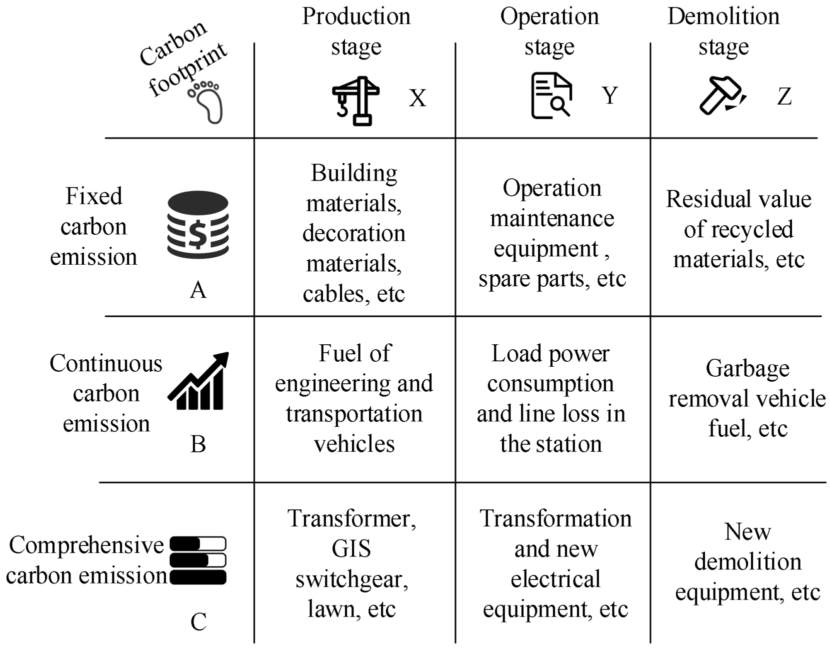

Fig. 3. carbon footprint model of substation

According to the analysis of the carbon footprint model in the above figure, the carbon footprint of A.X mainly involves building and electrical construction raw materials; B.X is composed of fuel oil or other energy consumption that is continuously increasing in the construction process; C.X is the fixed primary electrical equipment purchased by the substation, but these equipment are continuous maintained in the whole process, especially the transformer is filled with insulating grease that needs to be supplemented regularly, and the GIS switch may have SF6 which will be continuous leakage ; A.Y is the fixed equipment and facilities that must be added for maintenance; B.Y is the core carbon footprint of the substation, which is the embodiment of the continuous substation operation, and to a certain extent, has the characteristics of being adjustable and controllable; C.Y is for the renovation or upgrade of the old substation; A.Z is recyclable fixed materials and materials in the station; B.Z is the energy consumption for continuous removal and transportation during the recycling process; C.Z is the newly added equipment for demolition and demolition, which requires fixed investment and purchase, and the work will continue to generate carbon emissions.

3. Calculation of carbon footprint of substations

It can be seen from Figure 4 that the calculation of the carbon footprint of the substation involves the calculation of various contents about A.X, B.X, C.X, A.Y, B.Y, C.Y, A.Z, B.Z and C.Z. However, from the carbon emission characteristics, it can be classified according to the type A calculation with the data proportional characteristic, the B type calculation with the integral characteristic, and the C type calculation with the proportional integral characteristic.

3.1 Calculation of Class A Fixed Carbon Footprint

The calculation of Type A carbon footprint can basically follow the calculation method specified in the PAS 2050 specification, namely:

$$CE_{Ai} = Q_i \times CF_i \tag{1}$$

In the formula, CE_{Ai} is the carbon footprint of activity i in class A; Q_i is the activity level data; CF_i is carbon emission factor of the activity, that is the CO2 equivalent per unit of data.

Q_i in Formula (1) is generally the mass or volume of a certain raw material, but if it is a comprehensive equipment or facility, it should be further decomposed and summed according to its material table. In specific practice, there may also be situations where the content of specific materials cannot be detected, and the conversion should be carried out according to the purchase cost.

3.2 Calculation of Class B Continuous Carbon Footprint

For Type B carbon footprint calculation, since it is mainly continuous generation on the time line, it should be integrated according to time, namely:

$$CE_{Bj} = \int_0^T p_{jt} dt \times CF_j \tag{2}$$

In the formula, CE_{Bj} is the carbon footprint of activity j in class B; p_{jt} is the activity level data per unit time of the activity; T is the termination time of the continuous activity's carbon emission; CF_j is the activity's carbon emission factor.

In the substation scenario, p_{jt} in formula (2) is generally power, because most of the continuous carbon emission sources of the substation are energy consumption, the time integration of the energy consumption power can obtain the total energy consumption. However, in the statistics of energy consumption of transport vehicles, integration of mileage is usually used, and there is a general carbon emission per mileage to check.

In this paper, it is recommended to use formula (2) to calculate the carbon footprint of Class B uniformly. Even if the integration of mileage is more convenient in the transportation scenario, it should be converted into power first. The advantage of using this method is that in the case of further research, the power data in the time domain can be transformed in the frequency domain. A possible analysis form is as follows:

$$P_\omega = \int_{-\infty}^{\infty} p_t e^{-i\omega t} dt \tag{3}$$

In the formula, P_ω is the power frequency domain value at the frequency ω, p_t is the instantaneous power value of the time domain at the moment t, and $e^{-i\omega t}$ is the Fourier operator.

Formula (3) is used to determine which frequency or several frequencies of carbon emissions are more significant in the substation life cycle, which can be used for intelligent identification and optimization of carbon emissions. Of course, this in-depth analysis method requires a large amount of real-time power data support.

3.3 Calculation of Class C Comprehensive Carbon Footprint

The calculation of the class C carbon footprint is actually the integration of formula (1) and formula (2).namely:

$$CE_{Ck} = Q_k \times CF_k + \int_0^T p_{kt} dt \times CF_k \tag{4}$$

4. Engineering Application and Utilization of Emission Reduction Opportunities

In order to verify the practicability of the carbon footprint model of the substation, the model in this paper was applied in the actual design and construction of a 110kV substation. Through the calculation and analysis of the carbon footprint of the traditional substations A, B, and C, the opportunities for emission reduction were identified and utilized.

The traditional 110kV substation class A carbon emission is calculated using formula (1), the construction steel is 271 tons, and the cement is 75 tons. Combined with the conversion of the residual value in the recovery stage, the class A carbon emission is estimated to be about 400 tons. Calculated by formula (2), the converted carbon emission power of transport vehicles is 1.455kg/h, the annual emission is about 12.75 tons, the carbon emission power generated by the power consumption of the station is 8.185kg/h, and the annual emission is about 71.7 tons . The class C carbon emission is calculated by formula (3). The fixed part raw materials of the transformer are 28 tons of copper, 63 tons of silicon steel sheets, and 50 tons of other steel. The fixed part raw materials of the GIS switch are 16.6 tons of aluminum and 2.2 tons of steel. Considering the final recovery residual value, The converted fixed carbon emission is about 727 tons; Besides the transformer is a continuous carbon emission source, although the mineral insulating grease is injected into 22 tons at one time, but the annual overhaul needs to inject about 1.1 tons, and the converted annual carbon emission is 1.35 tons. The GIS switch continuously emits about 0.5 tons of SF6 gas one time, and the annual leakage is calculated at 0.5%, but its global warming potential GWP is 25,200 times that of CO2 gas, and the annual emission is about 63 tons after conversion. The factors involved in the formula can be obtained through the "IPCC 2006 Guidelines for National Greenhouse Gas Inventories" and related literature , and will not be listed one by one.

Through the above analysis, the identification of carbon emission opportunities as shown in Fig.4 can be obtained. In the class A carbon emission, the identification opportunities of emission reduction are that the use of the integrated assembly steel structure construction method has the opportunity to reduce the loss value of the direct use of steel and other materials, thereby reduce carbon. Identifying emission reduction opportunities in Class B carbon emissions are that the selection of electric-driven engineering and transportation vehicles has the opportunity to reduce the carbon emission power of fuel power; the selection of advanced intelligent control systems and energy-saving regulation of the electricity load in the station, have opportunities to reduce Continuous electrical energy consumption carbon emission power. Identifying emission reduction opportunities in class C carbon emissions is to choose advanced technology to optimize fixed and continuous carbon emissions. For example, choosing natural grease transformers instead of mineral oil transformers has the opportunity to reduce fixed carbon emissions from transformers and eliminate continuous carbon emissions; use clean air GIS switch Replacing SF6 GIS switch has the opportunity to reduce fixed carbon emissions, eliminate persistent carbon emissions, etc.

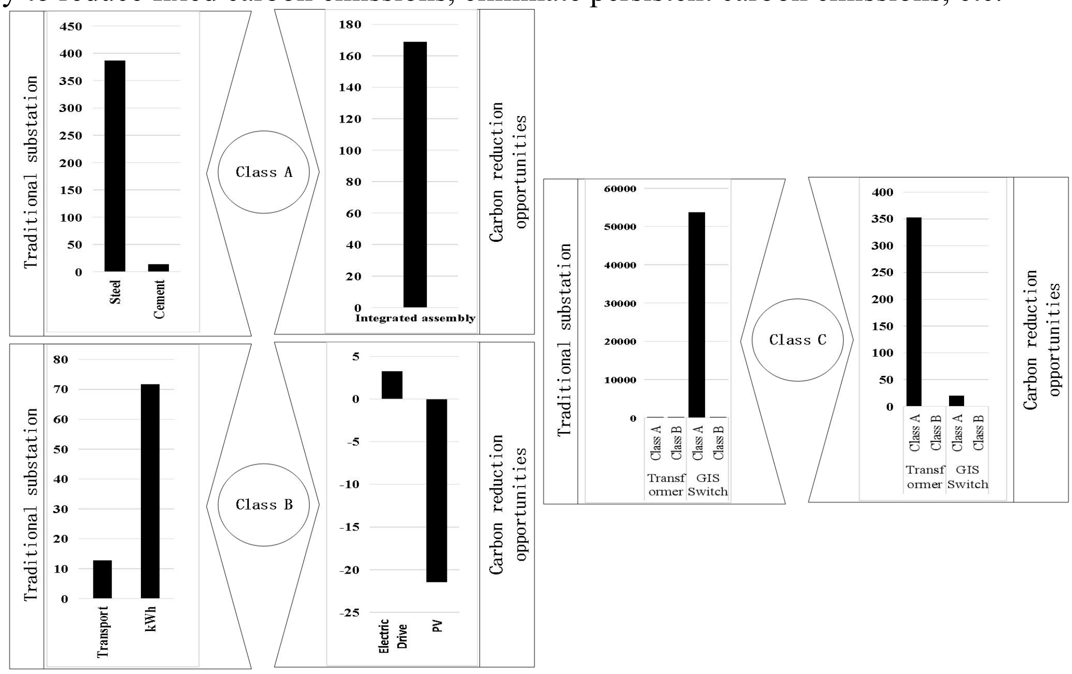

Fig.4. identification of carbon emission reduction opportunities

The carbon emission opportunities identified above are all applied to a new 110kV substation. During the infrastructure construction process of the substation, the integrated steel structure construction method was used, the electric construction method was adopted, clean air GIS and natural grease transformers were purchased. And 135kWp photovoltaics were built in this substation, the annual power generation is expected to be 140,000 kWh, which can cover 80.84 tons of carbon.Excluding 71.7 tons of annual emissions from substation load operation, there should still be a surplus of 9.14 tons of negative carbon every year, which can theoretically support the negative carbon operation of substations. Ultimately, these effects are manifested through an advanced carbon management system, which is also responsible for the optimal regulation of energy consumption in the station, as shown in Fig.5.

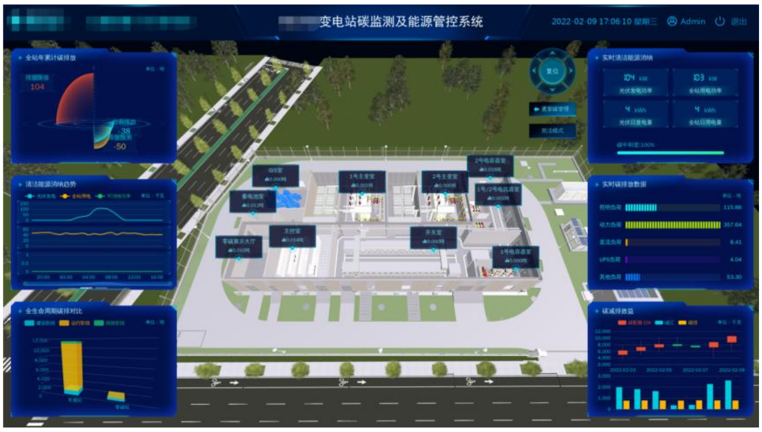

Fig.5. Substation carbon monitoring and energy control management system

5. Conclusion

This paper uses the life cycle carbon footprint theory to study carbon emissions in substations, analyzes the different characteristics of carbon footprints in substations, puts forward the definitions of fixed carbon emissions, continuous carbon emissions, and comprehensive carbon emissions, and introduces specific calculation methods and application migration. The final result is realized in the form of the developed substation carbon monitoring and energy control management system. The main conclusions include:

1) The carbon footprint of substations belongs to the power system and is closely related to power generation, transmission, distribution fields. In terms of time dimension, it can be divided into construction stage, operation stage and demolition stage. In terms of carbon emission types, it can be divided into fixed carbon emission and continuous carbon emission, and comprehensive carbon emissions.

2) The carbon footprint calculation of substations should be carried out according to different types of carbon emissions. Fixed carbon emissions have proportional characteristics, continuous carbon emissions have integral characteristics, and comprehensive carbon emissions are the combination of the first two.

3) Considering the emission reduction opportunities of substations from fixed carbon emissions, optimized construction techniques and environmentally friendly materials should be selected. Considering continuous carbon emissions, new energy access and energy-saving systems can be added. Considering comprehensive carbon emissions, advanced technologies should be selected, carbon-reducing equipment and facilities need to be used, increasing the green area will also have an effect. The practice has verified that the use of these emission reduction opportunities has a good effect.

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