A Rapid Estimation Method and Tool for Carbon Emissions in Substation Buildings

Zheng Huang [1,2*], Jingyun Wu [1,2], Hao Liu [1,2]

[1]State Grid Jiangsu Electric Power Design & Consulting Co. , Nanjing 210008, China
[2]Economic and Technical Research Institute of State Grid Jiangsu Electric Power Co. , Nanjing 210008, China

* Huang Zheng: 2310311@tongji.edu.cn

Abstract. In response to the dual-carbon strategy, the construction industry actively explores energy-saving and emission reduction pathways. Carbon emission calculation stands as the primary step in implementing energy-saving and emission reduction measures. However, distinct from conventional civilian buildings, substation structures, as industrial constructions, exhibit characteristics such as singular form, stable operation, and limited design variables. These features create favorable conditions for the rapid estimation of carbon emissions. This study proposes a rapid estimation method tailored for substation buildings' carbon emissions and, based on this, develops a corresponding computational tool. By leveraging the design constraints and characteristics unique to substation buildings, our approach efficiently conducts carbon emission calculations within the dual-carbon strategy framework, offering practical technical support for the sustainable development of the construction industry.

Keywords: Substation Buildings; Carbon Emission; Calculation Tool; LCA

1 Introduction

In recent years, the world's growing concern about climate change has prompted increased global attention. The surge in carbon emissions, primarily driven by human activities, stands out as a major factor in global warming. In response to this challenge, China set forth ambitious dual-carbon goals in 2020[1]. However, achieving these goals is particularly challenging in the construction industry, a vital sector of the Chinese economy known for its substantial energy and material consumption, major contributors to carbon emissions. Consequently, reducing carbon emissions in the construction industry is not only imperative for meeting national carbon neutrality targets but also holds significant implications for global climate change mitigation[2].

The accurate accounting of carbon emissions in construction is the primary step towards achieving energy efficiency and emission reduction in buildings. Currently, the calculation of carbon emissions in construction often employs the life cycle assessment(LCA) method[3]. The GB/T 51366, issued by the Ministry of Housing and

Q. Gao et al. (eds.), *Proceedings of the 2024 7th International Conference on Structural Engineering and Industrial Architecture (ICSEIA 2024)*, Atlantis Highlights in Engineering 30,
https://doi.org/10.2991/978-94-6463-429-7_6

Urban-Rural Development of China in 2019, adopts a process-based approach for carbon emission calculation of civilian buildings. However, in the realm of civilian buildings, where there are fewer design constraints and a myriad of building types and forms, the carbon emission calculation method involves a substantial and diverse list of materials, construction machinery, and complex operational stage energy consumption simulations. This complexity results in a time-consuming and intricate carbon emission calculation process[4].

In power systems, substations, vital components, often undergo large-scale national construction. Unlike typical buildings, substation structures, as industrial constructions, have a straightforward form, employing common building materials and construction machinery. Utilizing the same processes as civilian buildings for carbon emission calculations would neglect the advantages of substation buildings' simplicity, detailed budgeting, and singular functionality[5]. Hence, there is an urgent need for an efficient method for carbon emission calculations in substations, leveraging their simple form, precise budgeting, and singular functionality for timely evaluation and optimization of design schemes[6]. Consequently, the development of a tailored rapid carbon emission calculation method and software for substations is essential, enhancing calculation efficiency for large-scale construction demands and providing robust support for sustainable development and environmental policies.

2 Method

2.1 Rapid methodology for calculating life cycle carbon emissions

Following GB/T 51366-2019, this study addresses life cycle phases: production, transportation, construction, operation, and dismantling. As shown in formula (1) Carbon emissions in production, transportation, and construction result from multiplying activity levels generating emissions by corresponding emission factors[5]. Specifically, production-stage emissions derive from multiplying the quantity of building materials by their emission factors. Transportation-stage emissions involve multiplying types of vehicles, distances, and corresponding emission factors. Construction-stage emissions result from multiplying mechanical equipment working hours, power consumption rates, and relevant energy source emission factors[7].

$$C = \sum_{i=1}^{n} A_i \times F_i \tag{1}$$

Eq. (1) where C denotes carbon emissions, n denotes the number of activities generating carbon emissions, A denotes activities generating carbon emissions, and F denotes the corresponding carbon emission factor.

In comparison to typical civilian buildings, substation structures possess a stable inventory of design-used building materials and construction machinery. Moreover, China imposes strict requirements on the design budget for such industrial buildings, resulting in design material quantities and construction plans that closely match real-world conditions[8]. Therefore, establishing a database of carbon emission factors for materials and mechanical equipment specific to substation buildings will significantly enhance the efficiency of carbon emission calculations. This aspect is elaborated in detail in Section 2.2.

The utilization of software-based energy consumption simulations for carbon emission calculations during the operational phase demands a high level of expertise and is time-consuming for users. Considering the singular form and stable operation of substation buildings, this method involves pre-selecting a representative substation building and conducting detailed energy consumption simulations under various conditions, such as different orientations, areas, thermal transmission coefficients of enclosure structures, and scenarios for the arrangement of renewable energy sources[9]. The design parameter sets are then correlated with the corresponding operational phase carbon emission values and stored in the background[10]. Finally, the method allows for the retrieval of operational phase carbon emission values based on user-specified design parameters for substation buildings. This approach can meet the operational phase carbon emission calculation requirements for the majority of common substation buildings[11].

The carbon emission calculation during the dismantling phase employs an estimation method. In the absence of a detailed list of construction equipment for the dismantling phase, estimation using empirical data is a common approach. According to studies by relevant scholars, the proportion of carbon emissions during the dismantling phase is approximately 5%~10% of total carbon emission. This study adopts a value of 10%.

2.2 Carbon Emission Estimation Tool for Substation Buildings

A software application has been developed based on the carbon emission calculation method introduced in Section 2.1. The software comprises three main components: project information input, life cycle carbon emission calculation, and presentation of carbon emission calculation results. The life cycle carbon emission calculation encompasses five stages, namely, the production, transportation, construction, operational, and dismantling stage (Fig.1).

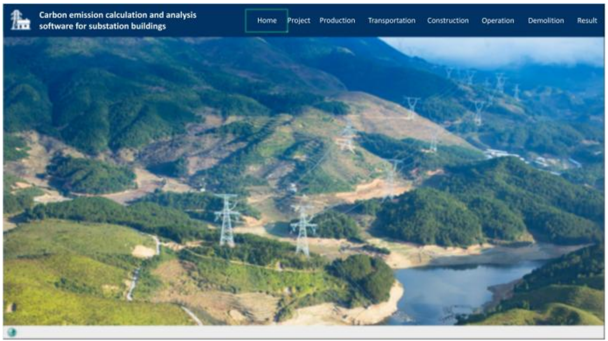

Fig. 1. Substation Building Life Cycle Carbon Emission Calculation and Analysis Software V1.0

The most significant innovation of this software lies in the integration of a substantial amount of reliable information, facilitating the direct retrieval and presentation of results through data input, thus avoiding complex simulation processes. This enables the rapid and automatic calculation of carbon emissions for substation buildings. The embedded information includes 377 sets of codes, names, and unit information for building materials, 90 sets of codes, names, energy types, and power information for construction machinery, 1890 sets of information on different design parameter schemes and their corresponding operational energy consumption, and 73 sets of information on different arrangements of photovoltaic systems and their corresponding annual electricity generation intensities. Taking the example of embedded data in the production stage, the information is sourced from the "Valuation Table for Sub-Project Quantities of Building Engineering" associated with various substation building projects. Users can easily copy and paste the relevant data for calculation without the need for additional operations.

The tool also addresses the incompatibility issue between the State Grid project budget and the calculation of material carbon emissions. For example, the Monolithic floor covering includes the following specifications: ①20mm cement mortar; ②One layer of cement slurry; ③80mm C20 concrete cushion layer; ④Compaction with plain soil. The material listed is the monolithic floor covering, but there is a lack of carbon emission factor information for it. As shown in Table 1, the tool splits the monolithic floor covering into cement mortar and concrete that can be used for carbon emission calculations based on the list description. Thus, the logical flow of this calculation process involves indexing the corresponding carbon emission factors for building materials using the input project code, multiplying them by the input material quantities, to obtain the carbon emissions during the production phase for the specified building material type and quantity. Finally, the total production phase carbon emissions are obtained by summing up the carbon emissions from each material.

Table 1. Complex material splitting logic

	Monolithic floor covering	Cement mortar	Concrete
Amount of material used	1㎡	0.01333t	0.08m^3
Carbon emission factors	/	735kgCO_2/t	295kgCO_2/m^3

The carbon emission calculations for the production and transportation stages necessitate a building materials list, and the tool offers data linkage functionality. The materials list only needs to be imported once, avoiding repetitive data input. However, there is inconsistency in the units corresponding to material quantities between the production and transportation stages. For example, during the production stage, concrete should be measured in cubic meters (m^3), while during the operational stage, it should be measured in tons (t). To mitigate this, the tool includes a unit conversion table, eliminating the need for manual unit conversions by users.

3 Case Study

3.1 Project Description

This section applies the automatic carbon emission calculation model and low-carbon optimization design method to a 110kV reinforced concrete structure substation building, aiming to showcase its energy-saving and emission-reduction potential. The substation building, constructed and operated by State Grid Jiangsu Company, is considered highly representative. The project is located in Nanjing, Jiangsu Province, falling within a hot-summer and cold-winter climate zone. The building consists of a partially two-story above-ground structure and one underground level with a total floor area of 1819㎡. The design service life is set at 50 years. The three-dimensional geometric form is illustrated in Figure 2.

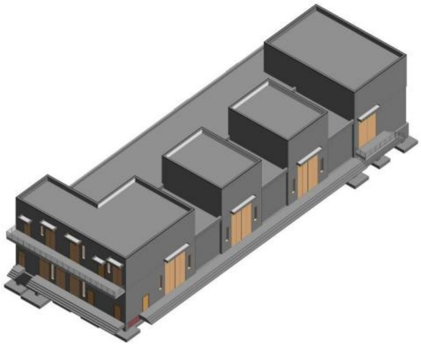

Fig. 2. Substation Building 3D Model

3.2 Carbon emission calculation results

This study calculates the carbon emission values for this case by using the Substation Building Life Cycle Carbon Emission Calculation and Analysis Software V1.0 presented in Section 2.2. Table 2 presents the carbon emissions at different stages of the life cycle of the substation, along with quantified data for carbon emissions per unit area. The total carbon emissions amount to 4,373,534 kg, with a corresponding carbon emission intensity of 2402 kg/m². Notably, the operational and production stages contribute significantly to the overall emissions, accounting for 53% and 37%, respectively, with corresponding carbon emissions of 2,330,110 kg and 1,610,172 kg.

Table 2. Comparison of three Building Carbon Calculation Software

	Carbon emission (kg)	Carbon Emission Intensity (kg/㎡)
Production	1610172	885
Transportation	107849	59
Construction	117140	64
Operation	2330110	1280

Demolition	208263	114
Total	4373534	2402

3.3 Comparison of estimated results with real carbon emission

The estimated values of carbon emissions during the production, transportation, and construction stages closely align with the actual values. This is attributed to the scientific reliability of the calculation methods and data sources employed. The carbon emissions for these three stages are determined using the process-based calculation method specified in GB/T 51366-2019. The corresponding foundational data sources are also clearly defined. Raw data, including types and quantities of building materials, transportation vehicles, construction equipment models, and work units, are all extracted from the preliminary budget of substation construction projects within the State Grid Corporation of China. Furthermore, due to the rigorous requirements set by the State Grid Corporation for the preliminary budget calculations, the deviations between its content and the actual project implementation are less than 5%. Consequently, the calculated results for the embodied stage closely approximate the actual values.

The accuracy of carbon emission estimation during the operational stage is related to the differences in form and function between the assessment scheme and typical substation building designs. This is because the estimation method is based on selecting typical substation building designs, utilizing EnergyPlus as the simulation engine to construct an operational energy consumption model. By altering design parameters such as orientation and the U value of the building envelope, Energy intensity of functional rooms for 1890 groups of scenarios are obtained. The operational stage carbon emissions are then calculated by selecting the corresponding functional room energy consumption intensity based on the design parameters of the target scheme, combined with the carbon emission factor. The calculation accuracy of this method depends on the differences in form and function between the target scheme and typical scheme. However, as substations, being industrial buildings, exhibit relatively small differences in design, this estimation method can be applied to the operational stage carbon emission calculations for most substation buildings.

The dismantling stage is estimated using 10% of the total carbon emissions. This method is derived from empirical values in the life cycle carbon emission calculations for typical civilian buildings, ensuring a controlled difference from the actual situation.

4 Comparison of Carbon Emission Calculation Software

In this study, three architectural carbon emission calculation and analysis software packages were chosen for a comprehensive comparison to gain a deeper understanding of their characteristics and functional differences. As shown in Table 3, these three software packages are PKPM·CC, Donghe Building Carbon Emission Calculation and Analysis Software V3.0.0, and the Substation Building Life Cycle Carbon Emission Calculation and Analysis Software V1.0 developed with the estimation method as the core by this study. For ease of reference, the following text will be referred to as Software A, Software B, and Software C, respectively.

Table 3. Comparison of three Building Carbon Calculation Software

	PKPM·CC	Donghe Building Carbon Emission Calculation and Analysis Software V3.0.0	Substation Building Life Cycle Carbon Emission Calculation and Analysis Software V1.0
Acronyms	A	B	C
Installation	Web	Web	Excel software installed
Input	Manual input	Donghe format Excel or Glodon format Excel	State Grid Budget Proposal Format Excel
Data linkage	None	Synchronization of production phase data with unit matching failures	Synchronized production stage data with automatic unit matching
Operational phase	Requires information on annual power consumption of equipment	Input building geometry, structure and schedule information for dynamic simulation	Recalls pre-built simulation results for 1890 operating conditions
Result page	Rough presentation of results through icons and data	Detailed presentation of results through icons and data	Detailed presentation of results through icons and data

In terms of installation methods, all three software packages do not require complex download and installation steps. The first two software packages operate based on web platforms, thereby being subject to the constraint of wireless networks. In contrast, the Software C is an independent offline calculation software based on Excel, resulting in fewer limitations in terms of usage scenarios.

In the process of carbon emission calculation, extensive input of construction materials and construction information is required from the user, including the type, quantity, and unit information of construction materials, as well as equipment power, work shifts, and fuel type information for construction. In the input process, Software A necessitates users to manually input each piece of information, making the process tedious, complex, and prone to errors. Software B requires users to convert their information into the Donghe format Excel or the Glodon format Excel before importing it for calculation. On the other hand, Software C seamlessly integrates with the format of the State Grid substation building preliminary budget file, allowing for direct data importation.

During the production, transportation, and dismantling stages, building material data undergoes repeated use. In this process, Software A lacks data linkage across stages, requiring manual input each time. Although Software B can call data in different stages, it still requires users to manually modify unit information. For instance, concrete materials need to be in cubic meters for production-stage carbon emission calculations and in tons for transportation-stage calculations. Software C not only achieves data linkage across stages but also offers automatic unit matching, eliminating the need for manual adjustments by users.

The carbon emission calculation during the operational stage is relatively complex. In this process, Software A requires users to provide annual electricity consumption information for equipment to perform calculations, a data point that is often challenging to obtain during the design phase. Software B necessitates users to input geometric, structural, and behavioral information, conducting hourly dynamic simulations to obtain the building's annual energy consumption data. Although this method involves a large amount of input information and a lengthy simulation time, it is relatively accurate. Software C leverages the simplicity of substation building forms and functions, conducting pre-simulations for typical substation buildings with different design parameters and embedding them in the software database. It significantly reduces the complexity of operational stage carbon emission calculations and enhances computational efficiency when simulating results based on user-input design parameters. However, this method has lower accuracy compared to numerical dynamic energy simulation methods. Additionally, the variability in design parameters is limited, accommodating only common substation building types in carbon emission calculations during the operational stage.

5 Conclusion

This study proposes a method for estimating the life cycle carbon emissions of substation buildings and has developed a practical computational tool based on this approach. The tool exhibits notable innovations in several aspects. Firstly, its calculation logic is based on the GB/T 51366, utilizing foundational data from relevant standards, internal data within the State Grid Corporation's civil engineering department, and other publicly available reliable sources, ensuring the scientific reliability of the calculation results. Secondly, the tool seamlessly integrates with the substation building project budget list exported by State Grid Corporation's software, reducing the complexity of user input. Simultaneously, it avoids the need for users to establish and simulate complex energy consumption models during the operational stage carbon emission estimation by incorporating thousands of built-in energy consumption simulation results, thereby alleviating user difficulty. Additionally, the tool maintains data linkage for material information during the production, transportation, and dismantling stages, preventing errors that may arise from multiple user inputs. Finally, the software visually presents the results of carbon emission calculations for each stage of the life cycle, facilitating user identification and in-depth analysis.

The carbon emission calculation and analysis software proposed in this study for substation building life cycles has not only achieved significant technological advancements but also provides robust support for the architectural industry's pursuit of low-carbon sustainable development goals. It is hoped that the widespread adoption and application of this software can make substantial contributions to future carbon reduction efforts.

However, despite significant progress in various aspects, the computational tool still has some limitations. Notably, the embedded operational stage energy consumption simulation results for substation buildings only consider ideal conditions, where there are no obstructions from other buildings or vegetation. Additionally, in the process of conducting life cycle carbon emission calculations, the carbon reduction effects of plants have not been fully taken into account. Therefore, future research directions could focus on addressing these aspects to provide a more comprehensive understanding and evaluation of the carbon emissions from substation buildings.

Acknowledgment

This research was funded by the State Grid Jiangsu Electric Power Design and Consulting Co.(B710K0234JQU)

References

1. Chen Z, Xiaodong L, Weina Z, etal. Embodied carbon emissions and mitigation potential in China's building sector: An outlook to 2060[J]. Energy Policy, 2022, 170.
2. Ji C, Hong T, Park H S. Comparative analysis of decision-making methods for integrating cost and CO2 emission – focus on building structural design –[J]. Energy and Buildings, 2014, 72: 186–194.
3. Roberts M, Allen S, Coley D. Life cycle assessment in the building design process – A systematic literature review[J]. Building and Environment, 2020, 185: 107274.
4. Ibn-Mohammed T, Greenough R, Taylor S, etal. Operational vs. embodied emissions in buildings—A review of current trends[J]. Energy & Buildings, 2013, 66.
5. Chen R, Tsay Y-S, Zhang T. A multi-objective optimization strategy for building carbon emission from the whole life cycle perspective[J]. Energy, 2023, 262: 125373.
6. Agrawal A, Pandey S N, Srivastava L. Pareto-Frontier Differential Evolution based Financial Approach for Multi-objective Congestion Management using Customer Participation and On-site Generation[J]. Renewable Energy Focus, 2022, 42: 253–265.
7. Yujie C, Zhixing L, Liu Y, etal. A new method for calculating the embodied carbon emissions from buildings in schematic design: Taking "building element" as basic unit[J]. Building and Environment, 2020, 185.
8. Schmidt M, Crawford R H. Developing an Integrated Framework for Assessing the Life Cycle Greenhouse Gas Emissions and Life Cycle Cost of Buildings[J]. Procedia Engineering, 2017, 196: 988–995.
9. Song Y, Zhang H, Mithraratne N. Research on influences of wall design on embodied and operating energy consumption: A case study of temporary building in China[J]. Energy and Buildings, 2023, 278: 112628.
10. Shekarchian M, Moghavvemi M, Rismanchi B, etal. The cost benefit analysis and potential emission reduction evaluation of applying wall insulation for buildings in Malaysia[J]. Renewable and Sustainable Energy Reviews, 2012, 16(7): 4708–4718.

11. Bushra N. A comprehensive analysis of parametric design approaches for solar integration with buildings: A literature review[J]. Renewable and Sustainable Energy Reviews, 2022, 168: 112849.