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Carbon Emission Evaluation Method and Comparison Study of Transformer Substations Using Different Data Sources

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Abstract: The construction of transformer substations in transmission lines is a systematic, technical, and complex project with the need for numerous materials and resources. Under the development of the green economy, the requirements for energy conservation and carbon reduction have improved; hence, an assessment of carbon emissions in transformer substations is urgently needed. A calculation method was proposed in the present study to analyze the carbon emissions of transformer substations with different kinds of data sources, which were collected from several practical projects in the west-to-east power transmission project. In this study, a detailed comparison and discussion regarding the differences in carbon emissions of 750 kV transformer substations caused by hydrology, geology, engineering quantity, and other factors were conducted. The mean value, standard deviation, and 90% confidence interval of carbon emissions were obtained by Monte Carlo simulation through MATLAB. Results show that the total carbon emissions of the selected 750 kV transformer substations are between [56,000, 68,000] t CO_2 eq. Construction engineering accounts for more than 50% of carbon emissions, followed by installation engineering and additional services. In terms of input items, electricity distribution buildings contribute more than 39% of total carbon emissions, followed by cable/earthing systems, which account for 14% of total carbon emissions. Gas insulated switchgear (GIS) and air insulated switchgear (AIS) could adopt different types of equipment foundations, and GIS equipment foundations would generate fewer carbon emissions due to the smaller land area and input materials. This study can provide experience and reference for similar projects and further guide the substation carbon emission reduction work.

Keywords: transformer substations; power transmission lines; carbon emissions; evaluation method; stochastic analysis

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Citation: Liu, X.; Zhang, J.; Hu, Y.; Liu, J.; Ding, S.; Zhao, G.; Zhang, Y.; Li, J.; Nie, Z. Carbon Emission Evaluation Method and Comparison Study of Transformer Substations Using Different Data Sources. *Buildings* **2023**, *13*, 1106. https://doi.org/10.3390/buildings13041106

Academic Editor: Antonio Caggiano

Received: 22 March 2023
Revised: 16 April 2023
Accepted: 19 April 2023
Published: 21 April 2023

1. Introduction

With the rapid growth of the economy, China's demand for electricity has recently soared from 5.56×10^3 TW h to 6.80×10^4 TW h [1,2]. The Eastern part of China is densely populated and has a large demand for industrial and residential electricity, while the Western region is rich in resources. The uneven distribution of energy sources promotes the construction of efficient and economical transmission channels [3,4]. West-to-east electricity power transmission is one of the national projects with the largest investment and engineering volume in China; the cumulative power transmission reached about 270 million kW [5]. In this circumstance, Xinjiang launched power-grid construction projects in 2012, but the 750 kV main transmission channel and ring network have not been completed yet. As the central hub of the power grid, the charging power generated in a 750 kV transmission line is 2–3 times greater than that of a 500 kV line of the same length, and as the key facility for power transmission, the transformer substation plays an important role in the power supply system.

With the constant consumption of energy and the emission of greenhouse gases, global climate change has become one of the most severe environmental challenges. The carbon dioxide (CO_2) emissions related to the construction industry have been a global concern [6–10]. Chau et al. state that the building sector contributes 40% to the total energy consumption and 36% to the global CO_2 emissions [11]. The construction process of a transformer substation involves energy and carbon-intensive products. Researchers have paid more attention to the impact of transformer substation construction on the environment in recent years. Yamagata et al. studied the ultra-high-voltage AC substation and its influence on the environment in Japan [12]. Tan et al. established optimization models to study the impact of clean energy and carbon emission mechanisms on the inter-regional energy exchange [13]. Daniels et al. used investment and asset data for the GB system for 2015–2023 to calculate the carbon impacts on electricity networks [14]. Garcia et al. assessed the environmental life cycle impacts of electricity generation and supply in Portugal [15].

A newly built 750 kV transformer substation would induce a lot of energy and material consumption; hence, it is urgent to evaluate the carbon emissions to guide the related projects. In previous studies, researchers calculated carbon emissions from power transmission infrastructure in Europe [16,17]. However, there are shortcomings in these studies. First, only primary materials, including concrete, steel, and gravel, are taken into account in construction engineering [18]. Materials for installation, including switch plants, reactors, filters, and reactive compensation equipment, require large amounts of metal and building materials, and the process of installation also needs manpower and machinery [19]. In addition, additional services for construction such as survey, design, project supervision, and staff training will all generate corresponding carbon emissions that cannot be ignored in the calculation. Therefore, ignoring the carbon emissions generated by installation materials, office equipment, vehicles, and labor will lead to a significant underestimation of the calculation results. Moreover, European data are of less reference value to developing countries due to differences in construction scale and technology. Thus, a calculation method that can comprehensively evaluate carbon emissions from newly built substations in Xinjiang province is urgently needed.

On account of the impact of engineering quantity and terrain, the scale of each substation is different, resulting in differences in carbon emissions. Therefore, it is essential to do a comparison of the carbon emissions of different substations and conduct stochastic analysis on this basis. Generally, parameter, scenario, and model are the three basic factors of stochastic analysis [20]. For the large amount of data involved, parameter stochastic has the greatest influence on calculation results [21–23]. Kang et al. used statistical analysis to describe the characteristics of construction materials [24]. Wang et al. proposed a combined data quality indicator method for stochastic analysis of carbon emissions [25]. Chou et al. used Monte Carlo simulation to research the distribution of carbon emissions during construction engineering [26]. Although numerous researchers have focused on the stochastic analysis of carbon emissions, studies on newly built transformer substations are still rarely seen. Due to the special geographical environment in Xinjiang, more consideration should be given to the impact of the construction process on the environment compared to other regions.

Currently, there is no research on the reasonable interval of carbon emissions, which may impede the development of low-carbon technology in substations. The quantification and analysis of carbon emissions in this paper would fill this gap, and it would provide technical support and a reference for similar projects.

Due to the excessive consumption of electricity in large cities in China, a large number of electricity infrastructures have been built to transfer electricity from west China to east China, especially in Xinjiang province. In addition, more electricity infrastructure is to be built soon to meet the rapid increase in demand for electric power in the Eastern part of

China. Power transmission lines involve a large number of items, and the workload of different processes could be different types, such as bills of engineering quantities or final account lists of projects. Therefore, it is important and necessary to find an appropriate way that is suitable for the calculation and evaluation of carbon emissions in power transmission lines and related facilities, such as transformer substations. Therefore, 750 kV transformer substations were selected to study the calculation and evaluation method for the carbon emissions of power transmission lines in the present study. A mass of data from several real projects of west-to-east power transmission project was collected for the analysis. Based on the mass data collected from design, construction, and maintenance organizations that took part in the construction processes of 750 kV transformer substations, this study aims to achieve the following goals: (1) propose a feasible and adoptable method to calculate the carbon emissions of newly built transformer substations; (2) analyze the differences in carbon emissions of each substation according to the hydrological and geological conditions; (3) adopt parameter stochastic analysis to determine the distribution and confidence interval of carbon emissions in Xinjiang province and find key influencing factors; and (4) compare the influence of different types of switchgear foundations on carbon emissions. Results of this study would facilitate references for the low-carbon construction of similar projects for power transmission lines, thereby promoting the development of the ecological environment.

2. Data Resources and Methods

2.1. Data Resource

As the starting point of the "West-to-east power transmission project" in China, Xinjiang plays the most significant role in ensuring the power supply for east China. Therefore, 5 regionally representative 750 kV transformer substations of power transmission lines in Xinjiang were selected for analysis in this study. To reveal the carbon emissions of newly built 750 kV transformer substations, detailed data were collected from design, construction, management, and finance organizations that were involved in the life of transformer substations on power transmission lines. Costs, construction materials, and engineering quantities at each stage all came from the summary table of the financial department, which is detailed and reliable. The items of installation engineering were collected and counted by the State Grid Corporation of China during the installation process.

The location of the selected 750 kV transformer substations is shown in Figure 1. The TC 750 kV transformer substation is located in northwestern Xinjiang province, near Karamay. The total area of land expropriated reaches 14.27 hm^2, with two sets of main transformers (1500 MVA), a two-circuit 750 kV overhead line, and a ten-circuit 220 kV overhead line. The AL 750 kV transformer substation is located in Altay, Northern Xinjiang. The total area of land expropriated reaches 14.88 hm^2, with two sets of main transformers (1500 MVA), a two-circuit 750 kV overhead line, and an eleven-circuit 220 kV overhead line. The HT 750 kV transformer substation is located in Southern Xinjiang; the total area of land expropriated reaches 13.56 hm^2, with two sets of main transformers (1500 MVA), one-circuit current-period 750 kV overhead line, and ten-circuit current-period 220 kV overhead line, but six-circuit 750 kV and fourteen-circuit 220 kV in the long term. The SC 750 kV transformer substation is located in southwest Xinjiang; the total area of land expropriated reaches 12.80 hm^2, with two sets of main transformers (1500 MVA), a three-circuit 750 kV overhead line, and an eleven-circuit 220 kV overhead line. The WJ 750 kV transformer substation is near Urumqi, with three sets of main transformers (1500 MVA) in its design but built with only two sets of current transformers. The 750 kV and 220 kV distribution devices are set with GIS, a four-circuit 750 kV overhead line, and a twelve-circuit 220 kV overhead line.

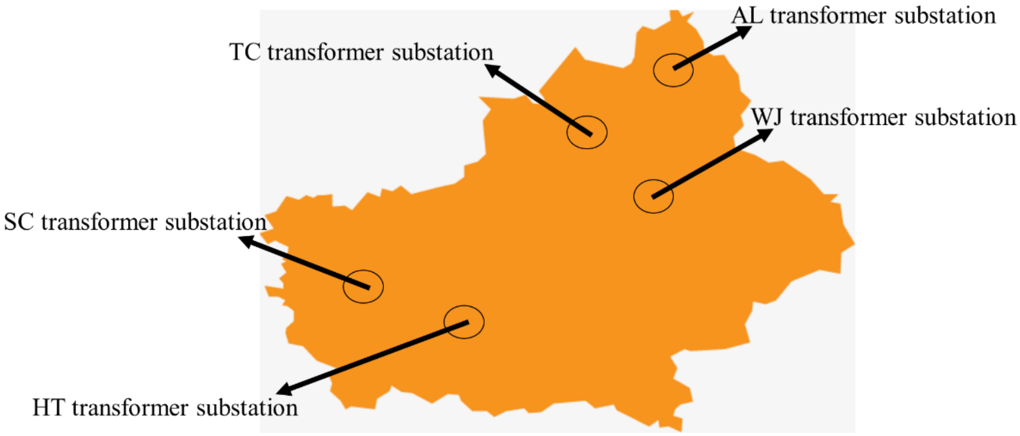


Figure 1. Location of the selected 750 kV transformer substation in Xinjiang province.

2.2. Proposed Method

Conventional carbon emission calculation methods can be divided into process analysis methods and input-output methods [27]. The former method starts from the life cycle of the buildings, realizing detailed calculations and analysis based on carbon emission coefficient and quantity. The latter method uses sectoral carbon intensity and input-output models to trace the carbon footprint, which is more suitable for macro-level calculation. Both methods have their advantages and have been widely used. Jones et al. used life-cycle assessment (LCA) to compare the carbon emissions of five power cables during the production and operation processes [28]. Harrison et al. utilized LCA to calculate emissions generated by transmission networks and found the majority of carbon emissions are caused by energy loss [29]. Acquaye et al. used input-output analysis as the model and used Monte Carlo simulation to analyze the solidified carbon emissions of buildings [30]. The results obtained by process analysis are more accurate, but there are truncation errors due to the limitation of the system boundary, while input-output analysis is more complete at the macro level but is less accurate. Further, in the installation engineering of the substation, most of the equipment has been prefabricated in the factory, so it is impossible to calculate the carbon emissions from raw materials to completion through the LCA method, and it is not possible to count the consumption of metals and building materials. The consumptions of energies and machinery are hard to count directly in additional service as well. Bullard proposed a hybrid method that incorporated the advantages of process analysis and input-output analysis, which provided a unified idea for calculating resource consumption and gas emissions [31]. With the development of the method, according to the different structures of the calculation model, the hybrid method can be divided into tiered hybrid analysis (TH), input-output-based hybrid analysis (IOH), and integrated hybrid analysis (IH) [32]. TH uses process analysis to study the main production process while using input-output data to estimate other processes; the sum is used as the total carbon emissions. TH has a small amount of calculation and extends the system boundary of process analysis to a certain extent. However, the internal connection between process analysis and input-output analysis cannot be considered, and the unclear boundary division will lead to major errors. IH uses process analysis to calculate total carbon emissions while using input-output data for upstream and downstream additional analysis and defining an error matrix. The internal structure and system boundaries of this model are more complete, but the additional assumptions make the calculation process more complicated. IOH uses detailed production and consumption data to split the sectors in the input-output table, which has strong pertinence. Since IOH is highly dependent on the degree of detail and accuracy of the data, this model is not suitable in the case of insufficient data or unknown accuracy. On this basis, Liu et al. found process analysis can generate a comprehensive input list, and input-output analysis can determine the energy and carbon cost per unit of products [33]. When there is sufficient data available, the items in the list constructed by IOH can be assigned a corresponding economic sector. Researchers have established a carbon intensity database due to the economic sector and environmental factors [34], from which the emissions can be calculated. With further research, IOH has been used to calculate the energy cost and greenhouse gas emissions in electricity systems and power grids [35–38]. To find a feasible and adoptable way to do carbon emission calculation and evaluation for complicated conditions such as transformer substations, the calculating and evaluating model in the present paper is shown in Figure 2.

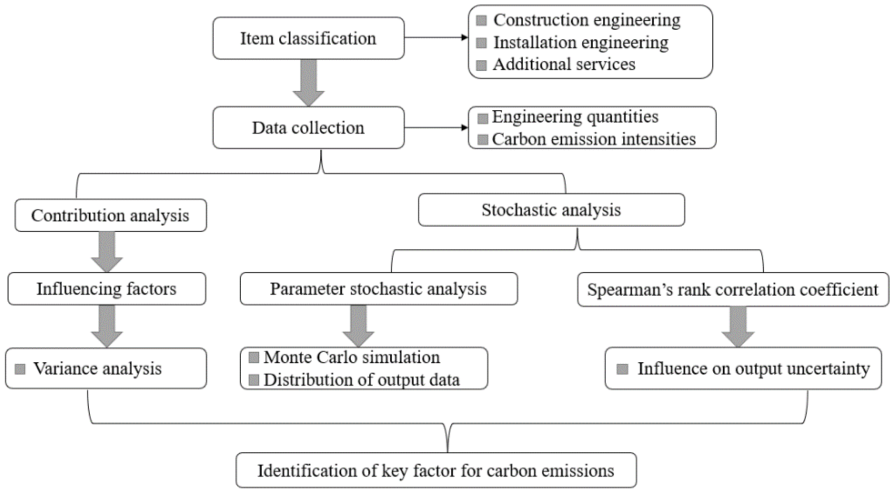


Figure 2. Calculating and evaluating the model of the present study.

Based on IOH, a preliminary calculation of carbon emissions can be obtained, and the specific steps are as follows: First, a detailed bill of quantities for the transformer substations, including construction, installation, and additional service, should be established, and all the items are measured in monetary units. Second, an appropriate database containing carbon emission intensities in different fields should be chosen. A 135-sector embodied carbon intensities database is adopted in this paper to study the carbon emissions in transformer substations [18,34]. A sector code can be found for each input item. For example, the code for the construction of the main production building is 95; the code for control cables in installation engineering corresponds to the manufacture of cable, wire, and electrical appliances, which is 79. Finally, multiply the monetary costs by the carbon emission intensities related to the economic sector, and then you can obtain the carbon emissions. The calculation can be obtained by Equation (1), where E_{total} represents the total carbon emissions, EF_i is the input's carbon intensity, k is the type of item, and C is the monetary cost.

$$E_{total} = \sum_{i=1}^{k} C \times EF_i \tag{1}$$

The construction project will always have a budget in the bidding process, while the engineering quantity, comprehensive unit price, and labor costs will be adjusted after the approval and modification of the contract. Therefore, the file types collected from different data sources may be different, and the discrepancy between the engineering quantities and the unit price in the budget file and the actual project will lead to a large error in the carbon emission calculation according to Equation (1). To find a feasible and adoptable multi-data source carbon emission calculation method, the undetermined coefficient formula method is proposed based on Equation (1). As shown in Equation (2), E_{total} means total carbon emissions, E_b and E_f corresponds to the carbon emissions calculated by Equation (1) using the budget file and final account file, respectively. Parameters a and b are undetermined coefficients. Since the final account file can reflect the actual engineering quantity and costs more accurately, carbon emissions are calculated according to the relevant data. When all of the data in the final account file is available, set b as 1 and a as 0. When part of the data can be obtained only through the budget file, undetermined coefficients can be set according to the proportion of the relevant part in the whole project or similar projects. To make the proposed calculation method more intuitive, the detailed carbon emissions generated by each item of the SC 750 kV transformer substation are listed in Appendix A.

$$E_{total} = \sum(aE_b + bE_f) \tag{2}$$

2.3. Parameter Stochastic Analysis

The result of the carbon emissions of a transformer substation is usually a single, definite value. Due to the impact of engineering quantity, terrain, and other factors, the carbon emissions of different transformer substations are quite different, and it is difficult for a single definite value to represent the impact of the environment on data due to the lack of an uncertainty range. Thus, it is essential to construct a model to analyze the uncertainty of carbon emissions based on a probability distribution [39,40]. Monte Carlo simulation is widely used in all stochastic modeling methods, which are based on probability and statistical distribution theory and used to generate random numbers for a certain kind of probability model. After generating the model and operating it enough times, the simulation results can be statistically analyzed. Monte Carlo simulation is less constrained by geometric conditions, and the probability of convergence is independent of dimension. Thus, Monte Carlo simulation is adopted in this paper to evaluate the influence of parameter stochastic on results. The beta distribution, which has upper and lower limits, represents the probability of a random variable in a closed interval. Moreover, beta distribution is flexible and may exist in various shapes; whether it is symmetrical or not depends on data distribution, so it is the most consistent with the substation carbon emission distribution [41,42]. However, beta distribution requires that the variables be in the interval [0, 1]. Therefore, beta-pert distribution, a special case of beta distribution, is considered in this paper. The maximum value, minimum value, and most optimistic values of carbon emissions are required to complete the estimation of probability distribution parameters. The probability density function, distribution function, and shape parameters are shown as follows:

$$f(r';\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} r'^{(\alpha-1)}(1-r')^{\beta-1} \tag{3}$$

$$F(r';\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \int_0^{r'} y^{\alpha-1}(1-y)^{\beta-1}dy \tag{4}$$

$$r' = \frac{r - r_0}{r_1 - r_0} \tag{5}$$

$$\mu = \frac{r_0 + 4r_m + r_1}{6} \tag{6}$$

$$\alpha = \frac{(\mu - r_0)(2r_m - r_0 - r_1)}{(r_m - \mu)(r_1 - r_0)} \tag{7}$$

$$\beta = \alpha \frac{(r_1 - \mu)}{(\mu - r_0)} \tag{8}$$

where the density function is shown in Equation (3) and the cumulative distribution function is shown in Equation (4), α and β are the shape parameters, r_0, r_1 and r_m represent the maximum value, minimum value, and most optimistic value, respectively, and r is the variable.

In this paper, the Monte Carlo simulation of a probability density function based on the beta-pert distribution was carried out by the MATLAB software. The input sample determines the accuracy of the calculation, and the calculated carbon emissions are within a certain range. A total of 10,000 sets of carbon emission samples are generated and analyzed in the research [13,14]. The simulated results, including the mean value, standard deviation, coefficient of variation, and confidence interval, can be used to characterize the carbon emissions of the 750 kV substation in Xinjiang.

The construction of the newly built transformer substations Involves a variety of items, and the impact of carbon emissions on the uncertainty of the results varies from one to another. Therefore, the normalized Spearman's rank correlation coefficient is used to express the influence of output data on the uncertainty (IU) through MATLAB [20]. The formula for the calculation is shown as follows:

$$CE_i = E_i / E_t \tag{9}$$

$$IU_i = rho_p^2 / \sum_{i=1}^{t} rho_p^2 \tag{10}$$

$$rho_p = 1 - \frac{6}{s(s^2-1)} \times \sum_{r=1}^{s} [rg(X_{i,r}) - rg(Y_r)]^2 \tag{11}$$

E_i is the simulation result of item i, and E_t is the result of carbon emissions from total engineering. s represents the total number of simulations, $X_{i,r}$ and Y_r are the input and output of the simulation r, respectively, and $rg(X_{i,r})$ and $rg(Y_r)$ represent the rank of $X_{i,r}$ and Y_r in all simulations. rho_p represents the rank correlation coefficient among the input i and the output results. IU_i is the influence of item i on carbon emissions.

3. Results and Discussion

3.1. Transformer Substation Carbon Emission Results

3.1.1. Carbon Emissions from Construction Engineering

The construction engineering of a 750 kV transformer substation can be divided into main production buildings, electricity distribution buildings, water supply buildings, fire-fighting buildings, station buildings, and special buildings. In this paper, five groups of real substation projects are selected, and the carbon emissions of construction engineering are presented in Figure 3.

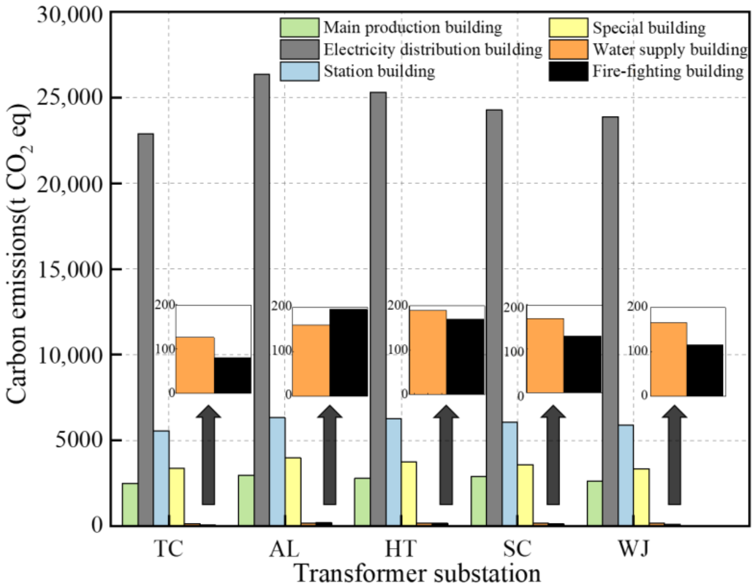


Figure 3. Carbon emissions of construction engineering in each transformer substation.

The main production building is the core of the transformer substation, responsible for operation, management, logistics, and other functions. It includes a main control and communication building, multiple relay rooms (750 kV, 220 kV, and 66 kV), a distribution room, an equipment room, a guardhouse, etc. The construction of the main production building mainly includes earthwork excavation, formwork erection, concrete spouting, masonry works, roof waterproofing, etc. Construction materials consist of reinforced concrete slabs, beams, columns, lump materials, and wall decoration. Carbon emissions generated by earthwork excavation and foundation engineering account for a considerable proportion, and soil quality is the main influencing factor. According to the geological report, the foundation soil of the TC transformer substation is mainly gravelly sand, and the mineral composition includes quartz and feldspar. The favorable soil condition facilitates earthwork excavation, resulting in low construction costs. Therefore, carbon emissions related to the main production building in the TC transformer substation are the lowest, accounting for 2500.18 t CO_2 eq. The foundation soil of the WJ and SC transformer substations is mainly silt and silty clay, which belongs to saline soil and has frost-heaving properties. Hence, part of the foundations should be treated with dynamic compaction or use gravel piles. The foundation soil of the HT and AL substations is mainly solid soil with a high content of gravel and crushed stone; excavation requires more manpower and machinery. In addition, there is severe salinization around the AL substation, which is on medium-saline soil. Sulfate-resistant cement is used in the concrete, and it is mixed with fly ash to reduce the sulfate corrosion of the foundation. Therefore, AL substation has the largest investment in the main production building, generating the most carbon emissions, reaching 2977.48 t CO_2 eq. Figure 4 shows the proportion of carbon emissions related to each item in the substations. In general, carbon emissions from the main production building account for 7.3% of construction engineering.

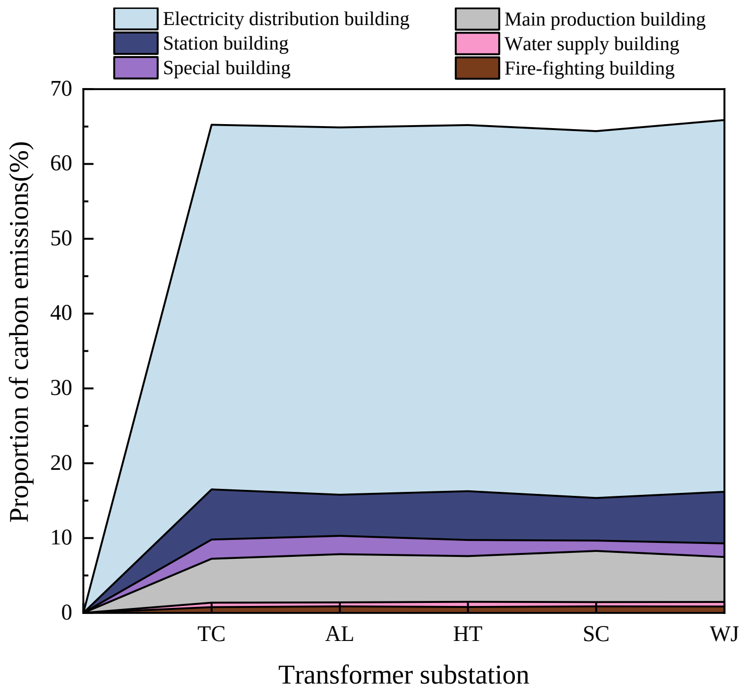


Figure 4. Carbon emissions proportion of each item in construction engineering.

The electricity distribution building is an important part of the transformer substation; it includes the main transformer system, frames and equipment foundations, high-voltage reactor system, station transformer system, lighting rod tower, conduit line, and barrier. Carbon emissions related to electricity distribution buildings account for 65.7% of construction engineering. Among them, the TC transformer substation produces the least, accounting for 22,288.31 t CO_2 eq, while the AL transformer substation generates the most, accounting for 26,369.47 t CO_2 eq. As the main structure of the transformer substation, the frames cover more than 50% of the area. The carbon emissions are closely related to the amount of steel and concrete used in the construction process. Based on the geological report, the TC substation is located in a favorable area for earthquake resistance; it has better formation stability, and the seismic intensity is 6 degrees. The seismic intensity of other substations is 7 degrees, belonging to the general area of earthquake resistance, which needs to apply the lattice frame, resulting in an increased cost. Furthermore, the horizontal tension caused by lateral wind pressure and the load caused by the ice-covering of wires and insulators should be considered in the construction of the frames. The AL transformer substation is located in the valley tuyere area of Northern Xinjiang province, with high wind speeds and low temperatures in winter. Therefore, the frame structure of the AL substation is more complex, covers a larger area, and generates more carbon emissions than other projects. In addition, carbon emissions from conduit lines and barriers are mainly associated with the land area.

Station buildings consist of site formation, station road and square, drainage pipeline, walls, and gate. Carbon emissions are responsible for about 16.2% of the construction engineering, and they are closely related to the size of the substation. Special buildings include foundation treatment, the construction of road and drainage outside the station, and the retaining wall. They are closely associated with soil quality, accounting for about 10% of carbon emissions. Furthermore, water supply buildings and fire-fighting buildings are responsible for 0.48% and 0.32% of carbon emissions in construction engineering, respectively.

3.1.2. Carbon Emissions from Installation Engineering

The installation engineering can be divided into the main transformer system, electricity distribution equipment, reactive compensation device system, control/direct current system, auxiliary power system, full station debugging, cable/earthing system, and communication/telecontrol system. Carbon emissions from installation engineering in each transformer substation are listed in Figure 5.

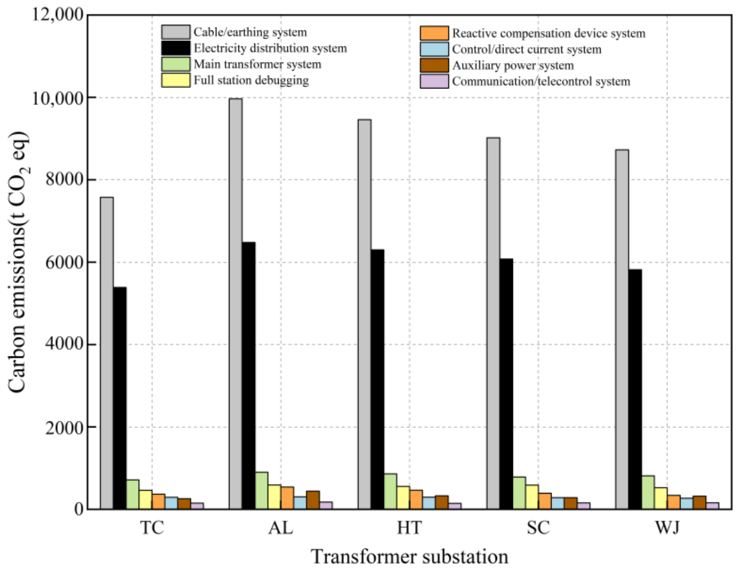


Figure 5. Carbon emissions of installation engineering in each transformer substation.

In a cable/earthing system, a large amount of power cables is used to transmit and distribute electrical energy, and control cables connect each electrical equipment and transmit the internal signals to implement the control and detection of transformer substations. In addition, cable auxiliary facilities, fire protection facilities, and earth grounding require a large number of materials and manpower, making carbon emissions related to cable/earthing systems responsible for more than 50% of installation engineering. The investment in the cable/earthing system is closely related to the station area and distribution equipment. Based on Figure 6, the TC transformer substation produced the least carbon emissions corresponding to the cable/earthing system, accounting for 7577.04 t CO_2 eq, while the AL substation produced the most emissions, amounting to 9967.36 t CO_2 eq. About 34% of the carbon emissions from installation engineering are generated by electricity distribution equipment. Carbon-intensive products, including switch plants, arresters, and voltage transformers, contain a large amount of metal and building materials. Due to geographical location and station area, the cost of distribution equipment in each substation is different, leading to the discrepancy in carbon emissions. The main transformer system is the core of the substation; it is the key device to ensure the safe and stable operation of the power supply. The transport and installation costs of transformers account for the largest proportion of this part. The AL transformer substation is located in Altay, Northern Xinjiang, with the most inconvenient traffic conditions and the longest transportation distance among the selected substations. The HT transformer substation is located in Southern Xinjiang, which is far away from the city, increasing the cost of transportation as well. The rest of the substations are relatively close to cities, resulting in lower transport costs and associated carbon emissions. Full station debugging consists of equipment debugging and gas trials; numerous amounts of energy and materials will be consumed during the process of debugging. As the carbon emission intensity of the relevant test is 1.33, which is lower than other items, the difference in carbon emissions among the substations is not obvious. The rest of the systems play a significant role in the transformer substation as well. On account of the limited quantities of relevant carbon-intensive products, carbon emissions generated by these systems amount to a relatively low proportion in the installation engineering.

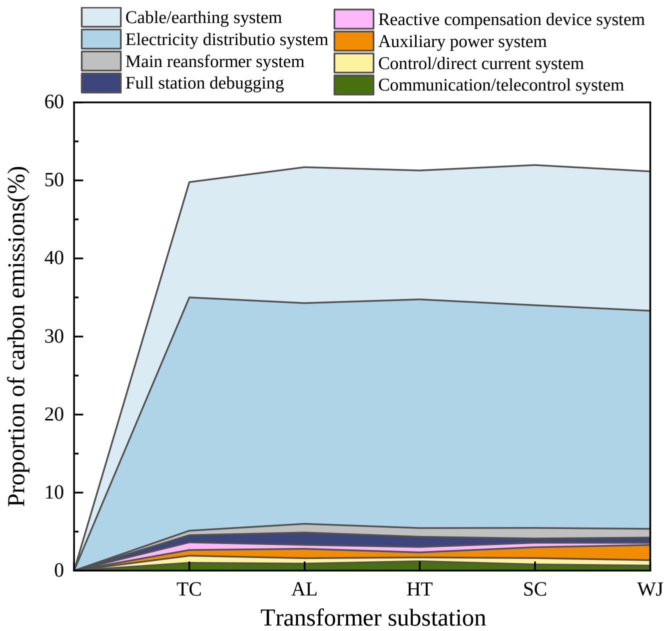


Figure 6. Carbon emissions proportion of each item in installation engineering.

3.1.3. Carbon Emissions of Additional Service

In the calculation of carbon emissions in newly built transformer substations, besides the construction and installation engineering, carbon emissions related to additional services cannot be ignored. Carbon emissions from additional service in each transformer substation are listed in Figure 7, and the proportion is shown in Figure 8. The cost of additional services incorporates technical service fees, construction management fees, project supervision fees, heavy cargo transportation measure fees, and production preparation fees. As the most significant part of the early stages of construction, the technical services can be categorized into feasibility study, survey, design, review, soil and water conservation study, pile test and inspection, etc. In the process of a feasibility study and survey, researchers will travel to the preselected site to conduct geotechnical experiments. Transportation and testing will produce numerous carbon emissions, which are easily overlooked. Carbon emissions in the process of design and review mainly considered the consumption of electricity caused by office equipment. Emissions related to environmental assessment and pile tests are associated with transportation and equipment as well. Carbon emissions of technical services that are not easy to calculate can be well estimated after using the calculation method illustrated in this paper and account for about 60% of the emissions of the additional services. The construction management fees are mainly composed of transportation fees, tool usage fees, bidding fees, cost consulting fees, etc. These items have low investment and carbon emission intensity. Thus, they generate fewer carbon emissions, only accounting for 4% of the additional services. The project supervision fees consist of construction supervision and equipment supervision. Due to the long cycle and largely involved contents, carbon emissions generated in the supervision amount to 18.5% of the additional services. Transportation costs for construction materials and electrical equipment have been accounted for in the related items. So, the costs of the remaining goods, such as office appliances and furniture, are attributed to heavy-cargo transportation measure fees, which generate about 5% of the carbon emissions. Furthermore, production preparation fees include vehicle purchase expenses and staff training fees, which produce about 7% of the carbon emissions. In general, each substation has a different proportion of carbon emissions from additional services due to its geographical location and design requirements, but the gap is not large.

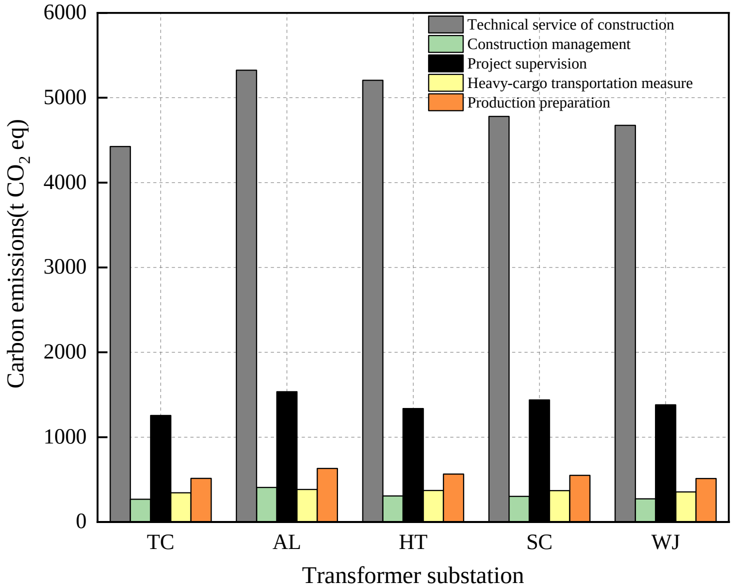


Figure 7. Carbon emissions of additional service in each transformer substation.

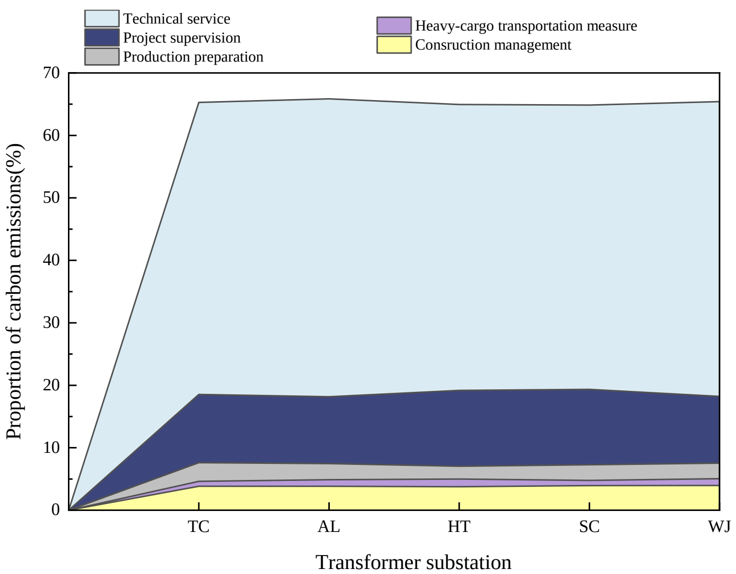


Figure 8. Carbon emissions proportion of each item in additional services.

3.1.4. Discussion about the Proposed Method and Carbon Emissions

The proposed method in the paper is capable of giving a comprehensive and accurate calculation of carbon emissions for 750 kV transformer substations. First, the energy structure of China is different from that of European countries; the carbon intensities used in this paper correspond to the economic sector of China, which is more in line with the actual situation [18]. Second, this paper has established a detailed construction list, which has a wider accounting scope, is not limited to a specific process or device, and can provide a reference for the same type of transformer substation. In addition, previous studies used the LCA method to calculate carbon emissions, which was based on the carbon emission factor of the base year. With the progress of technology and the change in energy structure, there is a lag in updating the relevant data, which results in poor accuracy of the calculation results [43]. While the hybrid method used in the paper is based on the economic sector, which has higher reliability.

The results of the carbon emissions are based on the construction lists of the newly built substations. However, in the actual engineering, part of the project will be reserved for future expansion or renovation due to the limitation of funds or materials. Furthermore, due to the long construction period of the expansion, there is a lag between engineering quantities and investment funds, resulting in calculation results that may be inconsistent with the actual situation. In addition, the distribution equipment and main transformer system of the ultra-high voltage (UHV) substation are different from the conventional substation, and the investment in the UHV substation includes dispatch costs and interface costs for different regions [16]. Further research should focus on establishing the substations' construction lists and comparing carbon emissions at different voltage levels.

3.2. Parameter Stochastic Analysis

Based on the data calculated in Section 3.1, due to the geographical location, soil quality, climatic conditions, land area, and other factors, the investment cost of each newly built 750 kV transformer substation is quite different, resulting in associated carbon emissions that differ from each other. Therefore, it is necessary to research the interval and distribution trend of carbon emissions from substations in Xinjiang and find possible carbon reduction methods to provide references for similar projects.

In order to evaluate the impact of input parameters and give the interval of carbon emissions, Monte Carlo simulation and analysis are conducted in the present paper. Due to the influence of geographical location, the selected transformer substations have certain regional representations in soil quality, foundation types, transportation cost, and other aspects. Beta-pert distribution requires the maximum, minimum, and most optimistic values, so the data of the selected transformer substations in Xinjiang Province, which were provided by construction organizations, were calculated and classified. After completing the data statistics, 10,000 sets of Monte Carlo simulations based on the beta-pert distribution were generated. It should be noted that the minimum and maximum values of carbon emissions are the sum of the minimum and maximum of each item in the substations, representing the theoretical range. While the most optimistic value is the average of several substations that are close in the data.

The results of the Monte Carlo simulation are shown in Figure 9. Interval [61,500, 63,000] has the largest frequency; the mean value and standard deviation are 62,317.59 t CO_2 eq and 2096.59 t CO_2 eq, respectively. The 90% confidence interval of the carbon emissions in the Monte Carlo simulation is [58,871.04, 65,759.34] t CO_2 eq, and the discreteness of the uncertainty analysis, which can be expressed by the coefficient of variation, is 0.034. The data obtained through Monte Carlo simulation has less discreteness, and the 90% confidence interval can be used to represent the carbon emission interval of the newly built 750 kV transformer substations in Xinjiang province or similar terrain.

Various items are involved in the calculation of carbon emissions, which can affect the results of the simulation. Therefore, it is necessary to evaluate the contribution of each item to the uncertainty of the results and explore appropriate carbon reduction schemes.

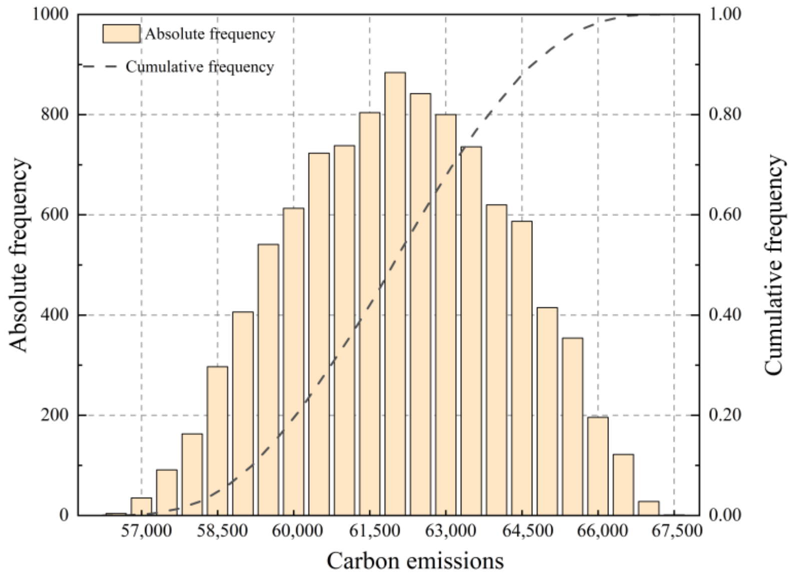
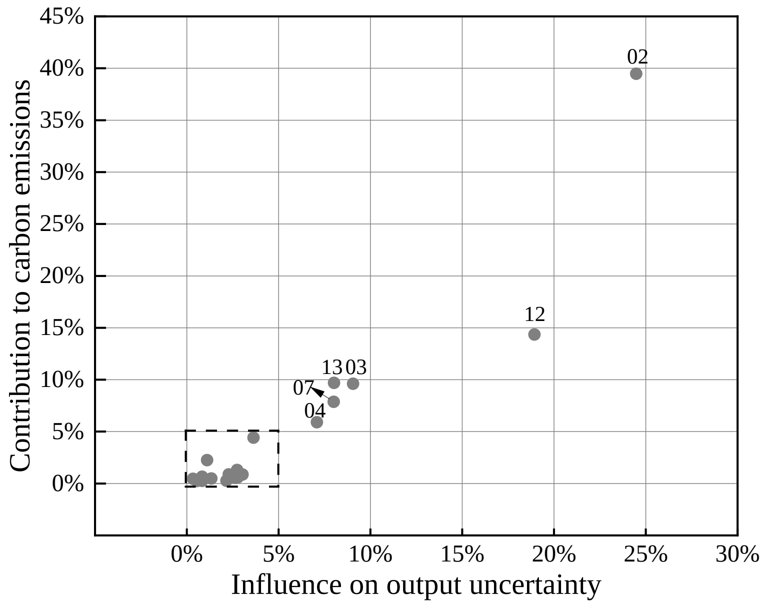


Figure 9. Results of Monte Carlo simulation in 750 kV transformer substations.

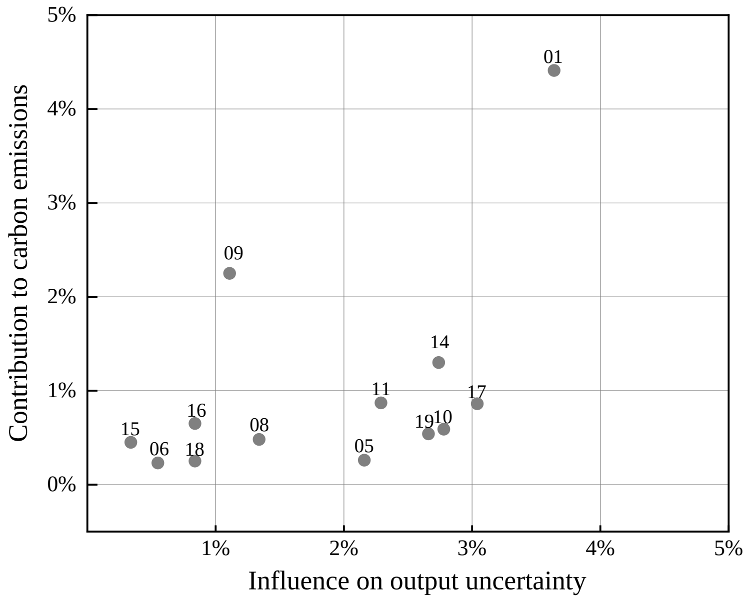
As shown in Figure 10, the electricity distribution building accounts for the largest proportion of total carbon emissions; the larger range of emissions has a more significant influence on IU. The cable/earthing system is another factor that contributes more than 15% to IU in substations. The contribution to carbon emissions and IU of most items is concentrated in the range of [0%, 5%], which is shown in Figure 10b. Generally, items with larger carbon emissions contain more carbon-intensive products; the uncertainty of the quantity will make the change in IU more obvious. Carbon-intensive products such as steel reinforcement, cement, masonry, and cables should be emphasized in carbon reduction. According to the calculated data and available technology, some carbon reduction measures have been proposed in this paper. Using environmentally friendly building materials, such as low-clinker content cement or low-carbon gel materials to substitute Portland cement in construction engineering, is an effective measure for carbon reduction. The newly built transformer substations under the existing technology are mainly cast-in-situ. However, building industrialization is considered one of the most effective ways of fostering sustainable development, and prefabricated buildings have been extensively promoted in China. With the advancement of related technology, the application of prefabricated assembly structures in transformer substations will become more extensive and have a more positive impact on carbon emission reduction. Buildings can use steel structures that can be dismantled for recycling after reaching their service life. Likewise, cable trenches and walls can be prefabricated to save on concrete. Moreover, using local materials as much as possible can save a large amount of carbon emissions from transportation.

3.3. Influence of Different Types of Foundations on Carbon Emissions

Currently, the construction and development of China's power grid have made a qualitative leap. With the development of a low-carbon economy and smart power grid, the construction of the power grid has been evolving in the direction of resource-saving and environment-friendly practices under the premise of ensuring safe operation. Carbon emissions related to the construction engineering of newly built transformer substations account for more than 50% of them, and the types of foundations have a significant impact. Therefore, it is necessary to investigate the foundation types and related carbon emissions, which is helpful to explore possible carbon reduction measures.



(**a**)



(**b**)

Figure 10. Influence of each item on output uncertainty. (**b**) is a partial enlargement of (**a**) within the range of [0%, 0%] to [5%, 5%]. Bubbles 01 to 19 represent the main production building, electricity distribution building, station building, special building, water supply building, fire-fighting building, technical service of construction, construction management, project supervision, heavy-cargo transportation measure, production preparation, cable/earthing system, electricity distribution system, main transformer system, full station debugging, reactive compensation device system, control/direct current system, auxiliary power system, and communication/telecontrol system, respectively.

The main production building (main control communication building, relay rooms, distribution rooms, equipment rooms, and guardhouse) is framed, and the foundations are mostly independent foundations. However, due to the soft foundation soil, the partial equipment room and guardhouse also use strip foundation. Foundation types, engineering quantities, and costs of the electricity distribution building are closely related to switchgear in selected substations. The selection of switchgear and device types is an important part of the design of transformer substations. At present, gas-insulated switchgear (GIS) and air insulated switchgear (AIS) are two ubiquitous distribution types [44]. GIS is an optimized combination of primary equipment except for transformers, which include circuit breakers, isolation switches, voltage transformers, arresters, and bus bars, which are all enclosed in a metal grounded shell and filled with SF_6 gas under a certain pressure. AIS is a traditional power distribution device that uses ceramic as the equipment shell and makes its primary equipment contact with the air directly. GIS has the advantages of a compact structure, a small occupied area, high reliability, and strong adaptability to the environment. The life of the design is up to 30 years, resulting in less work for maintenance. However, the disadvantage is that GIS is a completely closed piece of equipment with a high cost, and it cannot be quickly removed by external observation when a fault occurs. Compared to GIS, the overall structure for AIS is simple, it is conducive for daily overhaul and maintenance, and the clear equipment layout makes the expansion of the substation more convenient. However, the disadvantage of AIS is that it covers a wider area, and the exposed electrical components are easily affected by the environment. Moisture in the air attached to the surface may cause resistance reduction, breakdown of the insulation layer, or other failures that are not conducive to the safe operation of the substation. GIS has many advantages; however, due to the much higher purchase expenses of devices and relatively lower land acquisition costs in Xinjiang province, AIS has been widely used as well. Both of the switchgears will be taken into consideration in the substation design, and the most economical scheme will be selected.

Switchgear will lead to differences in foundation types and input costs, resulting in discrepancies in carbon emissions. As shown in Table 1, through the investigation of the selected substations, AIS has been adopted in the TC, AL, SC, and HT 750 kV transformer substations, and GIS has been adopted in the WJ substation. In order to compare the differences between substations that adopt GIS, the present paper analyzes the data of 750 kV transformer substation RQ, which is under construction. RQ 750 kV transformer substation is located in the southeast Gobi area of Tarim Basin. The type of foundation soil is hard soil, mainly composed of breccia, and saline foundation soil is highly corrosive to the concrete structure. According to the design, there are two sets of main transformers (1500 MVA), a four-circuit 750 kV overhead line, and a ten-circuit 220 kV overhead line.

Table 1. Form of switchgear in selected 750 kV transformer substations.

Form of Switchgear	Transformer Substation
AIS	TC, AL, SC, HT
GIS	WJ, RQ

There is no difference between GIS and AIS in the main transformer and secondary systems. The main transformer frames, 750 kV frames, 220 kV frames, and 66 kV frames, and the lightning rod tower of the two schemes all have independent foundations. When adopting the AIS scheme, the foundations of the main transformer, distribution equipment, HV reactor, and LV capacitor are built with slab foundations. While using the GIS scheme, distribution equipment (750 kV, 220 kV, and 66 kV) uses raft foundations with buttresses, and the foundations of the main transformer, HV reactor, and LV capacitor are built with block foundations. Furthermore, the firewall and enclosure inside the transformer substation all adopt strip foundation. As shown in Figure 11, carbon emissions related to the foundations are calculated through the final account document. When using the AIS scheme, due to the construction of a large number of independent foundations, related carbon emissions are responsible for the biggest proportion. Among them, the 750 kV frame is the most critical factor because of its high height and large load. Slab foundations and strip foundations have relatively less impact on carbon emissions. When using the GIS scheme, the small floor space and compact structure make the engineering quantity of distribution frames drop significantly, especially for 220 kV frames. Meanwhile, a large amount of construction and the higher cost of the raft foundations make the related carbon emissions almost equal to those of the independent foundations. When the equipment uses a slab foundation, it is always necessary to overlay the strip foundation. During the construction of the block foundation, the construction joint is set between the base slab and the superstructure, and the cost is lower. On the whole, the equipment foundation uses block foundations, which generate fewer carbon emissions. Generally speaking, the procurement and transportation costs of GIS are much higher than AIS, but it covers a smaller area and has a lower land acquisition cost. The investment in equipment foundations and related materials is also lower. GIS is convenient for installation and reliable for operation, and it generates fewer carbon emissions. With the continuous increase in land costs, GIS will be adopted more in the newly built transformer substation, which is more in line with the development direction of the green power grid.

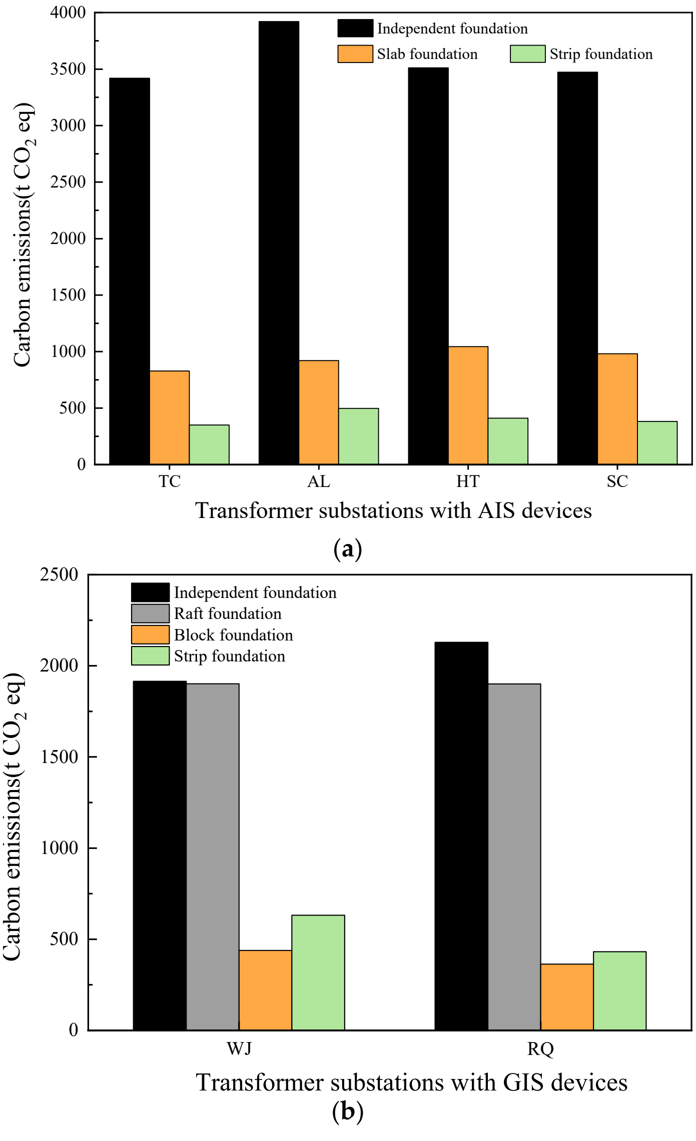


Figure 11. Carbon emissions related to the foundations of the 750 kV transformer substations. (**a**) is the carbon emission distribution of each type of foundation in substations adopting AIS devices. (**b**) is the carbon emission distribution of each type of foundation in substations adopting GIS devices.

4. Conclusions

To deal with different kinds of data sources and types feedbacked by different organizations involved in the construction process, when calculating and evaluating the carbon emissions in power transmission lines, the construction list and calculating method was proposed. Data were collected from a real project of west-to-east power transmission project to reveal and compare the actual situation of the emissions. Through the collection and analysis of field data from 750 kV transformer substations in Xinjiang, China, the confidence interval of carbon emissions in different transformer substations is calculated and revealed in detail. By identifying the key factors that affect the results through stochastic analysis and analyzing the influences of different types of foundations on carbon emissions, researchers can use them to guide carbon reduction efforts. The following conclusions are drawn according to the results:

1. The proposed method is capable of giving a comprehensive and accurate calculation of carbon emissions for transformer substations. The carbon emissions of the selected representative 750 kV substations are between 56,000 and 68,000 t CO_2 eq. In terms of item category, construction engineering generates the most carbon emissions, followed by installation engineering and additional services. From the economic sector, the manufacture of equipment for power transmission (code 78) and construction (code 95) have the most significant impact on carbon emissions.
2. Through Monte Carlo simulation, the mean value and the standard deviation of carbon emissions for a newly built 750 kV transformer substation in Xinjiang are 62,317.59 t CO_2 eq and 2096.59 t CO_2 eq, respectively. The 90% confidence interval is [58,871.04, 65,759.34] t CO_2 eq. The simulation results can be used to describe the distribution of carbon emissions from 750 kV substations in Xinjiang or similar terrain, and the influence of output data on the uncertainty is determined by studying the key factors of carbon emissions.
3. Due to the differences between AIS and GIS equipment, different types of foundations will be built. When arranged with AIS, the equipment foundation is mostly a slab foundation. While arranging with GIS, mostly use the raft foundation for electricity distribution equipment and the block foundation for the HV reactor, LV capacitor, and main transformer. Through the calculation, AIS has no obvious advantage on carbon emissions, while GIS covers a small area and has high reliability in operation, which is more in accord with the development direction of smart grids and low-carbon economies.
4. The expansion or renovation of substations will cause a change in carbon emissions, so the accuracy and timeliness of construction lists and investments are significant. Due to the differences in different voltage levels of substations, further research will focus on the establishment of construction lists and a comparison of carbon emissions at different voltage levels.

Author Contributions: X.L.: Conceptualization, Methodology, Writing—review and editing; J.Z.: Resources, Writing—original draft; Y.H.: Formal analysis, Investigation; J.L. (Jiao Liu): Formal analysis, Investigation; S.D.: Writing—review and editing; G.Z.: Supervision, Methodology, Investigation; Y.Z.: Formal analysis, Visualization; J.L. (Jiawei Li): Formal analysis, Investigation; Z.N.: Formal analysis, Investigation. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Research Project of the State Grid Xinjiang Electric Power Corporation (No. 5230JK220001).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. (Carbon Emission Calculation of SC 750 kV Transformer Substation).

Item Component	Sector Code	Monetary Cost (1×10^4 CNY)	Carbon Intensity (t $CO_2/1 \times 10^4$ CNY)	Carbon Emission (t CO_2 eq)
1 Construction engineering				
1.1 Main production building				
1.1.1 Main control communication building				
Construction engineering cost	95	189.95	4.88	926.96
Installation materials cost	95	33.81	4.88	164.99

Table A1. *Cont.*

Item Component	Sector Code	Monetary Cost (1×10^4 CNY)	Carbon Intensity (t CO_2/1×10^4 CNY)	Carbon Emission (t CO_2 eq)
1.1.2 750 kV relay chamber				
Construction engineering cost	95	96.41	4.88	470.48
Installation materials cost	95	18.41	4.88	89.84
1.1.3 Main transformer and 220 kV, 66 kV relay chamber No. 1				
Construction engineering cost	95	43.90	4.88	214.23
Installation materials cost	95	7.89	4.88	38.50
1.1.4 Main transformer and 220 kV, 66 kV relay chamber No. 2				
Construction engineering cost	95	43.91	4.88	214.28
Installation materials cost	95	7.88	4.88	38.45
1.1.5 Substation power chamber				
Construction engineering cost	95	68.91	4.88	336.28
Installation materials cost	95	12.25	4.88	59.78
1.1.6 Security equipment room				
Construction engineering cost	95	30.02	4.88	146.50
Installation materials cost	95	5.97	4.88	29.13
1.1.7 Guardhouse				
Construction engineering cost	95	28.71	4.88	140.10
Installation materials cost	95	5.26	4.88	25.67
1.2 Electricity distribution building				
1.2.1 Frames and foundation				
Construction engineering cost	95	111.32	4.88	543.24
1.2.2 Foundation of main transformer				
Construction engineering cost	95	29.77	4.88	145.27
1.2.3 Main transformer oil pit and pebbles				
Construction engineering cost	95	66.80	4.88	325.98
1.2.4 Main transformer system firewall				
Construction engineering cost	95	57.57	4.88	280.92
1.2.5 Emergency oil pond				
Construction engineering cost	95	25.92	4.88	126.51
1.2.6 750 kV frames and foundation				
Construction engineering cost	95	2464.56	4.88	12,027.04
1.2.7 750 kV equipment support and foundation				
Construction engineering cost	95	401.92	4.88	1961.39
1.2.8 220 kV frames and foundation				
Construction engineering cost	95	652.86	4.88	3185.95
1.2.9 220 kV equipment support and foundation				
Construction engineering cost	95	181.32	4.88	884.86
1.2.10 66 kV frames and foundation				
Construction engineering cost	95	49.88	4.88	243.41
1.2.11 66 kV equipment support and foundation				
Construction engineering cost	95	28.68	4.88	139.96
1.2.12 HV shunt reactor foundation				
Construction engineering cost	95	76.41	4.88	372.87
1.2.13 HV shunt reactor oil pit and pebbles				
Construction engineering cost	95	99.08	4.88	483.51
1.2.14 HV shunt reactor firewall				
Construction engineering cost	95	148.56	4.88	724.97
1.2.15 Substation transformer				
Construction engineering cost	95	54.56	4.88	266.23
1.2.16 LV capacitor				
Construction engineering cost	95	7.88	4.88	38.45
1.2.17 LV reactor				
Construction engineering cost	95	24.67	4.88	120.39
1.2.18 Independent lighting rod tower				
Construction engineering cost	95	49.61	4.88	242.11
1.2.19 Conduit line				
Construction engineering cost	95	344.07	4.88	1679.05
1.2.20 Barrier and floor				
Construction engineering cost	95	102.35	4.88	499.45
1.3 Water supply building				
1.3.1 Substation water pipe				
Construction engineering cost	95	0.26	4.88	1.27
1.3.2 Integrated pumped house				
Construction engineering cost	95	18.58	4.88	90.67
Installation materials cost	95	15.52	4.88	76.74

Table A1. *Cont.*

Item Component	Sector Code	Monetary Cost (1×10^4 CNY)	Carbon Intensity (t CO_2/1×10^4 CNY)	Carbon Emission (t CO_2 eq)
1.4 Fire-fighting building				
1.4.1 Foam equipment chamber				
Construction engineering cost	95	24.30	4.88	118.58
1.4.2 Fire protection, alarm and detection				
Equipment purchasing	72	1.79	3.79	6.78
1.4.3 Special fire protection system				
Equipment purchasing	84	1.08	2.72	2.93
1.5 Station building				
1.5.1 Site formation				
Construction engineering cost	95	275.93	4.88	1346.54
1.5.2 Station road and square				
Construction engineering cost	95	500.37	4.88	2441.81
1.5.3 Drainage pipeline				
Construction engineering cost	95	188.88	4.88	921.73
1.5.4 Walls and gate				
Construction engineering cost	95	271.75	4.88	1326.14
1.5.5 Sewage pool				
Construction engineering cost	95	8.03	4.88	39.19
1.6 Special building				
1.6.1 Foundation treatment				
Construction engineering cost	95	129.01	4.88	629.57
1.6.2 Offsite roadway				
Construction engineering cost	95	247.61	4.88	1208.34
1.6.4 Offsite water supply and drainage				
Construction engineering cost	95	76.38	4.88	372.73
1.6.5 Retaining wall				
Construction engineering cost	95	282.57	4.88	1378.94
Subtotal				**37,148.71**
2 Installation engineering				
2.1 Main transformer system				
2.1.1 Main transformer				
Installation materials cost	79	88.45	3.84	339.65
Installation engineering cost	95	91.32	4.88	445.64
2.2 Electricity distribution equipment				
2.2.1 750 kV distribution device				
Installation materials cost	79	538.61	3.84	2068.26
Installation engineering cost	95	314.77	4.88	1536.08
2.2.2 220 kV distribution equipment				
Installation materials cost	79	485.75	3.84	1865.27
Installation engineering cost	95	82.14	4.88	400.84
2.2.3 66 kV distribution equipment				
Installation materials cost	79	38.78	3.84	148.91
Installation engineering cost	95	12.14	4.88	59.24
2.3 Reactive compensation device system				
2.3.1 750 kV HV shunt reactor				
Installation materials cost	79	21.28	3.84	81.71
Installation engineering cost	95	32.94	4.88	160.75
2.3.2 66 kV capacitor				
Installation materials cost	79	0.93	3.84	3.57
Installation engineering cost	95	4.39	4.88	21.42
2.3.3 66 kV reactor				
Installation materials cost	79	6.03	3.84	23.15
Installation engineering cost	95	20.71	4.88	101.06
2.4 Control/direct current system				
2.4.1 Control system				
Installation engineering cost	95	19.67	4.88	95.99
2.4.2 Relay protection				
Installation engineering cost	95	15.97	4.88	77.93
2.4.3 Direct current system				
Installation engineering cost	95	22.85	4.88	111.51
2.5 Auxiliary power system				
2.5.1 Station transformer substation				
Installation engineering cost	95	11.51	4.88	56.17
2.5.2 Substation power distribution				
Installation engineering cost	95	0.92	4.88	4.49

Table A1. *Cont.*

Item Component	Sector Code	Monetary Cost (1×10^4 CNY)	Carbon Intensity (t CO_2/1×10^4 CNY)	Carbon Emission (t CO_2 eq)
2.5.3 Substation lighting				
Installation materials cost	81	52.90	3.70	195.73
Installation engineering cost	95	5.57	4.88	27.18
2.6 Cable/earthing system				
2.6.1 Power cable				
Installation materials cost	79	443.72	3.84	1703.88
Installation engineering cost	95	15.66	4.88	76.42
2.6.2 Control cable				
Installation materials cost	79	359.29	3.84	1379.67
Installation engineering cost	95	179.27	4.88	874.84
2.6.3 Cable auxiliary device				
Installation materials cost	78	365.21	3.57	1303.80
Installation engineering cost	95	72.72	4.88	354.87
2.6.4 Cable fire protection				
Installation materials cost	72	153.12	3.79	580.32
Installation engineering cost	95	27.23	4.88	132.88
2.6.5 Substation earthing				
Installation materials cost	79	533.87	3.84	2050.06
Installation engineering cost	95	115.34	4.88	562.86
2.7 Communication and motor system				
Installation materials cost	79	20.43	3.84	78.45
Installation engineering cost	95	16.29	4.88	79.49
2.8 Full station debugging				
Debugging	118	441.88	1.33	587.70
Subtotal				**17,589.79**
3 Additional service				
3.1 Technical service of construction				
3.1.1 Survey expenses	118	725.00	1.33	964.25
3.1.2 Design fees	118	1891.00	1.33	2515.03
3.1.3 Feasibility study and design	118	30.00	1.33	39.90
3.1.4 Inspection of the electric power device	118	124.00	1.33	164.92
3.1.5 Environmental monitor and inspection	118	330.00	1.33	438.90
3.1.6 Pile test, inspection and settlement	118	255.00	1.33	339.15
3.1.7 Inspection of soil and water conservation	122	20.00	2.55	51.00
3.1.8 Supervision of special equipment safety	118	200.00	1.33	266.00
3.2 Construction management				
3.2.1 Construction management fees	118	226.71	1.33	301.52
3.3 Project supervision				
3.3.1 Project supervision fee	118	1082.16	1.33	1439.27
3.4 Heavy-cargo transportation measure				
3.4.1Heavy-cargo transportation fees	97	150.70	2.45	369.21
3.5 Production preparation				
3.5.1 Vehicle purchase fees	74	102.30	3.26	333.50
3.5.2 Staff training and advance fees	126	128.38	1.68	215.68
Subtotal				**7438.33**
Total				**62,176.83**

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