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Optimization Model of Substation Building Envelope–Renewable Energy Utilization Based on Life-Cycle Minimum Carbon Emissions

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Abstract: Maximizing the carbon reduction in substations with minimum cost investments can be achieved by taking advantage of the potential of substations in terms of the envelope and renewable energy, which is significant in promoting carbon reduction in substations. Therefore, firstly, the relationship between building cost–energy consumption–carbon emissions is explored, and then the global optimal calculation model of substation envelope–renewable energy is established, with the lowest life-cycle carbon emission of the substation as the optimization goal. Finally, the validity of the model is verified based on a case study of a typical 110 kV outdoor substation. The model calculation results show that, without considering the cost constraint, Harbin has the highest maximum carbon reduction of 180,350 kg, which is 25.15% and 13.74% higher than the maximum carbon reduction in Shanghai and Haikou, respectively. Furthermore, based on the comparison of the cost and benefits of each carbon reduction technology, a prioritization of various carbon reduction technologies is given for each climate zone. The model established in this paper can provide the optimal configuration of substation carbon reduction technologies with different incremental cost constraints, and provide a reference for the low-carbon design of substations.

Keywords: substation; life-cycle carbon emission; carbon reduction technologies; coordination optimization; global optimal

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1. Introduction

With the increase in power conversion and consumption throughout society, the number of substations, which is the key node for power conversion and transportation, is increasing. More than 8000 substations were constructed from 2016 to 2020 [1]. Unlike general industrial buildings, the heat generated by indoor equipment in the substation is considerable, and heat production is much greater than heat dissipation. However, the traditional energy-saving design of substations mainly focuses on heat insulation and ignores heat dissipation, which leads to high energy waste. Therefore, substations have great potential for carbon reduction, and the low-carbon design for substations is one of the essential ways to achieve the goal of carbon reduction for the whole society.

Carbon reduction technologies for substations can be summarized in four categories: building energy efficiency, energy supply substitution, operation optimization, and equipment carbon reduction [2,3]. In terms of building energy efficiency, the research at present focuses on passive technologies, such as the energy-saving design of envelopes and optimization of building layouts [4,5]. In terms of energy supply substitution, scholars suggest the use of photovoltaic (abbreviated as "PV"), wind power, geothermal, and other clean

energy sources to solve station electricity demands [6]. In operation optimization, it is useful to build a substation carbon management system to improve the utilization rate of PV and equipment operation efficiency in the station [2]. In equipment carbon reduction, the use of low-carbon and environmentally friendly electrical equipment is a common strategy [7].

These carbon reduction technologies promote the low-carbon development of substations. However, only "local optimal solutions" to a certain carbon reduction technology were obtained. Xi Chang et al. pointed out that there are considerable constraints against different carbon reduction techniques, which can lead to limitations in the practical application of univariate optimization methods [8]. Thus, to optimize the carbon reduction potential of carbon reduction technologies, and to achieve maximum carbon reduction levels in buildings with minimum cost investment, it is necessary to obtain the global optimal solutions of the building as a whole, as a system. Taking the building cost and energy consumption levels as the objective functions, a multi-objective optimization model for building envelope and lighting was established by B. Lartigue et al. to optimize the design of the building envelope with multiple parameters [9,10]. A new hybrid approach integrating energy simulation, orthogonal array testing (OAT), and data envelope analysis (DEA) was developed by Hongxian Li to optimize five aspects of the external envelope, window form, shading form, window-to-wall ratio, and airtightness, which was used to discover the best solution for energy efficiency retrofitting of buildings considering economics [11]. Considering the interaction and cost-effectiveness of the building envelope and energy system, Hangxin Li et al. proposed a coordinated design optimization method based on a multi-stage approach, which was used to optimize the design of the whole building [11,12].

Most carbon reduction technologies focus on carbon emissions in the operational phase, ignoring the implicit carbon generated in other phases (production and transportation of materials, construction, and demolition of the building) of the building's life cycle [13], which has been demonstrated to be an important factor affecting the building's life cycle [14]. With the increased application of energy-efficient technologies, although the energy consumption in the operational phase of the building gradually decreases, more materials are used in the building and the implied energy accordingly takes up a larger share; therefore, the life-cycle carbon emissions may increase [15]. L.J. Hurst indicated that, in some types of buildings, the implied carbon can account for 50~70% of the total life-cycle carbon emissions [16], even increasing to 112% in zero-energy buildings [17,18]. Hence, the studies related to low-carbon buildings usually consider the comprehensive cost-effectiveness of the construction and operation phases, take the building life-cycle carbon emissions and the total cost as the optimization objective functions, and establish a multi-objective optimization model to maximize the carbon reduction with limited cost investments [19].

Optimization means finding the best solution among all available options to satisfy the constraint [20]. A large number of optimization methods have been developed to deal with numerous types of optimization problems. The classification of optimization problems and algorithms is an important basis for the development of new optimization strategies and the selection of appropriate algorithms for a given problem, and for this reason, a systematic description of the optimization problems in the field of building is presented in the literature [21–23]. Main optimization methods can usually be divided into the following three categories: 1. exhaustive or enumerative methods, based on the analysis of all possible points in the search space to find the best solution; 2. calculus methods, based on mathematical expressions or gradients, to find the value of the variable that provides the best value for the objective function [24]; and 3. stochastic methods, which are usually guided by bio-inspired or other methods to select and generate points in the search space [25], for example, genetic algorithms [26], simulated annealing, and bee colony algorithms. Optimization methods applied to building design or retrofit should be selected according to the specific optimization objectives and optimization variables.

To date, for building optimization problems, the common form is to use genetic algorithms in optimization tools combined with simulation software, with factors such as the building envelope as the optimization variable and cost and energy efficiency as the optimization objective. For example, M. Fesanghary et al. proposed a multi-objective optimization model based on the harmony search (HS) algorithm with minimizing the life-cycle cost (LCC) and carbon dioxide equivalent (CO2-eq) emissions of the building as the objective functions, with the building envelope parameters being used as a design variable [27]. Maria Ferrara et al. used a combination of TRNSYS (dynamic energy simulation software) and GenOpt (generic optimization program) to find the optimal cost building configuration within the regulatory framework used at present, using the global cost function (EN15459 standard) as the objective function for optimization, and the particle swarm optimization algorithm was used to minimize the objective function [28]. Gerber D chose Model Center as the process integration and design optimization software, and used genetic algorithms to create a multi-objective optimization model to optimize the configuration of building geometry and structural parameters [29]. Sadik Yigit et al. developed a package that combined customized thermal simulation software with MATLAB's Optimtool [30]. Daniel Tuhus-Dubrow et al. combined genetic algorithms with building energy simulation engines to build optimization models [31]. Fatima Harkouss et al. proposed a simulation-based multi-criteria optimization method for near-zero energy buildings (NZEBs) in order to minimize thermal and electrical demands and the life-cycle cost (LCC) while achieving a net-zero energy balance, using a non-dominated ranking genetic algorithm (NSGA-II) to obtain the Pareto optimum of selected design parameters [32].

In addition, many scholars considered the coupling effect of building and energy systems for the integrated optimization of building envelope and air conditioning systems, such as, Fanny Pernodet Chantrelle et al., who developed a multi-objective optimization tool for building renewal, MultiOpt, using genetic algorithms (NSGA-II) coupled with TRNSYS and economic and environmental databases to focus on the building envelope, air conditioning loads, and control strategies [24]. Ivalin Petkov et al. proposed a multi-stage multi-objective scalable optimization framework (called MANGOret) to provide optimal configurations for multi-energy systems and envelope retrofitting of existing buildings [33]. Nawal Abdou conducted a multi-objective optimization using the multi-objective building optimization tool Mobo in combination with TRNSYS to find the optimal building envelope design and renewable energy system sizing for a net-zero energy building in Tetouan (Morocco) [34]. Yu-Hao Lin et al. developed a multi-objective optimization decision model (MOBELM) for a building envelope and air conditioning system energy performance with the help of MATLAB software, with the optimization objective of minimizing building costs and carbon emissions [35].

In addition, the comparison of different optimization algorithms for specific building optimization problems has also received attention from scholars. Youssef Bichiou et al. demonstrated a comprehensive energy simulation environment to optimize building envelope characteristics, as well as heating and air conditioning system designs and operation settings, with the objective of minimizing the whole life-cycle cost, and they compared the robustness and effectiveness of three algorithms, namely, genetic, particle swarm, and sequential search algorithms, in the simulation environment [36]. Yuehong Lu et al. conducted a comparative study of two design optimization methods for building renewable energy systems, including single-objective optimization using a genetic algorithm and multi-objective optimization using a non-dominated ranking genetic algorithm (NSGAII), showing that single-objective optimization provides the "best" solution directly for a given objective, while multi-objective optimization provides designers with a wealth of information to make better compromise decisions [37].

In addition to the commonly used optimization algorithms, Bo Wang et al. used a differential evolution (DE) algorithm with the optimization objective of maximizing energy efficiency and minimizing whole-life costs to find the most cost-effective building retrofit solution in the long term [38]. Junghans et al. introduced a hybrid single-objective building

optimization algorithm that combined an evolutionary genetic algorithm with an improved simulated annealing algorithm to compensate for the limitations of the GA algorithm when used alone [39].

Previous studies have focused on the optimization of building or energy systems in the operation phase; however, there are still few studies that consider the whole-life carbon emission and cost constraints to optimize all aspects of substations. Therefore, in this paper, we develop an optimization model of low-carbon substation technologies for the life cycle to obtain the maximum carbon reduction outcome under various incremental cost constraints.

The study is divided into three main steps. The first step explores the relationship between building costs–energy consumption–carbon emissions. The second step builds a global optimization model of the low-carbon substation with the lowest total carbon life-cycle emissions of the substation as the optimization objective and various carbon reduction technical parameters as the optimization variables. In the end, the validity of the model is verified by using a typical 110 kV outdoor substation as an example. Based on the model calculation results, an optimal configuration of building envelope–renewable energy for substations under various incremental cost constraints in different climate zones is presented, and suggestions are presented for the priority of using various carbon reduction technologies in different climate zones. The innovation of this paper lies in the comprehensive analysis of the relationship between cost, carbon emission, and energy consumption, and the calculation of the model that can optimize to the carbon reduction potential of a building envelope–renewable energy under a given cost constraint, and it also proposes an optimal allocation scheme to maximize the carbon reduction outcome, which provides a reference for low-carbon substation designs.

2. Methods

2.1. Theoretical Analysis

Firstly, the impact of carbon reduction technologies on energy consumption as well as carbon emissions calculated differently for the whole life cycle of substations was analyzed, taking building envelope insulation and photovoltaic power generation technologies as examples. Then, the coordinated configuration of multiple carbon reduction technologies in substations under limited costs was discussed to reveal the relationship between substation costs–energy consumption–carbon emissions.

2.2. Research Framework of the Optimization Model

The overall framework for the optimization model of minimizing carbon emissions from a substation building envelope–renewable energy system configuration based on the overall life cycle is shown in Figure 1, which is divided into three main steps. The first step was to obtain carbon reduction technologies that could be used in substations based on the field research, selecting optimization variables and setting up multi-factor crossover experiments, to obtain the correlation between carbon emissions and optimization variables, and the mutual constraints between the optimization variables through energy consumption simulations and mathematical calculations were calculated. The second step was to define the objective function based on the relationship equation between carbon emissions and variables obtained in the first step. At the same time, we set the constraints and initial values of the optimization model based on the inter-constraint relationship between the variables obtained in the first step and the boundaries of carbon reduction technologies obtained based on the field research. Finally, we chose the appropriate solution algorithm to solve this based on whether the optimization variables were derivable or not. Finally, the model calculation results were obtained, i.e., the optimal allocation scheme of the substation building envelope–renewable energy system for minimizing carbon emissions under the cost constraint for the life cycle.

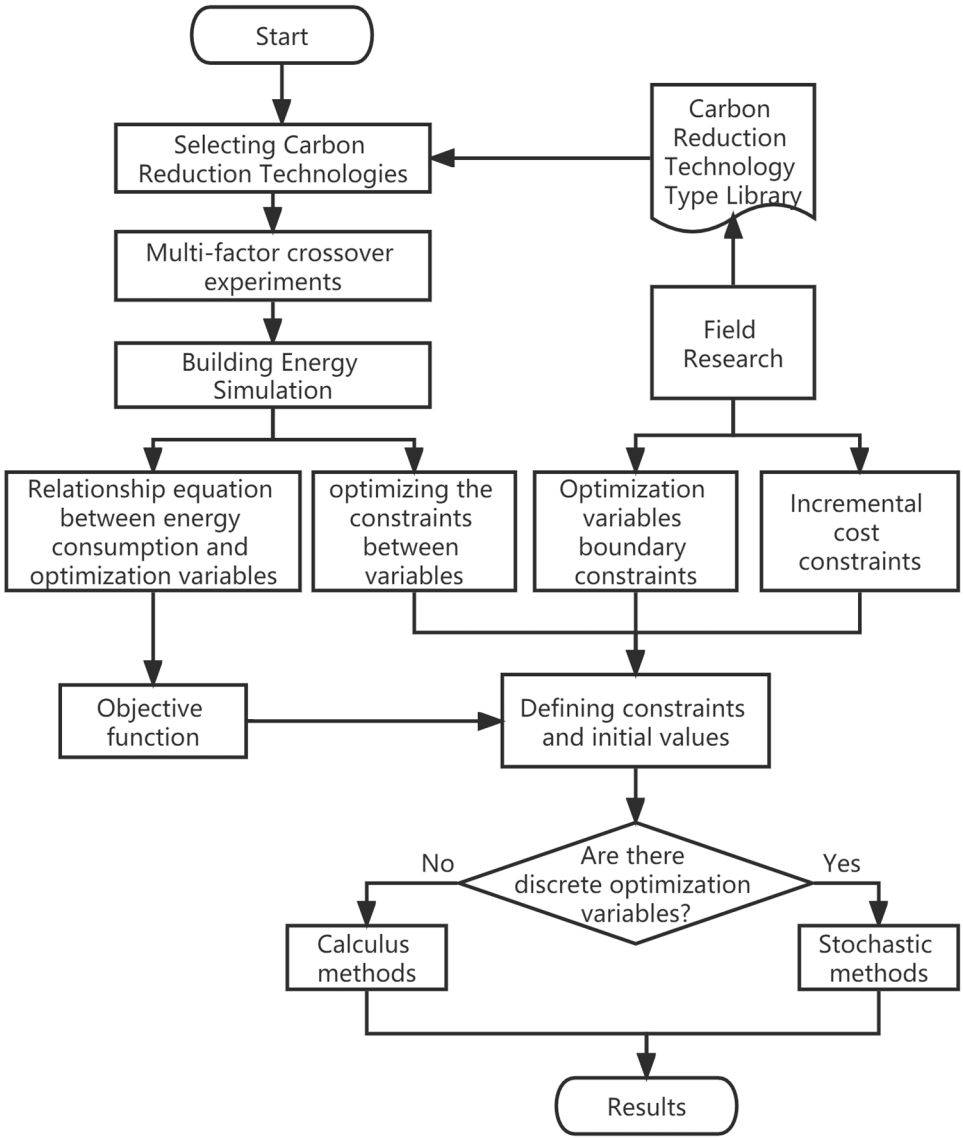


Figure 1. The optimization flowchart.

2.3. The Case Study

In this paper, a typical 110 kV outdoor substation was used to validate the optimization model. The general plan of the substation is shown in Figure 2. This paper mainly considered the synergistic optimization of the building envelope design of substations and the use of renewable energy, specifically the heat insulation technology for building facades, roofs, and exterior windows, as well as PV power generation technology.

The carbon reduction effect of building envelope energy savings and renewable energy use is influenced by climate, which varies greatly in the north and south of China. Different approaches were used to design low-carbon substations in different climatic conditions. To clarify the connection between buildings and the climate, the Chinese standard "Code for Thermal Design of Civil Buildings" divides the building thermal climate zones into medium, summer, warm, cold summer, cold, and cold regions, and three different climate zones were selected for study to illustrate the differences in the calculated results of the developed optimization model in different climatic zones, as shown in Table 1.

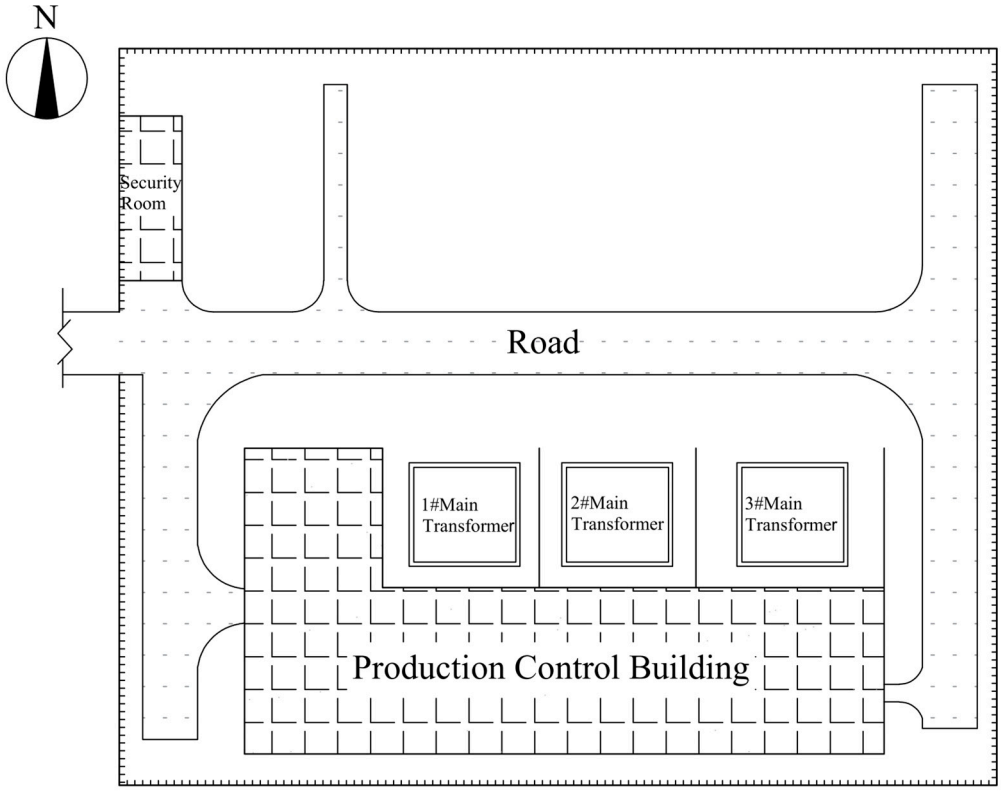


Figure 2. The general plan of the substation.

Table 1. Climate characteristics.

Climate Zone	Climatic Characteristics	City
Northern cold area	Severe cold and cold regions in China, the demand for heating in winter is high, and the demand for cooling in summer is low	Harbin
Central hot summer–cold winter area	Hot summer and cold winter regions in China, the demand for heating in winter is mid-level, and the demand for cooling in summer is mid-level	Shanghai
Southern hot summer–warm winter area	Hot summer and warm winter regions in China, the demand for heating in winter is low, and the demand for cooling in summer is high	Haikou

3. Coupling Relationship of Building Cost–Energy Consumption–Carbon Emission

Previous studies have shown that most low-carbon design strategies are beneficial in reducing energy demand levels during the operational phase of a building. However, this increases the hidden carbon emissions during installation and maintenance, as well as during demolition, and also increases the investment costs. Therefore, the interplay between building envelope–energy consumption and the cost needs to be thoroughly considered, and each carbon reduction technology needs to be optimally configured from a whole life-cycle perspective to obtain the maximum carbon reduction outcome under the cost constraints.

3.1. Analysis of the Carbon Reduction Effect of Typical Carbon Reduction Technologies in the Life Cycle

Envelope insulation is a common building energy efficiency measure that, to a certain extent, can effectively reduce the building air conditioning load and thus reduce carbon emissions during the building operation phase. However, the installation, enclosure and removal of materials during the use of insulation technology increases the invisible carbon

emissions during the whole life cycle of the building. In addition, due to the considerable heat generated by equipment in the substation building and the high environmental requirements, as the thickness of the insulation layer increases, the operating carbon emissions of the building show a trend of first reducing and then increasing. Therefore, when aiming for the lowest carbon emission in the whole life cycle, a local minimum may appear with the increase in the insulation thickness, as shown in Figure 3. Therefore, for special industrial buildings, such as substations, careful calculation and analysis are needed to find the global minimum value when using insulation technology for energy-saving renovations. the design of the envelope should not only consider energy saving outcomes in the operational phase and increase the thickness of building insulation, but also consider the carbon reduction capability during the whole life cycle.

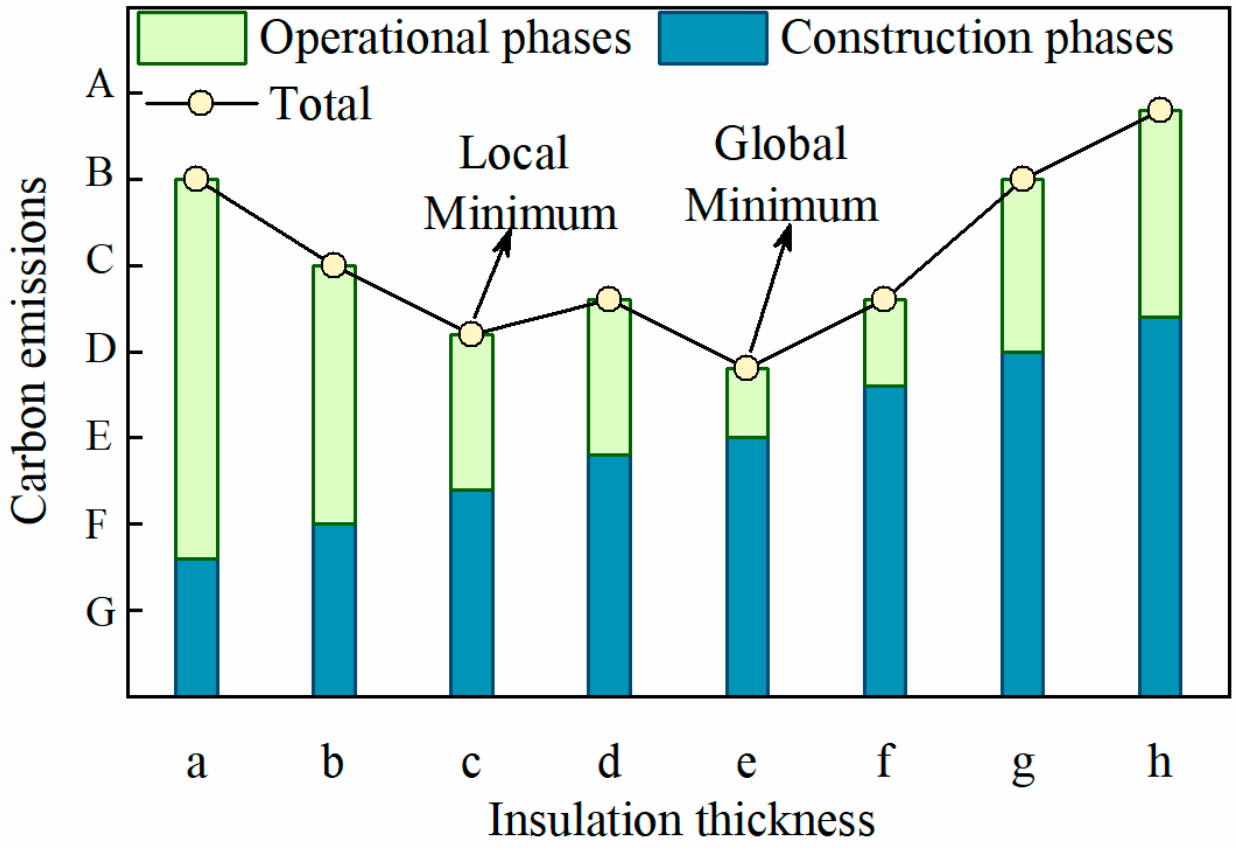


Figure 3. The impact of insulation thickness on the carbon emissions of buildings during the life cycle.

3.2. Coordinated Configuration of Multiple Carbon Reduction Technologies in Substations under Cost Limitations

The energy demand for room air conditioning can be reduced by reasonable building envelope configuration and, combined with renewable energy use for energy supply substitution, the carbon emission of the building can be significantly reduced [12,40]. However, it is necessary to compare the cost-effectiveness of different carbon reduction technologies to obtain the maximum carbon reduction by the optimal configuration of different carbon reduction technologies at a limited cost. Taking a substation in Shanghai as an example, the optimization model calculates that, when the incremental cost constraint is CNY 600 thousand, the best configuration improves the carbon reduction by 11.23% over the worst arrangement of carbon reduction technology throughout the life cycle.

Therefore, it is essential to coordinate various carbon reduction technologies to maximize the carbon reduction, producing minimum incremental costs. Considering the limited incremental cost, the first step was to filter the types of carbon reduction technologies that

could be utilized in the substation according to regional and climatic characteristics. Then, the carbon reduction targets, incremental cost limits, and the binding relationships between each carbon reduction technology were clarified. Finally, based on the costs and benefits of each carbon reduction technology, a cooperative optimization model of multiple carbon reduction technologies was established, and a suitable algorithm was selected to solve the problem and obtain carbon reduction technology configuration options that maximized the carbon reduction at a limited cost.

4. Coordinated Optimization Model of Multiple Carbon Reduction Technologies for Life-Cycle Substation

4.1. Optimization Objective Function

Carbon emissions from substation buildings are mainly produced in the construction and operation phases. Usually, the design and demolition phases only account for about 10% of the life-cycle carbon emissions. In this paper, the optimization goal was to minimize the total carbon emissions of the substation building in its life cycle. The objective function for building the optimization model is shown in Equation (1):

$$E_c = E_{de} + E_{co} + E_{ma} + E_{di} = (E_{co} + E_{ma})/(1 - 10\%) \quad (1)$$

where E_c is the total life-cycle carbon emissions of the substation (kg), E_{de} is the design-phase carbon emissions (kg), E_{co} is the construction-phase carbon emissions (kg); E_{ma} is the operational-phase carbon emissions (kg); and E_{di} is carbon emissions from the demolition phase (kg).

E_{co} consists of the construction-phase carbon emissions of the benchmark building and the carbon emissions produced by the use of various low-carbon technologies, as shown in Equation (2):

$$E_{co} = \sum_{i=1}^{n} E_{co,i} \times EF_i + \sum_{k=1}^{K} \sum_{i=1}^{n} E_{co,j} \times EF_j \quad (2)$$

where $E_{co,i}$ is the total energy of the i-th energy consumed during the construction phase of the benchmark building, e.g., coal, electricity, natural gas, etc. (kwh or kg); $E_{co,j}$ is the total amount of j-th energy used in the construction phase of the k-th low-carbon technology (kwh or kg); and i and j are the carbon emission factors of energy type i/j used in the baseline building and the added low-carbon technology, respectively. EF_i is the carbon emission factor of i-th energy used in the benchmark building. EF_j is the carbon emission factor of i-th energy used for the added low-carbon technology (kg $CO_2 \cdot kWh^{-1}$ or kg $CO_2 \cdot kg^{-1}$).

The carbon emissions from the operational phase of the substation building are equal to the carbon emissions from the operational phase of the benchmark building minus the reduction in carbon emissions due to the use of various low-carbon technologies, as shown in Equation (3):

$$E_{ma} = (E_{ma\text{-}bm} - E_{PV} \times EEF - E_{GF} - \sum_{k}^{l} E_{T,k}) \times n \quad (3)$$

where $E_{ma\text{-}bm}$ is the carbon emissions generated by the benchmark building during the operation phase (kg); E_{PV} is the annual PV power generation in the substation (kwh), calculation method (Ref. [41]); EEF is the grid carbon emission factor (according to the latest information released by the National Grid in 2022, the value is 0.5703 kg $CO_2 \cdot kWh^{-1}$); E_{GF} is the greenfield carbon sink of the substation and the value of carbon sink per unit area of green space is 0.34 kg$\cdot m^{-2}$; $E_{T,k}$ is the reduction in carbon emissions during the operational phase of the building due to the use of the k-th carbon reduction technology, which is calculated by the energy simulation software in Grasshopper (kg); and n is the substation building design life (a)—take the value of 30a.

4.2. Constraints

There are certain boundaries in the construction of carbon reduction technology. For example, the amount of insulation and the improvement of the thermal performance of windows are finite. The parameter setting of the constraint requires examining the performance boundaries of carbon reduction technology and setting the technical parameters of carbon reduction constraints, as shown in Equation (4):

$$Th_l \leq Th_k \leq Th_u \tag{4}$$

where Th_k is the kth carbon reduction technology setting parameter; Th_l is the lower bound of the kth carbon reduction technology setting parameter; and Th_u is the upper bound of the kth carbon reduction technology setting parameter.

There are interactions between various carbon reduction technologies and the corresponding constraints should be established considering the interactions between the different technologies.

$$f\left(E_{de\text{-}p}, E_{de\text{-}q}\right) = 0 \tag{5}$$

where $E_{de\text{-}p}$, $E_{de\text{-}q}$ are the carbon reduction values of the p-th and q-th carbon reduction technologies, respectively (kg).

The constraint on the total incremental cost of multiple carbon reduction technologies for substations can be expressed as Equation (6):

$$\sum_{k=1}^{K} C_k \leq C \tag{6}$$

where C_k is the cost of the kth technology (CNY); C is the incremental investment cost constraint of the substation (CNY).

4.3. Model Solving

Optimization models include linear optimization models, nonlinear optimization models, mixed-integer linear or nonlinear optimization models, multi-objective optimization models, and many other types. The efficient and accurate solution algorithm can be selected according to the model characteristics, such as gradient descent, Newton's method, genetic algorithm, etc.

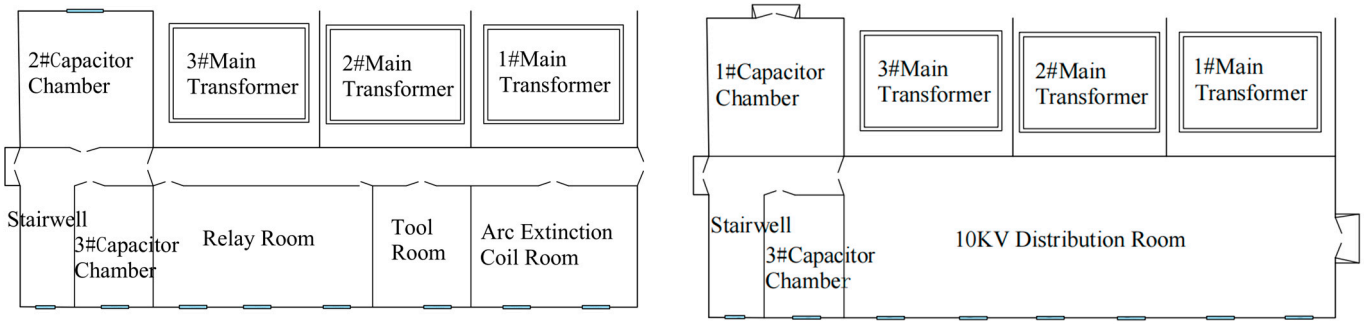
The optimization model established in this paper aimed to achieve the lowest total carbon emissions for the whole life cycle of the substation; it was a single-objective optimization model. The relationship between the optimization variables and carbon emissions was obtained through calculations based on simulation software, which was divided into nonlinear optimization programming and mixed-integer linear programming according to whether the optimization variables were continuous reachable variables, corresponding to the choice of calculus or stochastic methods for solving through MATLAB2021a software.

5. Case Study

5.1. Overview of the Substation

In this paper, a typical 110 kV outdoor substation was used to validate the optimization model. The total area of the substation was 2632 m^2, of which the area of the operation floor and path was 200 m^2, and the total roof area was 549 m^2. Buildings in the substation area included the production control building and the security room, and this paper used the production control building as the main object of study.

The production control building of the substation was used to store power distribution equipment. The building had a two-story frame structure with a total building area of 1015 m^2, the height of the first floor was 5 m, and the height of the second floor was 4.8 m. The floor plan of each layer is shown in Figure 4 and the thermal performance parameters of the building envelope are shown in Table 2.



(**a**) Floor plan (**b**) Second-floor plan

Figure 4. Substation building plan.

Table 2. Thermal properties of envelopes.

	Layers	Thickness (mm)	Density ($kg \cdot m^{-3}$)	Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific Heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
External wall	Plaster	20	1800	0.93	1.05
	Hollow blocks	240	1230	0.46	1.05
	Plaster	20	1800	0.93	1.05
Roof	Plaster	20	1800	0.93	0.84
	Reinforced concrete	100	2500	1.74	0.92
	APP-modified asphalt waterproofing roll	3	98,000	0.23	-
Windows	Plaster	20	1800	0.93	1.05
	Aluminum single glazing	3	2500	0.62	0.84

The heating and ventilation values of the substation buildings can be observed in Refs. [42,43]. The equipment information and heating and ventilation requirements for each room are shown in Table 3. Only the relay room used split-type air conditioning to precisely control temperature and humidity levels, and other rooms used mechanical ventilation to assist with natural ventilation.

Table 3. The information for equipment and thermal environment control systems.

Rooms	Equipment Density ($W \cdot m^{-2}$)	Air Exchange Rate ($Times \cdot Hr^{-1}$)	Indoor Temperature and Humidity in Summer	Indoor Temperature and Humidity in Winter
10 kV distribution room	100	≥6	≤35 °C; 40~70%	≥5 °C; 40~70%
Relay room	80	≥2	≤26 °C; 40~70%	≥ 5 °C; 40~70%
Capacitor chamber	80	≥6	≤35 °C; 40~70%	≥5 °C; 40~70%
Arc extinction coil room	80	≥6	≤35 °C; 40~70%	≥5 °C; 40~70%
Tool room	10	≥2	≤35 °C; 40~70%	≥5 °C; 40~70%

5.2. Model Parameter Setting

This paper mainly considered the synergistic optimization of the building envelope design of substations and the use of renewable energy, specifically the heat insulation technology for building facades, roofs, and exterior windows, as well as PV power generation technology. We set the carbon reduction technical parameters' boundaries as follows:

1. Building envelope insulation technology

The performance limits of the carbon reduction technology for the envelope in the Chinese region were examined. The constraints for setting the thickness of the insulation layer and the heat transfer coefficient of the exterior windows are shown in Equations (7)–(9):

$$0 \text{ mm} \leq Th_{wall\text{-}in} \leq 200 \text{ mm} \quad (7)$$

$$0 \text{ mm} \leq Th_{roof\text{-}in} \leq 200 \text{ mm} \tag{8}$$

$$1 \leq wk \leq 6 \tag{9}$$

where $Th_{wall\text{-}in}$ is the thickness of the external-wall insulation layer, mm; $Th_{roof\text{-}in}$ is the thickness of the roof insulation layer, mm; and wk is the window heat transfer coefficient, $W \cdot m^{-2}$.

2. Renewable energy utilization technology

The substation area was finite and the constraints for PV, green space, and the total area of the station area are shown in Equations (10)–(12):

$$S_g + S_{PV} = S_{available\text{-}area} \tag{10}$$

$$0 \leq S_{PV} \leq S_{available\text{-}area} \tag{11}$$

$$0 \leq S_g \leq S_{available\text{-}area} \tag{12}$$

where S_{PV} is the PV pavement area, m^2; S_g is the green area, m^2; and $S_{available\text{-}area}$ is the total area available for PV pavement in the station area, m^2.

3. Incremental cost constraints

The incremental costs of the exterior-wall insulation technology, roof insulation technology, high-performance exterior windows, and PV power generation technology are shown in Equations (13)–(16):

$$C_{wall} = S_{wall} \times Th_{wall\text{-}in} \times P_{wall\text{-}in} \tag{13}$$

$$C_{roof} = S_{roof} \times Th_{roof\text{-}in} \times P_{roof\text{-}in} \tag{14}$$

$$C_{window} = S_{window} \times P_{window\text{-}wk} \tag{15}$$

$$C_{PV} = S_{PV} \times 0.1 \times EPV \tag{16}$$

where C_{wall} and C_{roof} are the costs of increasing the thickness of the external wall and roof insulation, respectively; C_{window} is the increased cost of using high-performance windows; S_{wall}, S_{roof}, S_{window} are the surface areas of the exterior walls, roof, and windows, respectively; $P_{wall\text{-}in}$, $P_{roof\text{-}in}$ are the unit prices of exterior-wall and roof insulation materials, respectively (both values are 320 $CNY \cdot m^{-3}$); $P_{window\text{-}wk}$ is the price per unit area of external windows—the window price and thermal performance in the market were obtained through field research, and the fitting relationship between the window price and the value of k was obtained through fitting, that is, $P_{window\text{-}wk} = 5994/wk - 1010$. S_{PV} is the PV pavement area, m^2; EPV is the price of the PV, 4 $CNY \cdot W^{-1}$.

5.3. Quantitative Relationship between Optimization Variables of Carbon Reduction Technologies and Carbon Emissions

In order to obtain the quantitative relationship between the energy saving and carbon emission outcomes of the substation enclosure structure, this paper established a substation model in the Rhino and Grasshopper, and different thicknesses of roof and exterior wall insulation and different heat transfer coefficients of exterior windows were set (see Table 4 for variable settings) to simulate and calculate the carbon emissions of the substation in the operation phase under different building envelopes. Additionally, according to Ref. [12],

the quantitative relationship between PV pavement ratio and PV power generation under different climate zones was calculated.

Table 4. Carbon reduction technology variable settings.

Variable Name	Unit	Range	Step
City		Harbin/Shanghai/Haikou	
The thickness of external-wall insulation	mm	[50, 200]	10
The thickness of roof insulation	mm	[50, 200]	10
Heat transfer coefficient of windows	k	[2, 6]	1
The proportion of paving for PV	%	[0, 100]	10

Based on the model results and Equations (1)–(9), the increased carbon emissions in the construction phase and the reduced carbon emissions in the operation phase of the substation under the energy efficiency of the building envelope and renewable energy use were obtained. Moreover, through data fitting, the quantitative relationship of roof insulation thickness, exterior-wall insulation thickness, exterior-window heat transfer coefficient, and PV paving ratio with the increased carbon emissions during the construction phase and reduced carbon emissions during the operation phase of the substation were obtained.

4. Thickness of the roof insulation

In different climate zones, with the change in roof insulation thickness, the carbon emissions increased during the construction phase (abbreviated as "CP-IN") and reduced during the operation phase (abbreviated as "OP-DE") of the substation, and are shown in Figure 5.

It can be seen that there is a considerable difference in the OP-DE due to the increase in insulation thickness for different climate zones. In Haikou, the increase in the insulation thickness led to an increase in operational carbon emissions; however, the increase in roof insulation thickness values in Harbin and Shanghai contributed to the reduction in carbon emissions during the operational phase, and the OP-DE was much higher than the increase in carbon emissions during the construction phase. This demonstrates the feasibility of roof insulation technology for substations in the Harbin and Shanghai areas. In addition, for the same insulation thickness, the substation in the Harbin area could reduce the OP-DE much more considerably than in the Shanghai area; however, with the increase in the insulation thickness, the rising trend of the carbon reduction effect of the roof insulation gradually decreased.

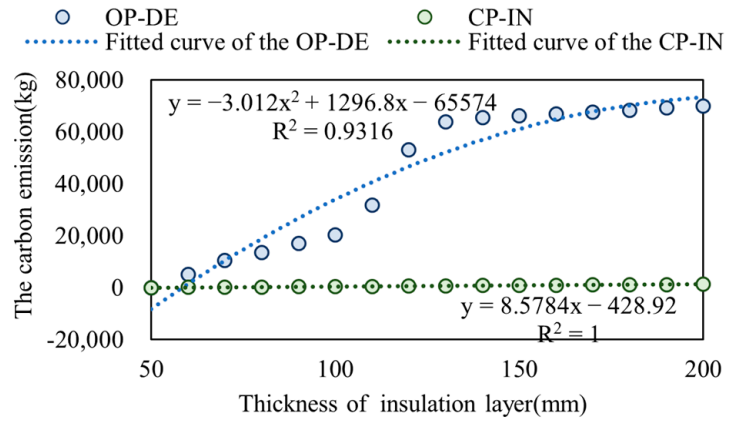
5. Thickness of external-wall insulation

The CP-IN and OP-DE values of the substation with the change in the thickness of the external-wall insulation in different climate zones are shown in Figure 6.

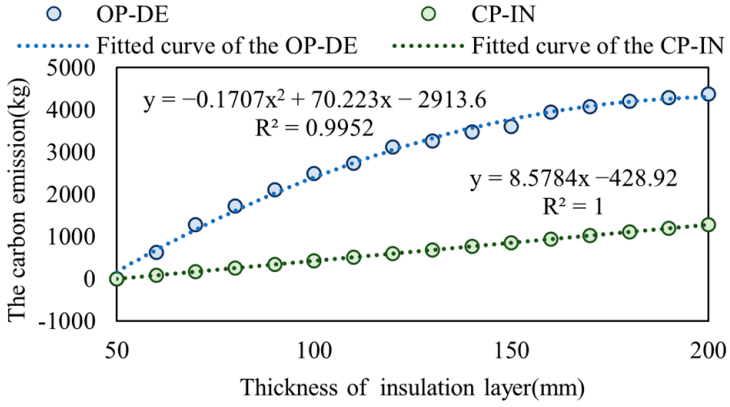
Due to the increase in the thickness of the external-wall insulation, the OP-DE varied considerably between the different climate zones. The increase in the thickness of the exterior-wall insulation helped to reduce the CP-IN of the building in Harbin, and the reduction in carbon emissions during the operation phase was much greater than the OP-DE, indicating the feasibility of exterior-wall insulation technology for substations in Harbin. However, in Haikou and Shanghai, the increase in the thickness of the external-wall insulation layer not only did not reduce the OP-DE of the substations, but it also increased in varying degrees, which indicates that external-wall insulation technology does not apply to Haikou and Shanghai.

6. Heat transfer coefficient of the exterior windows

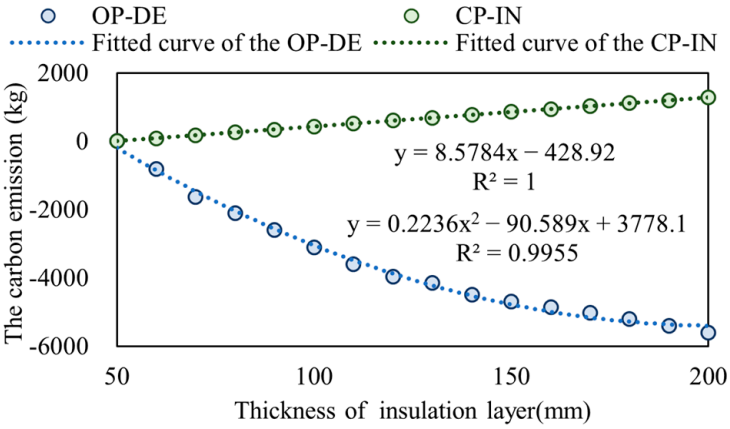
The CP-IN and OP-DE of the substation with the change in the heat transfer coefficient of the exterior windows in different climate zones are shown in Figure 7.



(**a**) Harbin.



(**b**) Shanghai.



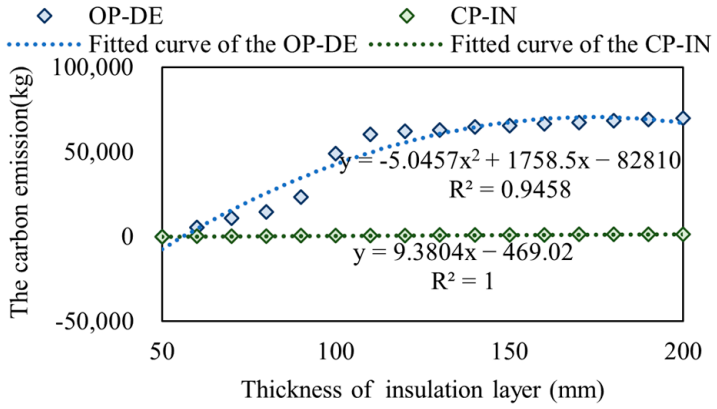
(**c**) Haikou.

Figure 5. Variations in carbon emissions of the substation with roof insulation thickness.

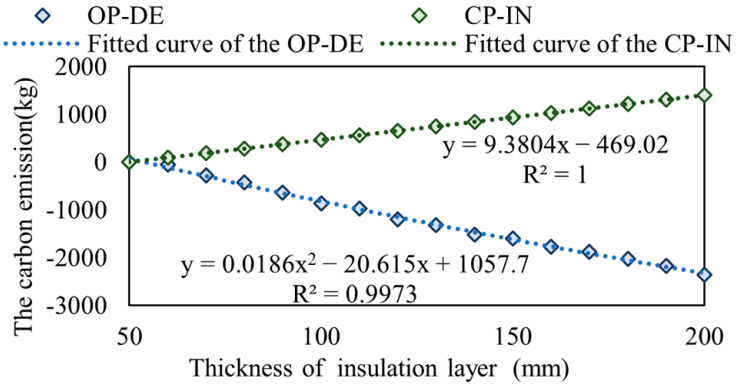
Due to the reduction in the heat transfer coefficient of exterior windows, the OP-DE varied considerably in different climate zones. In Harbin and Haikou, the reduction in the heat transfer coefficient of external windows had a significant effect on the OP-DE. However, in Shanghai, the OP-DE increased and then decreased as the heat transfer coefficient of the windows increased, reaching the highest point at a k-value of 3.95.

7. The PV paving ratio

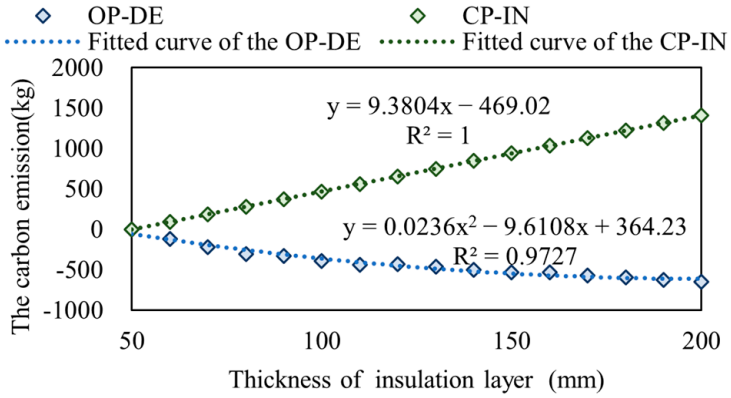
The intensity of solar radiation varies in different climatic zones. According to Ref. [13], PV power generation was calculated separately for different PV paving ratios in three regions. The latest grid factor of 0.57 was used to calculate the carbon emissions from the substation operation offset. The carbon emissions generated per kW of installed PV effect in the construction phase were taken as 1.5 kg·kW^{-1}. The quantitative relationship between the PV paving ratio with substation carbon emissions is shown in Figure 8.



(**a**) Harbin.



(**b**) Shanghai.



(**c**) Haikou.

Figure 6. Variations in carbon emissions of the substation with the thickness of external-wall insulation.

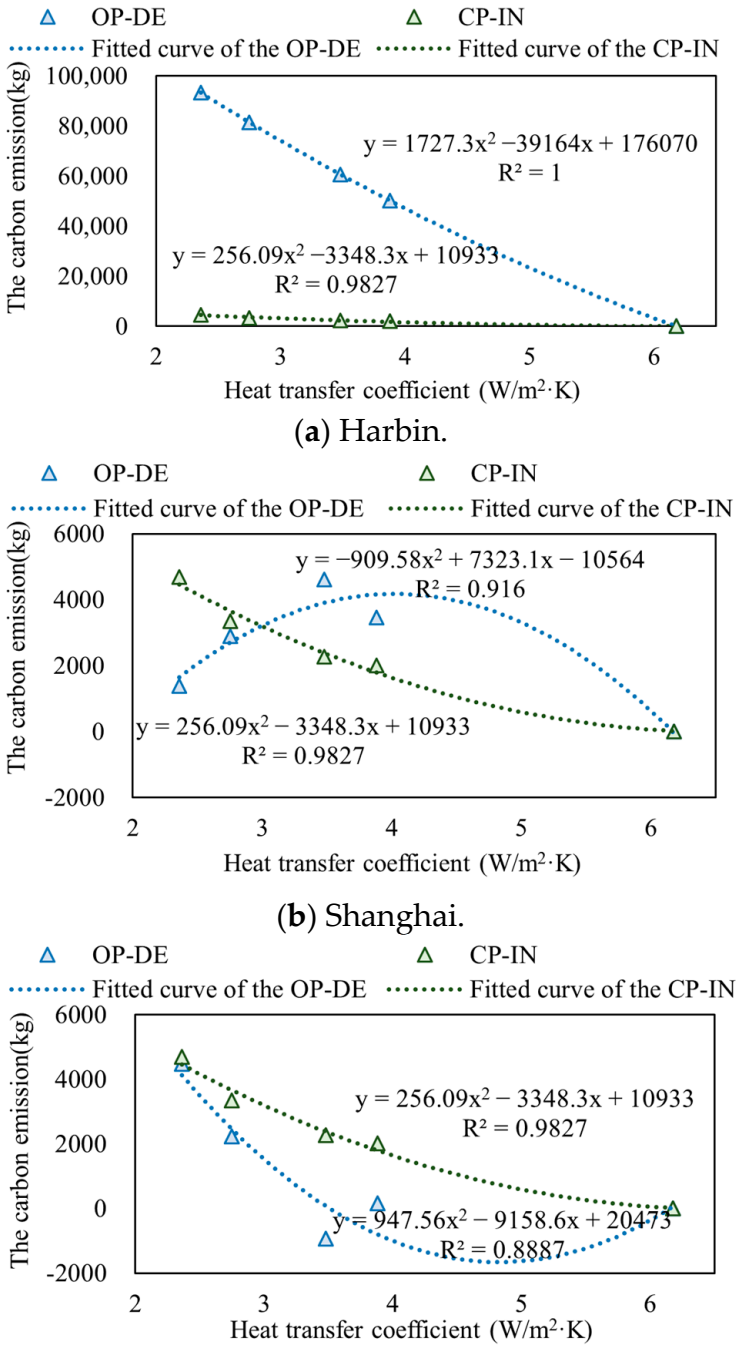
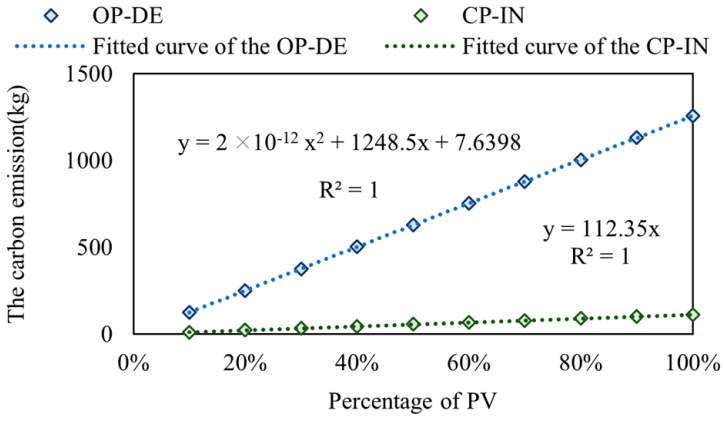
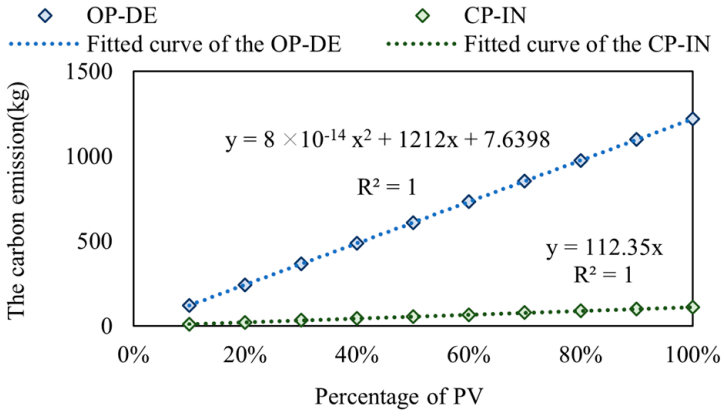


Figure 7. Variations in the carbon emissions of the substation with the heat transfer coefficient of external windows.

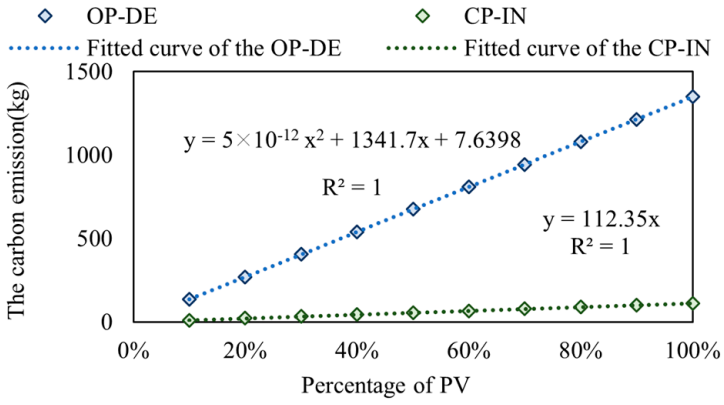
It can be seen that the increase in the CP-IN of the substation using PV power generation technology was much lower than the carbon sink achieved during the operation phase. In different climate zones, the OP-DE of the substation increased linearly with the increase in the PV paving ratio. However, due to the differences in solar energy resources in different climate zones (the average annual solar radiation values of Harbin, Shanghai, and Haikou were 1307 kWh·m^{-2}, 1269 kWh·m^{-2}, and kWh·m^{-2}, respectively), the carbon reduction achieved by the same PV paving ratio varied, with the best carbon reduction by PV technology being in Haikou, followed by Harbin, and the worst occurred in Shanghai.



(**a**) Harbin.



(**b**) Shanghai.



(**c**) Haikou.

Figure 8. Variations in the carbon emission of the substation with the proportion of PV paving.

6. Results and Discussion

According to the basic information presented about the substation and quantitative relationships between the substation envelope performance, the PV pavement ratio with carbon emissions during different phases in the whole life cycle of the substation was obtained from the simulation. They were substituted into the optimization model to obtain the coordinated optimal configuration scheme of the substation envelope–renewable energy system under different incremental cost constraints.

6.1. Optimal Configuration of Low-Carbon Substation Envelope–Renewable Energy System without Incremental Cost Constraints

According to the optimization model, firstly, no incremental cost constraint was set and the coordinated optimal configuration scheme of the substation enclosure–renewable energy system was obtained by the model calculation in different climate zones, as shown in Table 5.

Table 5. Carbon reduction technology configuration solutions for substations without incremental cost constraints.

	Coordinated Optimization of Building Envelope–Renewable Energy Configuration Solution				Carbon Reduction in the Life Cycle (kg)	The Unit Cost of Carbon Reduction (CNY·kg^{-1})	Carbon Reduction Costs (CNY Thousand)
	Thickness of the Roof Insulation Layer (mm)	Thickness of the Exterior-Wall Insulation Layer (mm)	Heat Transfer Coefficient of Exterior Windows (W·m^{-2}·K^{-1})	PV Paving Ratio (%)			
Harbin	177	160	2	100	180,350	6.27	1130.79
Shanghai	196	0	4.64	100	144,111	7.06	1017.42
Haikou	0	0	2	100	158,564	5.51	873.69

The configuration parameters of the building envelope–renewable energy system in the optimal solution were different in different regions. In addition to the 100% PV installation in all regions, a 196 mm-thick roof insulation layer and a higher heat transfer coefficient of 4.64 W·m^{-2} for exterior windows were required in Shanghai, and a higher level of upgrade was required in Harbin in all three areas (facade, roof, and exterior windows); however, in Haikou, only the thermal performance of the exterior windows needed to be upgraded. In addition, compared to the benchmark model, without considering the cost constraint, Harbin had the highest maximum carbon reduction of 180,350 kg, which was 25.15% and 13.74% higher than the maximum carbon reduction in Shanghai and Haikou, respectively, in the whole life cycle. We can see that the cost of carbon reduction varies greatly from region to region. The costs of carbon reduction in Harbin, Shanghai, and Haikou were CNY 1130.79 thousand, 1017.42 thousand, and 873.69 thousand, respectively.

The reasons for this result were the hot climate in Haikou and the high level of heat generation by the equipment in the substation; therefore, it was more important to dissipate heat through the envelope with small thermal resistance in the area, and there was no need to increase the insulation of the peripheral sheath. Moreover, Haikou had sufficient solar energy resources, with annual peak power generation hours of up to 1404 h; therefore, the carbon reduction effect of PV in the region was good. Shanghai is in the hot summer and cold winter region. The optimal thickness of the insulation layer was different in winter and summer, and the maximum carbon reduction was considered for the whole year, which did not meet the maximum carbon reduction levels in both winter and summer. In addition, Shanghai's solar energy resources were relatively poor. Thus, the carbon reduction effect of PV power generation technology was poor.

6.2. Variation in the Minimizing Carbon Emissions Achievable with the Incremental Cost

Setting different incremental cost constraints creates a change in the minimum life-cycle carbon emissions achievable by the substation as the incremental investment increases, as shown in Figure 9.

Figure 9 shows that, with the increase in incremental investments, the carbon emissions of the whole life cycle of the substation in different zones show a decreasing trend. For every additional CNY 100 thousand investment, the substations in Shanghai, Harbin, and Haikou can reduce their carbon emissions by 228,913, 210,852, and 254,165 kg, respectively. After incremental investments of CNY 600 thousand in Shanghai and Haikou, and after an incremental investment of CNY 700 thousand in Harbin, the carbon emissions from the substations were no longer reduced. Additional investments in the envelope and

renewable energy use no longer presented carbon reduction benefits. In addition, the maximum carbon reduction achieved by the substation differed in different zones, with the maximum carbon reduction achieved in Harbin at 1,882,475 kg, while the maximum carbon reduction achieved in Shanghai was only 1,226,548 kg.

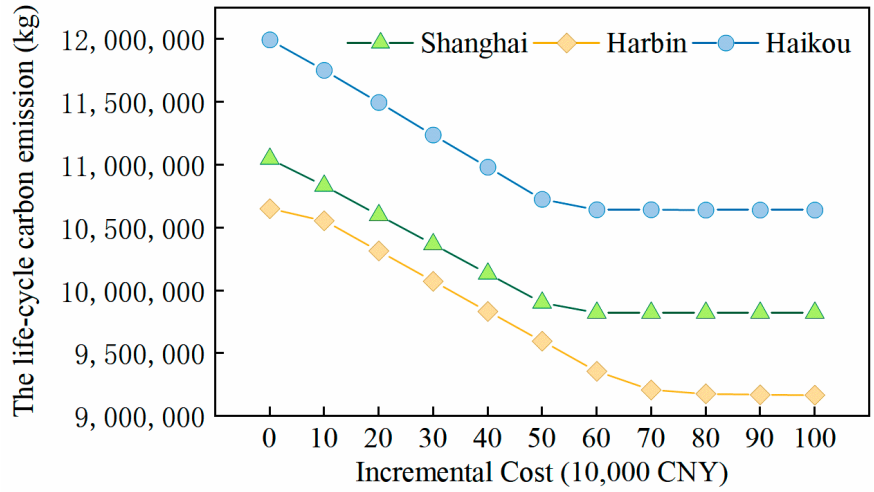


Figure 9. Minimum life-cycle carbon emissions achievable from substations with different incremental cost constraints.

6.3. Carbon Reduction Costs of Building Envelope–Renewable Energy Systems

The carbon reduction effect of the same carbon reduction technology in different climate zones varied. Disregarding the differences in the purchase, installation, and maintenance prices of products for building envelope energy efficiency and renewable energy utilization schemes in different regions. The carbon reduction cost of each carbon reduction technology in different climate zones was calculated and shown in Figure 10.

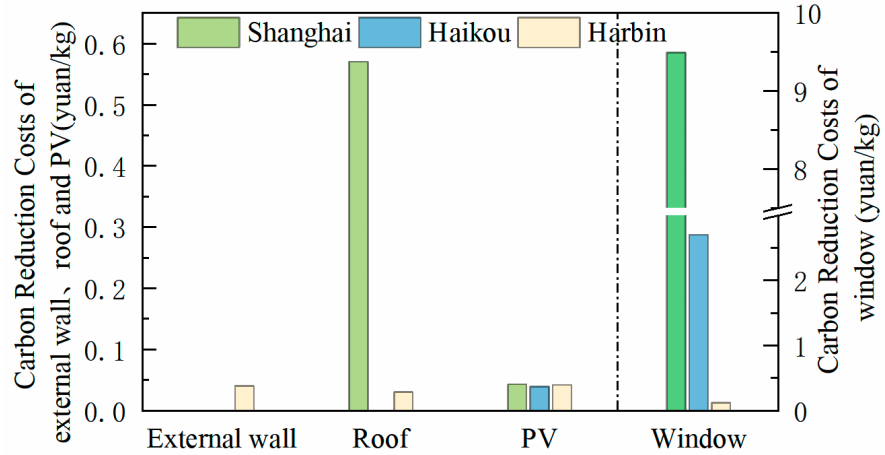


Figure 10. Carbon reduction costs of various carbon reduction technologies in different climate zones.

As can be seen from Figure 10, in cold Harbin, the carbon reduction costs for exterior-wall insulation, roof insulation, and PV power generation are similar, costing around 0.04 CNY·kg^{-1}, and the carbon reduction cost of the thermal performance improvement of exterior windows was slightly higher at about 0.125 CNY·kg^{-1}. In Shanghai, a hot summer and cold winter region, the carbon reduction costs of various types of carbon reduction technologies varied widely, with the carbon reduction cost of the thermal performance improvement of exterior windows being as high as 9.49 CNY·kg^{-1}, followed by the carbon reduction cost of roof insulation technology at about 0.572 CNY·kg^{-1}, and the lowest carbon reduction cost of PV was about 0.043 CNY·kg^{-1}; however, the exterior-wall insulation

technology did not reduce carbon and increased the building life-cycle carbon emission. In hot Haikou, the insulation of the external walls and roofs had no carbon reduction effect and, considering the carbon emissions of materials in the construction phase, the increase in insulation in the substation in the area significantly increased the substation's carbon emissions; however, because the solar energy resources in the area were more abundant, the carbon reduction effect of PV was better and the carbon reduction cost was only 0.039 CNY·kg^{-1}.

Comparing the carbon reduction costs of different carbon reduction technologies in the same climate scenario, we can see that, except for Harbin, where the carbon reduction cost was lower in terms of improving the thermal performance of the external windows, the carbon reduction cost through the thermal performance of external windows in the other two regions was much higher than the other three carbon reduction technologies. Therefore, the carbon reduction technology used for exterior windows only presented a good carbon reduction outcome in cold Harbin. Comparing the carbon reduction costs of the same carbon reduction technology in different climate zones, we can see that there is a considerable difference. Overall, Shanghai had the highest carbon reduction cost for all types of carbon reduction technologies and Harbin had the lowest carbon reduction cost for all types of technologies.

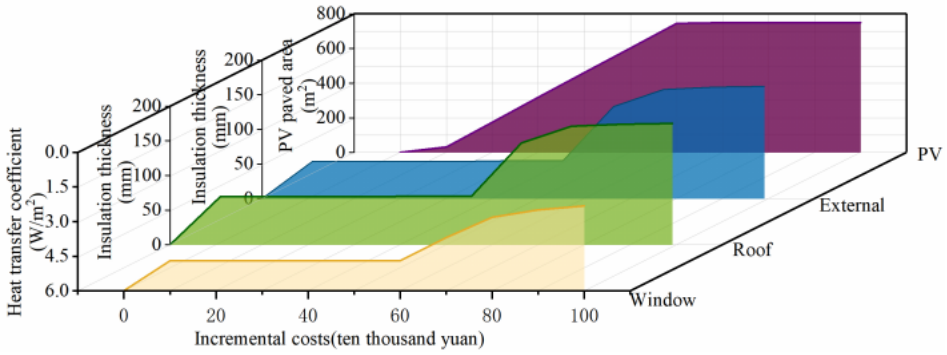
6.4. Prioritization of Carbon Reduction Technologies

We explored the sequencing of the application of various energy-saving technologies in the building envelope and renewable energy within the limited incremental cost constraint. An optimization model was used to calculate the coordinated configuration scheme of the building envelope–renewable energy system that minimizes the carbon emissions of the substation by increasing the incremental cost from CNY 100 thousand to 1000 thousand, as shown in Figure 11.

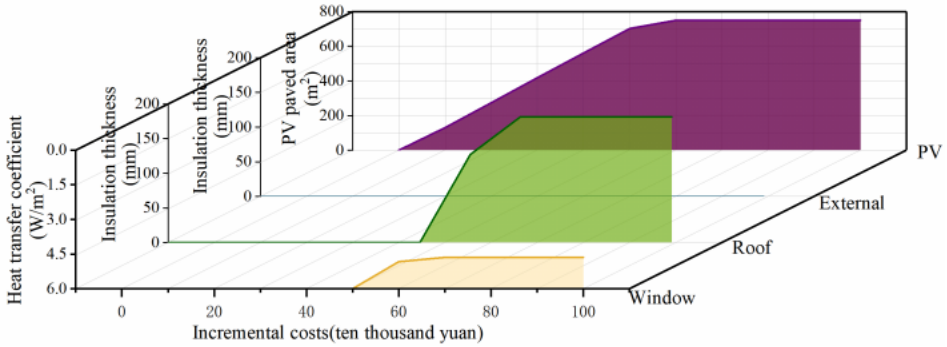
It can be seen in Figure 11a that, when the incremental cost is less than CNY 500 thousand, the cost is first used for PV, and after the PV paving rate reaches 100%, the increased investment can be used for the insulation of the roof and external wall. After the incremental cost reaches CNY 700 thousand, the increased investment can be used for exterior-window thermal performance enhancement; however the carbon reduction is very low. The priority of low-carbon technologies in Harbin can be obtained as follows: PV > roof insulation > exterior-window performance improvement.

As shown in Figure 11b, in Shanghai, when the incremental cost is less than CNY 500 thousand, the cost is first used for PV, and after the PV paving rate reaches 100%, the increased investment can be used for roof insulation and exterior-window thermal performance enhancement. After the incremental cost reaches CNY 700 thousand, the optimized building envelope-renewable energy system coordinated configuration scheme no longer has carbon reduction benefits. The priority of low-carbon technologies in Shanghai can be obtained as follows: PV > roof insulation = exterior-window performance improvement.

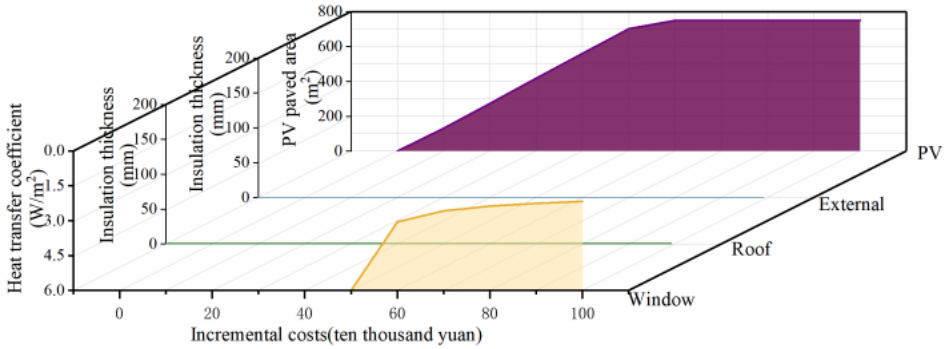
From Figure 11c, it can be seen that, in Haikou, the insulation of the external wall and roof cannot reduce carbon. Therefore, only the priority of PV power generation and thermal enhancement of external windows was analyzed. It can be seen that, when the incremental cost is less than CNY 500 thousand, the cost is first used for PV, and after the PV paving rate reaches 100%, the increased investment can be used for exterior-window thermal performance enhancement. After the incremental cost reaches CNY 700 thousand, optimizing the building envelope–renewable energy no longer results in carbon reduction. The priority of low-carbon technologies in Shanghai can be obtained as follows: PV > exterior-window performance improvement.



(**a**) Harbin.



(**b**) Shanghai.



(**c**) Haikou.

Figure 11. Coordinated configuration scheme of substation building envelope–renewable energy system under different incremental cost constraints.

It can be seen that the priority of each building envelope low-carbon technology and renewable energy utilization technology used in different climate zones varies greatly. In the actual engineering application, the applicability of each carbon reduction technology in the region should be considered and, under the constraints of different incremental costs, the differences in carbon reduction effects of each carbon reduction technology should be considered, the low-carbon and carbon-negative technologies applicable to the scenario should be selected in order of priority, and the building envelope–renewable energy system should be reasonably configured.

7. Conclusions

We established a comprehensive optimization model of substation building energy–saving technology and renewable energy utilization technology with the lowest life-cycle carbon emission as the optimization target. Based on the model calculation results, the maximum carbon reduction under different incremental cost constraints and the optimal carbon reduction technology configuration scheme were obtained. The priority of various carbon reduction technologies under different climate zones is also given. The main findings were as follows:

1. The optimization model developed in this paper can be used to calculate the maximum carbon reduction that can be obtained at different incremental costs and the corresponding configuration scheme of building envelope–renewable energy use. According to the model results, the configuration options of the substation building envelope–renewable energy for minimizing carbon emissions vary considerably in different climate zones. Without considering the cost constraints, Harbin has the highest maximum carbon reduction of 180,350 kg, which is 25.15% and 13.74% higher than the maximum carbon reduction in Shanghai and Haikou, respectively. The costs of carbon reduction in Harbin, Shanghai, and Haikou are CNY 1130.79 thousand, 1017.42 thousand, and 873.69 thousand, respectively.
2. By comparing the carbon reduction costs and effects of various carbon reduction technologies, such as building envelope–renewable energy use under different climate zones, it is found that the cost of carbon reduction for all types of carbon reduction technologies in Shanghai is higher than in Haikou and Harbin. The carbon reduction cost of exterior-window technology is higher than roof insulation technology, exterior-wall insulation technology, and PV power generation technology.
3. Based on the analysis of the optimal configuration of building envelope–renewable energy for minimizing substation carbon emissions under different incremental cost constraints, the paper presents the ranking in priority of various carbon reduction technologies in three typical zones. However, the specific parameter settings for the optimal configuration under different incremental cost constraints in other climate zones should be determined based on the model calculation results.

This paper explored the relationship between incremental costs–energy consumption–carbon emissions for substation buildings. The optimal configuration of each carbon reduction technology for low-carbon substations under different incremental cost constraints was given by the optimization model. The applicability of various carbon reduction technologies in substations from a whole life-cycle perspective was revealed, providing a reference for low-carbon substation building designs. However, the setup of the model did not take into account the cost differences of carbon reduction products in different regions, and the model needs to be further optimized in the subsequent study.

Author Contributions: S.Z.: Conceptualization, Methodology. Y.Z.: Resources, Funding acquisition. P.L.: Visualization, Investigation. Y.H.: Conceptualization, Writing—review and editing. C.X.: Data curation, Formal analysis. Y.C.: Writing—original draft preparation, Software. All authors have read and agreed to the published version of the manuscript.

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