Low-carbon Design Principles and Operational Strategies for Concrete Substation Buildings

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Abstract. As the economy continues to advance, and the populace's demand for material well-being grows, urban areas are witnessing an increasing need for electricity supply. Substations, playing a pivotal role in the power industry, are proliferating in terms of both quantity and construction scale. Reinforced concrete substation buildings are a common infrastructure that provides a suitable physical environment for the operation of power equipment. A thorough examination and analysis conducted through on-site investigations have unveiled deficiencies in the low-carbon design and operation of substation buildings, resulting in energy wastage and extra carbon emissions. Consequently, this study endeavors to introduce a method for calculating carbon emissions during the operational phase of reinforced concrete structure substations. It also presents corresponding strategies for low-carbon design and operation. These strategies encompass low-carbon design principles for the building envelope structure, the utilization of renewable energy, low-carbon design considerations for artificial lighting, and the implementation of intelligent environmental control systems. The strategies proposed in this research provide valuable ideas for making the power and construction industries more environmentally friendly and energy-efficient.

1 Introduction

With the ongoing global population growth and relentless progress in industrialization, there has been a notable surge in the demand for electrical power, resulting in a swift escalation in the consumption of energy resources. This, however, has been underpinned by a notably high dependence on fossil fuel-based methods of electricity generation. Regrettably, this approach has yielded not only a precipitous increase in the emission of greenhouse gases into the atmosphere but has also precipitated the onset of profound environmental challenges, inclusive of climate change, atmospheric pollution, and the depletion of finite natural resources. Consequently, the imperative of energy conservation and emissions abatement within the electric power industry extends far beyond immediate concerns regarding environmental quality and societal stability, resonating with far-reaching implications for the prospects of survival and advancement of forthcoming generations on a global scale.

A substation is a crucial electrical facility within the power system, responsible for voltage transformation, energy reception, distribution, and power flow control. Substation buildings are specialized structures in the power industry designed to house equipment and provide operational environments[1]. With the continuous growth in total electricity consumption across society and the ongoing development of the electrical grid in China, the number and scale of substation constructions have been on the rise. During the "Thirteenth Five-Year Plan" period, the State Grid Corporation of China constructed more than 8,000 substations, and this trend is set to continue during the "Fourteenth Five-Year Plan" period. Hu et al. [2] demonstrated that the carbon emissions per unit area throughout the operational lifespan of a conventional steel and reinforced concrete substation structure reached levels of 1784 kg/m^2 and 1280 kg/m^2, respectively. Failure to prioritize the low-carbon, environmentally sustainable design of novel substation constructions may potentially lead to an estimated annual increment of approximately 49,024 kg of CO_2 emissions.

It has been reported that the construction sector contributes to over 30% of global carbon emissions, with emissions trending upward, necessitating energy-saving and emission reduction measures to address climate change challenges [3]. As China's commitment to green, low-carbon, and sustainable development strengthens, green practices in substation construction have become a focal point in the power industry. During the operational phase, substation buildings employ air conditioning and mechanical ventilation to maintain suitable working conditions for equipment and personnel. Implementing low-carbon design and operational strategies can effectively reduce carbon emissions during the operation of substation buildings.

Given the standardized nature of substation designs, both in appearance and functionality, as well as the similarity in control methods and indoor environmental

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requirements during the operational phase, low-carbon research specific to substation buildings can be readily applied to other projects. Reinforced concrete structure substations, known for their durability, versatility, and structural integrity, are widely used. Therefore, this study aims to explore a carbon emission calculation method suitable for concrete structure substation buildings and propose low-carbon design and operational strategies for their development.

2 Current State of Substation Building Design and Operation

2.1. Substation Building Design

Substation buildings fall within the specialized category of structures in the electrical industry, designed to house and facilitate the operational functionality of electrical equipment. These buildings typically comprise various room types, including the main transformer room, 110kV GIS room, capacitor room, reactor room, cable room, 10kV distribution equipment room, secondary equipment room, and battery room.

In terms of layout configurations, substation buildings exhibit diverse designs, such as linear, U-shaped, H-shaped, and others. Depending on the equipment arrangement, substation buildings can be broadly classified into three main types: outdoor substations, indoor substations, and semi-indoor substations.

Structurally, substation buildings commonly employ reinforced concrete and steel structures, with fewer instances of brick and mixed-material constructions. Notably, reinforced concrete substation buildings are widely favored due to their exceptional stability, durability, and fire resistance. This study centers on the development of a 3D model for a typical 110kV semi-indoor substation building with a reinforced concrete structure, achieved using Revit software and visually represented in Figures 1-2.

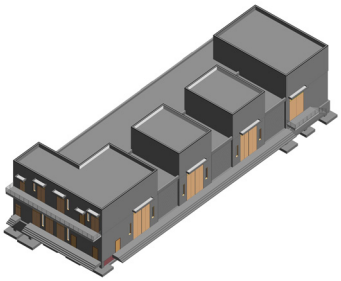

Fig. 1. Model of a Typical Substation Building.

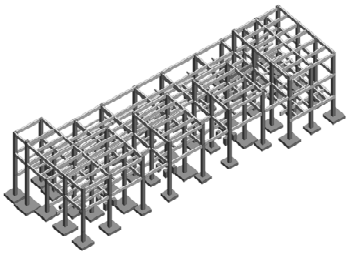

Fig. 2. Reinforced Concrete Structure Model of a Typical Substation Building.

In contrast to the indoor thermal environment control typically found in conventional civilian buildings during their operational phase, the operational strategy for substation buildings is primarily geared toward meeting the specific environmental requirements necessary for equipment operation. The temperature control parameters for various room types showed in Table 1 are determined based on the HVAC construction plans designed for substation buildings. All key functional areas within substation buildings are equipped with mechanical exhaust fans, serving ventilation and cooling purposes during regular operation. Among these areas, the 10kV distribution equipment room, secondary equipment room, and battery room feature autonomously controlled split air conditioning systems designed to regulate room temperatures.

It is essential to note that an increasing number of unattended substations lack permanently stationed personnel for continuous operation and maintenance. To minimize energy wastage, the activation schedules of air conditioning equipment for human comfort in these rooms should be synchronized with the intermittent maintenance personnel schedules.

Table 1. The indoor air temperature ranges.

	Temperature Range (℃)	
	Summer	Winter
Main Transformer Room	≤45	-
110kV GIS Room	≤40	-
Capacitor Room	≤40	-
Reactor Room	≤40	-
Cable Room	≤40	-
10kV Distribution Equipment Room	≤35	≥5
Secondary Equipment Room	26~28	18~20
Battery Room	≤30	≥20

The green design during the architectural design phase is an indispensable component for achieving low carbon emissions. Its main components include envelope design, optimized natural ventilation, and efficient HVAC systems and selections. Previous studies have indicated that, from a whole life cycle perspective, reinforced concrete structural solutions tend to be lower in carbon emissions compared to steel structural solutions[2]. Low-carbon operation is essential to minimize energy consumption for air conditioning and ventilation while meeting the indoor temperature and humidity requirements.

2.2. Substation Building Operation

To investigate the actual operational patterns of substation buildings, this study analyzed indoor temperature variations during weekdays and weekends by conducting real-time temperature measurements. The sensors used in this study were HOBO S-THC-M002, with a measurement accuracy of ±0.2℃. Researchers installed temperature sensors inside the 10kV

distribution equipment room of a typical concrete structure substation in Jiangsu Province to monitor indoor temperature variations (Figure 3). The testing period covered 48 hours, including weekdays and weekends, specifically on February 2nd and February 28th, 2023.

Fig. 3. The Installation Site of Temperature Sensors in the 10kV Distribution Equipment Room.

The measured results indicate that, whether on weekdays or weekends, outdoor temperatures exhibit significant fluctuations throughout the day, varying by more than ten degrees Celsius. In contrast, the indoor temperature within the 10kV distribution equipment room fluctuates within the range of 12 to 17℃ (Figures 4-5). This temperature range is narrower than the requirement of 5-35℃. The discrepancy is primarily due to suboptimal control logic in the operation of the substation building's HVAC system, which remains active regardless of whether there are personnel present. Consequently, there is an urgent need to propose low-carbon design and operational strategies tailored to substation buildings, which are feasible in effectively reducing the carbon emissions during building operation.

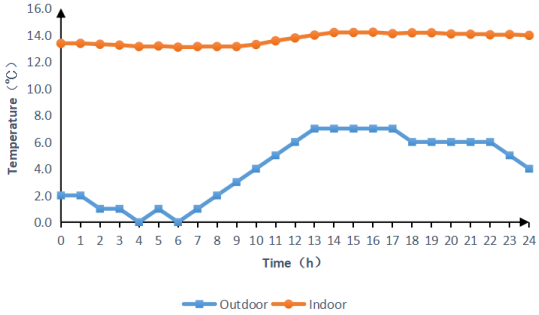

Fig. 4. Indoor and Outdoor Temperature of a 10kV Distribution Equipment Room on a Rest Day.

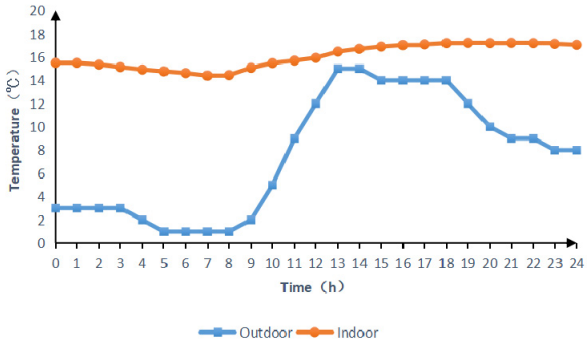

Fig. 5. Indoor and Outdoor Temperature of a 10kV Distribution Equipment Room on a Working Day.

3 Carbon Emission Calculation Method During Operational Phase

The 'Building Carbon Emission Calculation Standard' GB/T 51366-2019 issued by the Ministry of Housing and Urban-Rural Development of China is applicable to carbon emission calculations during the design, construction, operation, and dismantling phases of newly constructed, renovated, or expanded civilian buildings. Although substations are specialized industrial buildings within the power industry, they can refer to the carbon emission calculation methods and data specified in this standard for their carbon emission calculations. This paper focuses on the calculation of carbon emissions during the operational phase of buildings, and the detailed process is described below:

The calculation of energy consumption during the operational phase of buildings is a complex process, often performed using energy simulation software. The logic behind this is to simulate the consumption of various types of energy within the building and calculate carbon emissions based on the carbon emission coefficients of these energy sources. Internationally recognized energy simulation software includes EnergyPlus, OpenStudio, DesignBuilder, DesT, IES-VE, and TRNSYS, among others[4]. EnergyPlus is a widely used international energy simulation engine, and it includes a program for whole-life cycle calculations. The main steps in energy consumption simulation include collecting project data, creating a three-dimensional geometric model, zoning for thermal analysis, specifying building materials, construction, occupants, plug loads, lighting, HVAC systems, and all operational schedules. Geometric modeling is often done using 3D modeling software like SketchUp, Rhino, or Revit. Since energy consumption simulation requires a simplified 3D model, the 3D models used in building design cannot be directly applied to energy simulations and typically require modeling engineers to create simplified models for this purpose.

Currently, P-BIM (Performance-Based Building Information Modeling) technology facilitates the integration of various types of data and the automatic calculation of results mentioned above. It divides all necessary analyses into model ontology information, simulation performance information, monitoring

performance information, and external reference information. Typically, this technology employs Autodesk Revit as the carrier for building information modeling, uses a MySQL relational database to store external data (carbon emission factors, personnel and equipment schedules, etc.), utilizes Rhinoceros industrial design software as an intermediary for data linking, and invokes external energy simulation engine EnergyPlus to achieve multidimensional data correlation and automatic carbon emission calculations (Figure 6). In addition to carbon emissions calculation, building energy simulation software can also assess the impact of different design and operational strategies on building carbon emissions, enabling the selection of low-carbon design and operational strategies[5].

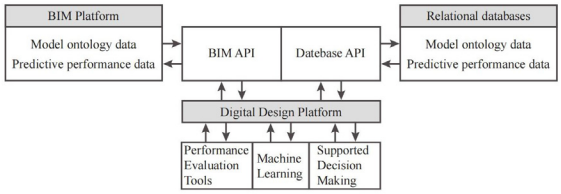

Fig. 6. P-BIM Technical data correlation Diagram.

The advantage of building energy simulation software is its capability to simulate the impact of almost all building materials, equipment, and components on operational carbon emissions. However, its main disadvantages include the need to configure a large number of parameters, steep learning curve, and discrepancies between simulated and actual results. For example, the IDF (Input Data File) for a certain building simulated with EnergyPlus has 6,414 lines, with each line representing an input parameter (Figure 7). While some simulation software now includes built-in templates to expedite the modeling process, calibrating the data within these templates one by one is required for more accurate energy modeling results[6].

```
Construction,
    Interior Ceiling,        !- Name
    M11 100mm lightweight concrete,  !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    F16 Acoustic tile;       !- Layer 3

Construction,
    Interior Door,           !- Name
    G05 25mm wood;           !- Outside Layer

Construction,
    Interior Floor,          !- Name
    F16 Acoustic tile,       !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    M11 100mm lightweight concrete;  !- Layer 3

Construction,
    Interior Wall,           !- Name
    G01a 19mm gypsum board,  !- Outside Layer
    lightweight concrete 150mm,  !- Layer 2
    G01a 19mm gypsum board;  !- Layer 3

Construction,
    Interior Window,         !- Name
    Clear 3mm;               !- Outside Layer
```

Fig. 7. Parameters in the EnergyPlus Input File.

For existing buildings, when operational carbon emissions are already available, it is necessary to adjust the simulation outputs to match the actual operational energy consumption[7]. This significantly reduces the likelihood of using building energy simulation software during the operational phase. Currently, there is an urgent need for simpler methods of calculating operational carbon emissions. Based on information such as the building's expected future operational conditions and changes in carbon emission factors for electricity, one can estimate future carbon emissions over a certain period. This approach is simpler than energy simulation but has limitations as it cannot estimate changes in carbon emissions resulting from energy-efficient retrofits or optimized operational strategies. Additionally, scholars have employed process analysis methods to analyze the carbon emissions of buildings during the operational phase. For existing buildings, analyzing their historical operational energy consumption and identifying potential strategies to reduce carbon emissions are crucial. Strategies can be analyzed at both macro and micro levels, including annual operational energy consumption, monthly energy consumption, and HVAC system energy consumption[8]. For a large number of buildings, data mining algorithms can be employed to analyze low-carbon design and operational strategies from a macro perspective. For example, Zhang Zhang et al.[9] used data mining techniques to analyze many office buildings, identifying more carbon-efficient design strategies, such as lower carbon emissions in buildings with centralized heating. The prerequisite for using data mining techniques is the collection of extensive data on building design and operations, which limits the widespread application of this technology.

4 Low-carbon design strategies

China's building carbon emission calculation standards also provide viable directions for summarizing low-carbon design strategies. In a broad sense, low-carbon building design encompasses architectural structural design, passive design, active design, HVAC design, lighting system design, the use of low-carbon materials, and low-carbon technologies, among others[10]. In this section, we will focus on common low-carbon design strategies in substations, namely, building envelope structure, rooftop photovoltaics, and artificial lighting. Additionally, this section will quantitatively analyze the emission reduction potential of various low-carbon design strategies using a typical reinforced concrete substation in Nanjing, Jiangsu Province, as an example. The geometric appearance and structural system of this substation have been previously presented (Figure 1-2). The total building area of the project is 1819 square meters, with two above-ground floors and one underground floor, and it has a design lifespan of 50 years.

4.1. Exterior envelope design strategies

In the passive design of the exterior envelope, there are significant differences between substation buildings and typical residential or commercial buildings. This difference mainly stems from the widely varying indoor thermal environment requirements for different functional areas within a substation building, with most rooms having only a maximum temperature requirement but no minimum temperature limit. Therefore, when designing the exterior envelope structure for substation

buildings, careful consideration should be given to its thermal performance.

Furthermore, the thermal transmittance coefficient (U-value) of the exterior wall directly affects the energy consumption for heating and cooling in a building. Optimizing the U-value of the exterior wall can contribute to energy savings and emission reductions.

Taking the typical substation building mentioned earlier as an example, let's conduct a quantitative analysis of the energy savings and emission reductions resulting from optimizing the U-value of the exterior wall. According to the project's HVAC construction drawings, the U-value for exterior walls should be less than or equal to 1.1 W/㎡·K. The original design for this project had an exterior wall U-value of 0.67 W/㎡·K, resulting in a 50-year heating and cooling energy consumption of 728,722 kWh. Then U-value of the exterior wall was adjusted to 1.1, 1.0, 0.9, 0.8, 0.7, 0.6 ,and 0.5 and simulated (Table 2). This is due to the fact that indoor equipment generates a lot of heat, and the lower U-value of the external wall blocks the heat loss, which in turn requires more energy for cooling.

Table 2. Relationship between U-value of external walls and energy consumption for heating and cooling.

U-value（W/㎡ • K）	Cooling&heating（kWh）
1.1	711 272
1.0	715 259
0.9	718 948
0.8	722 922
0.7	726 811
0.6	730 348
0.5	734 974

4.2.Renewable Energy Utilization Design Strategies

In terms of renewable energy utilization design, substation buildings typically have large flat roof spaces suitable for the installation of solar photovoltaic panels[11]. During the solar energy utilization design process, the following aspects should be considered:
Firstly, during the site selection of substation buildings, the region's renewable energy resources should be thoroughly assessed, including the annual average solar radiation, to determine whether rooftop photovoltaic design is feasible.

Secondly, careful consideration should be given to the shading effects of surrounding buildings, structures, and vegetation on the placement of rooftop solar panels, aiming to minimize the reduction in electricity generation efficiency caused by external shading.

Additionally, in the design process of solar photovoltaic arrays, efforts should be made to ensure that the layout and tilt angle of the photovoltaic array maximize the capture of solar energy and its conversion into electricity. The optimal tilt angle can be determined based on photovoltaic design standards or through iterative approaches like genetic algorithms[12].

Lastly, a suitable energy storage system should be designed for substation buildings. These buildings consume a significant amount of electricity to maintain indoor temperatures for equipment operation. As a result, nighttime electricity consumption is typically lower. Moreover, intermittent maintenance activities often occur during the daytime, and there is no need to consider lighting and air conditioning energy consumption for maintenance personnel during the night. When designing an energy storage system, it is crucial to consider nighttime electricity usage. The system should neither be overdesigned, leading to unnecessary redundancy, nor underdesigned, resulting in wasted renewable energy generated by photovoltaics[13].

Taking the typical substation building mentioned earlier as an example, a quantitative analysis of renewable energy emission reduction is conducted. First, the project is located in Nanjing City, Jiangsu Province. The region has an annual sunshine duration of 2,021 hours and an annual total solar radiation of 4,586.5 MJ/(㎡·a), indicating relatively limited solar energy resources. However, there is relatively little obstruction around the substation building, which is advantageous for improving photovoltaic electricity generation efficiency.

Considering the self-shading effect of the building, photovoltaic panels are installed only on the second floor to achieve efficient utilization. According to the "Photovoltaic Power Generation Design Code GB 50797-2012", for Nanjing City located at a latitude of approximately 32°N, the recommended tilt angle for photovoltaic equipment as an independent system is 37°. The total roof area of the second floor of the project is 494 square meters. After considering boundary setbacks and self-shading of the photovoltaic panels, the actual photovoltaic area is determined to be 142 square meters. Additionally, considering degradation factors affecting photovoltaic capacity, a typical service life of 25 years is assumed.

Through simulation calculations, the total energy consumption of this typical substation building over 50 years is estimated to be 3,309,800 kWh. By using a batch of rooftop photovoltaic panels with a 25-year lifespan along with suitable energy storage equipment, electricity savings of 394,483 kWh can be achieved, resulting in a building energy savings and emission reduction of 11.9%. If two batches of rooftop photovoltaic panels with a 25-year lifespan are employed, along with appropriate energy storage equipment, electricity savings of 788,966 kWh can be realized, leading to a building energy savings and emission reduction of 23.8%.

4.3. Artificial Lighting Design Strategies

In terms of artificial lighting design, energy savings and emissions reduction can be achieved through the use of high-efficiency lighting fixtures. High-efficiency lighting fixtures, such as Light Emitting Diode (LED) fixtures, can directly convert electrical energy into light energy, unlike traditional incandescent or fluorescent

lamps that require energy conversion through heating filaments or fluorescent powders. This direct electrical-to-light conversion process allows LED fixtures to more efficiently utilize energy. Additionally, LED lighting fixtures typically have a longer lifespan compared to traditional lighting products. The lifespan of the lighting elements in LED fixtures can reach tens of thousands of hours or even longer. In contrast, incandescent lamps typically have a lifespan of only a few thousand hours. The extended lifespan of LED fixtures reduces the need for more frequent replacement of lights, further saving energy.

Moreover, replacing general illumination with zonal lighting can also avoid unnecessary energy consumption. Lighting systems can be divided into different zones and controlled using separate switches or dimmers. This allows for flexible adjustment of lighting intensity based on the specific requirements of different zones. For example, areas that require personnel for maintenance can provide higher brightness, while brightness can be reduced or lights can be turned off in unoccupied areas. Zonal lighting control can precisely meet the lighting needs of different areas, avoiding excessive energy use for overall illumination.

Furthermore, combining lighting fixtures with motion sensors that detect human activity and automatically turn the lighting system on or off based on the presence of people is an effective strategy. Motion sensors can be widely used in areas like corridors, restrooms, and storage rooms where intermittent lighting is needed, thus achieving energy savings and emissions reduction.

Using the typical substation building mentioned earlier as an example, a quantitative analysis of energy savings and emissions reduction in artificial lighting can be conducted. As shown in Table 3, ordinary fluorescent lamps, energy-saving fluorescent lamps, LED energy-saving lamps compared to ordinary incandescent lamps energy-saving 20%, 50% and 80% respectively. The original artificial lighting used energy-efficient fluorescent lamps, consuming a total of 775,167 kWh over 50 years. Replacing them with LED energy-efficient lamps would result in a 60% energy savings, equivalent to 465,100 kWh.

Table 3. Energy savings from different artificial lighting.

Type of artificial lighting	Energy consumption
Incandescent light lamps	100%
General fluorescent lamps	80%
Energy-saving fluorescent lamps	50%
LED energy-saving lamps	20%

5 Low-carbon operating strategies

In light of the operational status described earlier for substation buildings, it is evident that there is significant room for improvement in terms of energy-efficient and low-carbon practices. In recent years, with the ongoing digitization process in China, the development of smart buildings has entered a new phase. At present, many large public buildings in China are equipped with numerous sensors and smart metering systems capable of recording detailed energy usage data. The development of IoT-based building intelligence has already shown promising results in terms of energy efficiency. This technology relies on data mining techniques to extract inefficient operational patterns from building data and, subsequently, determine optimal operational strategies[14].

Substation buildings, which are constructed and operated by power utility companies, often have clear ownership structures, making them conducive to adopting smart operational technologies. During the operational phase, various types of environmental sensors can be installed in heating and cooling rooms, including temperature and humidity parameters, outdoor meteorological data, and hourly parameters provided by the building management system. These parameters can be used to train predictive models for indoor environmental conditions, including temperature, humidity, carbon dioxide concentration, and HVAC energy consumption. The following steps outline the process:

1. Deployment of Environmental Monitoring Devices. Environmental monitoring devices are deployed in the substation's HVAC rooms to monitor temperature, humidity, outdoor weather conditions, indoor occupancy, and other relevant data. This data is integrated into an online data management platform.

2. Training of Building Environmental Prediction Models. Using the collected monitoring data, predictive models for indoor environmental conditions and HVAC energy consumption are trained. Time-series forecasting deep learning algorithms are used for model training, aiming to predict indoor thermal comfort and HVAC energy consumption.

3. Training of Reinforcement Learning Agent Controller. A virtual training environment is set up using the predictive model. Deep reinforcement learning algorithms are employed to train an agent controller within this virtual environment. After approximately two months of training, the model achieves convergence, optimizing system energy consumption while ensuring indoor comfort.

4. Deployment of Agent Controller. Once training is complete, the trained agent controller is connected to the HVAC control equipment in the substation building. This integration enables the intelligent control of the HVAC system while maintaining indoor comfort.

These intelligent control strategies leverage real-time data, predictive modeling, and advanced control algorithms to optimize energy consumption in substation buildings. This approach not only reduces carbon emissions but also contributes to more sustainable and efficient building operations.

6 Conclusion

This study elucidates the functional and operational characteristics of substation buildings as exemplified by a typical reinforced concrete structural substation building, revealing the energy saving and emission reduction effects of a range of design and operational strategies. These strategies encompass low-carbon design methodologies for the building's envelope structure, approaches for harnessing renewable energy sources, low-carbon design techniques for artificial lighting, and strategies for intelligent environmental control. The strategies presented herein not only offer insights but also have practical implications for enhancing low-carbon energy efficiency in both the power industry and civil engineering.

These strategies can be applied in real-world substation projects by following steps. Firstly, during the early stages of project design, comprehensive site assessments should be conducted to evaluate the available solar resources and the extent of sunlight obstruction in the vicinity. This evaluation aids in determining the necessity of photovoltaic systems and how to optimally allocate photovoltaic area and placement. Furthermore, during the design phase of construction drawings, due consideration should be given to the thermal conductivity properties of the building's envelope (U-value). In conjunction with relevant standards, decisions should be made to select an appropriate U-value, thus ensuring the building's energy performance. Then, in the process of lighting system design, a priority should be given to choosing LED light sources with higher operational efficiency, aiming to reduce carbon emissions during operation. This can be achieved through meticulous design of the lighting system and the selection of appropriate LED fixtures. Lastly, during the operational phase, environmental monitoring and modeling conducted by professionals to develop intelligent control models, optimizing equipment operation to avoid the additional energy consumption and carbon emissions associated with manually manoeuvring equipment. By adopting these strategies, power industry professionals and construction experts can effectively reduce energy wastage and carbon emissions, ultimately contributing to a more sustainable and energy-efficient urban electricity supply. However, the practical application of these strategies may encounter challenges, such as initial investment costs and resistance to change within established industry practices.

Additionally, it is important to recognize the limitations of this study. These limitations, including the absence of optimized designs for doors, windows, and shading components, as well as the lack of detailed sizing and operational algorithms for energy storage devices, serve as a foundation for future research. Future studies can further refine and expand upon the concepts and strategies presented in this paper, addressing the potential variations in building types, site characteristics, and climate conditions. Research can also extend to explore a wider array of low-carbon strategies, such as low-carbon building materials and prefabricated construction methods, contributing to a more environmentally responsible energy infrastructure. These future research avenues will help bridge the gap between theory and practice, ensuring the continued development of sustainable and energy-efficient substation buildings.

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