A case study of energy-efficient strategies for substation building in hot and humid climate zone

Dishan yang[1,a], Xiaoyu Huang[1,b], Yubin Lin[1], Jinbo zhang[1,c], Chenyuan Zheng[2,d,*], Feng Shi[2,3,e*]

[1]State Grid Fujian Economic Research Institute, Fujian, 350000, China
[2]School of Architecture and Civil Engineering, Xiamen University, Fujian, 361005, China
[3]Fujian Province University Key Laboratory of Intelligent and Low-carbon Building Technology, Xiamen University, Xiamen, 361005, China

`[a]550818454@qq.com;[b]375718021@qq.com`
`[c]18606932711@163.com;[d]45257509@qq.com`
`*Correspondence:[e]cyuan_zheng@163.com;[f]shifengx@xmu.edu.cn`

Abstract. Buildings in China account for 45.5 % of the country's total energy consumption. As part of the electric infrastructure, substation buildings house large-scale equipment prone to over-heating, necessitating substantial energy for cooling. In this study, we aimed to investigate the energy-saving potential of natural ventilation and the impact of a renewable energy tech-nology on the Xiamen Substation, located in a hot, humid region in China. The simulations revealed significant findings: substituting natural ventilation for air condi-tioning led to a substantial annual ESP of 25.8 %. Moreover, the incorporation of renewable energy technologies, particularly photovoltaic panels in substation construction, could generate a substantial energy output ranging from 1.105 to 160.98 mwh annually. This study proposes passive strategies and renewable energy technologies for retro-fitting existing substations with energy-saving measures and for designing future green substa-tions.

Keywords: substation building; passive strategies; renewable energy technology; energy saving

1 Introduction

In the context of global energy scarcity, to achieve carbon peaking and carbon neutrality goals, the development of passive strategies is crucial for improving energy efficiency and reducing carbon emissions. Currently, passive technology has received more attention in energy-saving research for residential and office buildings, while its application in industrial buildings remains limited. Substations, despite their compact size, are numerous and pose challenges due to significant internal equipment heat dissipation and the requirement for maintaining a constant indoor temperature, resulting in substantial cooling energy consumption. Efforts have been directed towards reducing the energy consumption of substations by enhancing equipment efficiency. Ding et al. [1] proposed

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that the primary approach for achieving energy-efficient substation designs is through adoption of more efficient air-conditioning systems, utilizing natural ventilation, and replacing electric heaters with reclaimed heat from room heating. While limited, a few studies have focused on using passive strategies to optimize substation building designs, thereby reducing energy consumption. Li et al. [2] exemplified this by focusing on the primary control and communication building of a typical substation in a hot summer and warm winter area. In addition to sunshade design strategies, additional passive optimization strategies should be employed in substation designs to enhance their performance and accomplish energy-saving goals. Gong et al. [3] proposed a method that combines orthogonal and list techniques by optimizing seven passive design measures for each city. This approach aimed to explore how these measures can be optimized to reduce the energy consumption of residential buildings.

The potential of passive building strategies to reduce building energy consumption and improve indoor environments has been demonstrated. However, there is a gap in the literature that must be addressed. First, most studies have been conducted on office and residential buildings, with limited focus on the effects of passive strategies in substations. Based on these observations, this study used the Xiamen Substation as the research object and explored the impact of natural ventilation and photovoltaics panel on energy conservation in industrial buildings. Building energy consumption and energy efficiency served as evaluation indicators. The findings will provide methods and case studies for optimizing the designs of such buildings in the region, ultimately achieving low-energy buildings.

2 Materials and Methods

2.1 Analysis of the current state of substation buildings and energy consumption

2.1.1. Substation Basic Information.

The Substation (Figure 1) is located in Xiamen, Fujian Province, and operates in a hot summer and warm winter climate. The single-story building has a total floor area of 960 m2. The floor height measures 7.5 m in the GIS chamber and transformer room and 4 m in all other rooms, presenting a rectangular layout. The building design includes windows in all rooms except the transformer chamber. These windows are 0.9 m in height and vary in width, either 1.8 m or 3.6 m, according to the size of the room. The Building specifications is listed in Table 1. The floor plan of the substation is shown in Figure 2.

Fig. 1. View of substation.

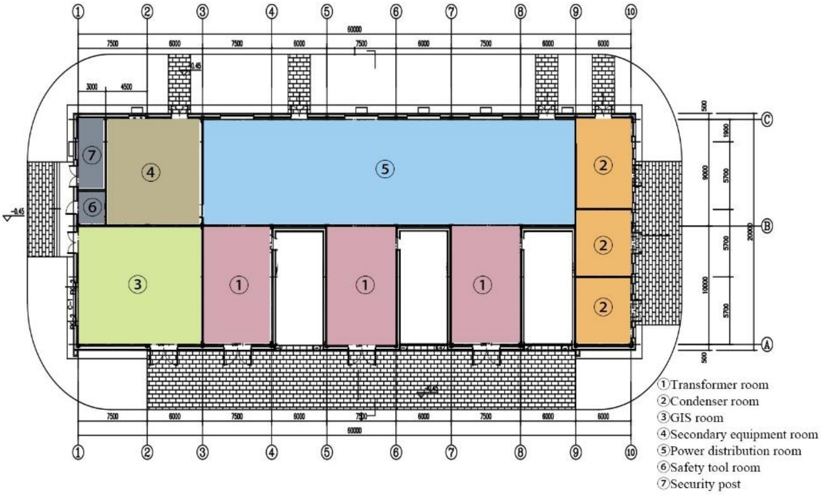


Fig. 2. Plan of substation.

Table 1. Building specifications (baseline case).

Parameters	Specification
Type of building	Industrial building
Number of floors	1
Total floor area (inner)	960 m^2
Air-conditioned area	591 m^2
Floor to floor height	4 m / 7.5 m
Cooling system	Fan coil Unit(4-Pipe) Air cooled Chiller
Window type	6 mm single blue glass
Wall structure	12 mm thick cement fiber board
	50 mm thick rock wool board
	6 mm thick cement fiber board
Roof structure	Polymer cement mortar: 20 mm
	Cement mortar: 10 mm.
	Waterproofing membrane: 10 mm
	Extruded polystyrene thermal insulation board: 30 mm
	Cement mortar levelling layer: 10 mm
	Lightweight aggregate: 30 mm
	Reinforced concrete slab: 120 mm.

2.1.2. Substation energy consumption and characteristics analysis.

The primary energy-consuming systems in the substations included various types of equipment, air conditioning, ventilation, and lighting. According to on-site research, the assembled external wall consists of a 12 mm thick cement fiber board, 50 mm thick rock wool board, and 6 mm thick cement fiber board. Energy-saving lamps and lanterns are used for building lighting. Each room has natural ventilation by way of shutters wherever possible. Rooms requiring mechanical ventilation adopt natural air intake through shutters and under the door gaps, coupled with exhaust facilitated by axial fans (equipped with a temperature control device). Rooms that require air conditioning use energy-saving air conditioning systems. The substation equipment generally operates in full-power throughout the year, with the air conditioning system representing the largest power consumption. Therefore, our subsequent analysis focuses on the heat dissipation characteristics of each functional room within the substation to determine the parameters essential for the ensuing simulation.

2.2 Simulation software and setting

2.2.1. Building performance simulation system.

Design Builder software was used as the primary analytical tool. Design Builder is an energy-efficient building design software that considers the environment from the planning stage by linking it with EnergyPlus[4-6]. In this study, building energy consumption was simulated and analyzed using Design Builder, and the impact of the adoption of natural ventilation and one renewable energy technology (photovoltaic panels) on the energy efficiency of industrial buildings was investigated using building energy consumption and energy efficiency as evaluation indicators.

2.2.2. Building simulation setting.

The building parameters were set based on the basic input, envelope design, indoor air-conditioning design, and room thermal disturbance parameters. The basic inputs for the building parameters are listed in Table 2. The envelope was mainly designed for the roof, exterior walls, and windows. The thermal parameters are listed in Table 3. Indoor air-conditioning varies depending on the room type and the specific equipment within each room. To accommodate equipment that cannot operate in high-temperature environments, the summer temperature was set to 26 °C, and the winter temperature was set to 20 ℃. These conditions must be maintained in the equipment room 24 hours a day, throughout the year. The air-conditioning in the duty room depends on the situation including the personnel; the specific settings are shown in Table 4.

Table 2. Baseline case simulation inputs.

Parameters	Unit	Value
Humidification setpoint	%	35
Dehumidification setpoint	%	65
Design Illuminance Living	lux	300
Cooling COP	-	3

Parameters	Unit	Value
U Value: Wall	W/ m^2	2.09
U Value: Roof	W/ m^2	3.993
Solar reflecta	-	0.17
Solar Heat-gain Coefficient	-	0.819
Visual Light Transmittance	-	0.881
Occupancy	person/ m^2	0.038
Air change rate	%	0.7

Table 3. Thermal parameters of substation enclosure.

Object	Heat transfer coefficient / [W/(m^2·K)]	Solar heat gain coefficient (SHGC)
Concrete ground	0.44	-
Exterior walls	0.97	-
Interior walls	0.97	-
Ceiling	0.7	-
Window glazing	2.96	0.722

Table 4. Indoor air-conditioning design parameters.

Name	Summer Temperature/°C	Winter Temperature/°C	Air-conditioned Work and Rest
Transformer room	26	18	-
Condenser room	26	18	24 hours
GIS room	26	18	-
Secondary equipment room	26	18	24 hours
Power distribution room	26	18	24 hours
Safety tool room	26	20	-
Security post	26	20	According to demand

The indoor heat disturbance of a building comprises the heat and moisture dissipation by people, lighting, and equipment. In the computational model, the time-by-time heat generation is described by setting two parameters: the heat dissipation index and the rest pattern. The heat index was used to describe the intensity level of heat generation, and the rest mode was used to describe the variation in heat generation over time. The indoor heat disturbance parameters for each substation room are listed in Table 5.

Table 5. Indoor thermal disturbance parameters for main rooms.

Name	Personnel/person	Lighting/ (W/ m^2)	Equipment/(W/m^2)	Area(m^2)
Transformer room	-	4	293	225
Condenser room	-	4	395	114
GIS room	-	4	277	135
Secondary equipment room	-	4	280	94.5
Power distribution room	-	4	83	364.5
Safety tool room	-	4	0	9
Security post	1	4	0	18

2.3 Passive strategies of building

2.3.1. Ventilation strategies.

Building ventilation is applicable in air-conditioned cooling rooms. When the outdoor environment is suitable, turning off the air-conditioning unit and realizing natural ventilation can reduce the cooling load. Ventilation settings are listed in Table 6.

Table 6. Ventilation settings.

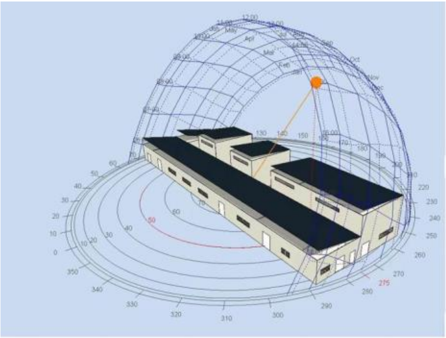
Object	Operation time	Conditions for opening	Ventilation efficiency
Ventilation	24 hours	18 ℃ < Indoor temperature < 26 ℃	0.3

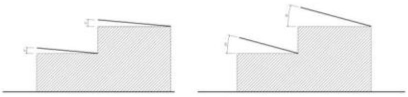
2.3.2. Photovoltaic strategy.

The potential of using daylight to reduce energy consumption was explored by erecting photovoltaic (PV) panels on the roof, façade, and windows to produce electricity from solar energy. We compared the power generation capacity of roof photovoltaic panels with angles of 5 ° (parallel to the roof), 15 °, and 25 °, and installed photovoltaic panels in the east, west, and south directions for power generation analysis. Additionally, we used a horizontal photovoltaic shading panel, an inclined photovoltaic shading panel (45 °), and a vertical photovoltaic shading panel as the parameters of the photovoltaic device in the window to investigate its power generation effect. A schematic of the PV system is shown in Figure 3. The PV setup is listed in Table 7. The electrical parameters of the photovoltaic panelis listed in Table 8.

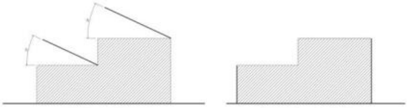
Table 7. Photovoltaic set-up scenarios.

Object	Area/ $m^{2}\cdot$	Site	Angle
Roof PV 1	960	Roof	5°
Roof PV 2	960	Roof	15°
Roof PV 3	960	Roof	25°
Façade PV	481.01	Façades	0°
Horizon PV shading panel	12.84	Window-based	0°
Inclined PV shading panel	12.84	Window-based	45°
Vertical PV shading panel	12.84	Window-based	90°





(a) Roof PV 5° (b) Roof PV 15°



(c) Roof PV 25° (d) Facade PV

(a) Horizontal PV shading panel (b) Inclined PV shading panel (45°) (c)Vertical PV shading panel

Fig. 3. Schematic diagram of PV equipment.

Table 8. Electrical parameters of the photovoltaic panel.

Parameter	Value	Unit
Cell efficiency in laboratory conditions	17.5	%
Rated power	285	W

2.4 Building Evaluation Indicators

2.4.1 Energy performance index.

The energy performance index (EPI), also known as the EUI, was estimated for the baseline using Equation 1[7]:

$$EPI = \frac{Total\ energy\ consumed\ in\ a\ year(kWh)}{Total\ floorarea\ of\ the\ building(m^2)} kWh/m^2/year \tag{1}$$

2.4.2 Energy-saving potential.

Each passive design scenario was simulated, and the corresponding EPI values were estimated. The energy saving potential (ESP) of each scenario was estimated as the percentage reduction in the EPI compared with the baseline EPI. The calculation formula is given in Equation 2:

$$ESP = 1 - \frac{Design\ building\ energy\ performance\ index}{Reference\ building\ energy\ efficiency\ index} \times 100\% \tag{2}$$

3 Results

3.1 Impact of passive ventilation strategies.

Figure. 4 shows the energy performance of the passive strategies to increase natural ventilation, with an EPI value of 368.71 kwh /m^2 and an ESP as high as 25.80 %. This is because natural ventilation, achieved by opening windows and doors at low outdoor temperatures, enables adequate indoor and outdoor airflow. Natural ventilation helps cool the room without consuming additional energy compared with air conditioning, which requires electricity. Consequently, it can save energy and reduce operating costs.

Figure. 5 compares the energy consumption when using natural ventilation in combination with air conditioning and when using only air conditioning for cooling over 12 different months. There was a small difference in energy consumption between the use of natural ventilation and air conditioning in July and August. However, this difference gradually became significant in the other months, especially during winter. Using natural ventilation can save up to 17.17 MWh of energy compared with the baseline case. During summer, owing to the high outdoor temperatures, indoor equipment produces a significant amount of heat. Therefore, the time required to utilize passive strategies with natural ventilation is limited, resulting in higher energy consumption. However, during other seasons, especially when the outdoor temperature drops significantly during winter, the time required to utilize passive strategies using natural ventilation increases. By opening windows and utilizing natural ventilation, indoor heat can be quickly discharged outdoors, thereby reducing cold energy consumption.

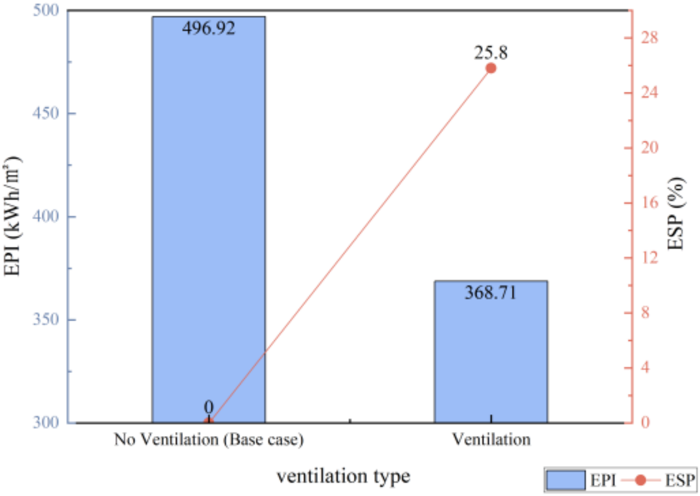


Fig. 4. EPI and ESP of different types of ventilation studied.

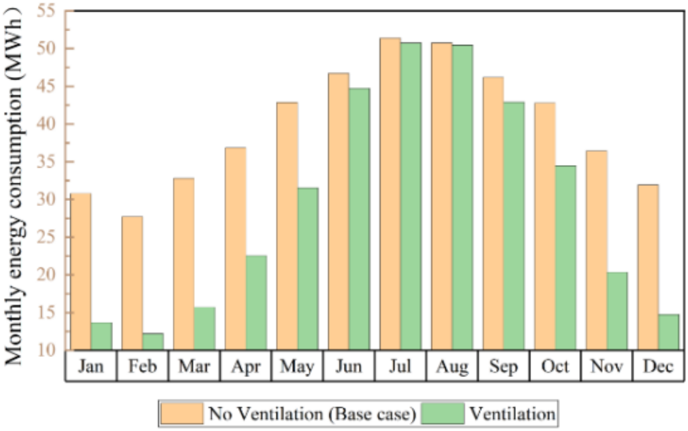


Fig. 5. Monthly building energy consumption by different ventilation type.

3.2 Impact of photovoltaic panel

Figure. 6 demonstrates the influence of photovoltaic equipment on building energy consumption and production efficiency, which can be observed through roof, façade, and window measurements. With a 5 % inclination angle for the baseline case, placing photovoltaic panels parallel to the roof can save 9799.94 kWh of energy and produce 160982.7 kWh of energy. As the inclination angle gradually increased, the energy consumption of the building increased, and the amount of solar power generated decreased. Photovoltaic (PV) applications on façades have poor energy savings and production efficiency. When the photovoltaic panels are installed at the east, west, and south elevations of the building, the energy consumption is reduced by 38.82 kWh relative to the baseline case. The resulting energy output was 42,775.73 kWh, which was approximately one-third of the rooftop photovoltaic power capacity. Regarding the impact of the three forms of photovoltaic shading panels on the indoor energy consumption, their contribution to reducing building energy consumption was relatively small, with an average energy consumption of approximately 477 MWh. However, there are differences in their power-generation capabilities. The annual power generation of the inclined photovoltaic shading panels (45 °) was the highest, reaching 1706.70 kWh. This tilt design allows sunlight to illuminate the photovoltaic panels more effectively, thereby improving power generation efficiency. In contrast, the power generation of horizontal photovoltaic shading panels is 1420.81 kWh, and that of vertical photovoltaic shading panels is the lowest, at 1105.67 kWh. By optimizing rooftop photovoltaics and incorporating tilt designs into photovoltaic shading panels, power generation efficiency can be improved, leading to reduced building energy consumption and increased renewable energy utilization.

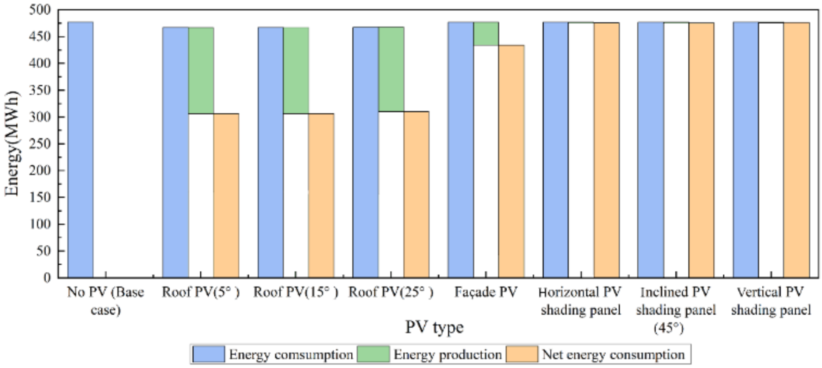


Fig. 6. Annual energy consumption of different types of PV.

4 Conclusions

The results of this study are beneficial for comparing the energy-saving potential of passive strategies and one renewable energy technology for the construction of the substation. Based on the annual and monthly analyses of building energy consumption using Design Builder simulations in the substation case studies; the following findings are worth noting:

For natural ventilation in buildings, choosing natural ventilation over air conditioning for cooling the indoor environment when the outdoor environment is suitable can maximize energy efficiency, with an EPI of 368.71 kWh/m^2 and an ESP of 25.80 %.

Concerning the application of photovoltaic panels in architecture, rooftop photovoltaics can reduce building energy consumption significantly, with a maximum reduction of 9799.94 kWh. Parallel photovoltaic panels mounted on the roof yield the highest power generation at 160982.7 kWh. Façade photovoltaic panels produce approximately one-third of the power generated by rooftop photovoltaics and are not recommended for large installation areas due to their large size. Inclined photovoltaic shading panels (45 °) achieve the highest annual power generation, around 1706.70 kWh, compared to other types of photovoltaic shading panels.

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