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Article

Evaluation of Energy Consumption and Energy Saving of Large Public Buildings

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Abstract: Due to rapid economic and technological developments, energy consumption has increased considerably, significantly impacting the environment. This concern is a priority for both governmental and societal sectors presently. This study aims to examine the energy consumption of a proposed teaching theater building, using the E-Quest simulation software. Initially, the building's original energy usage is assessed. Subsequently, employing the single-variable principle, modifications are made to the roof, exterior walls, window glass materials, and visor dimensions. The results from these modifications are then with the original energy data to evaluate the variations in energy savings, cost reductions, and carbon emissions.

Keywords: Building energy consumption simulation; E-Quest; Energy saving

1. Introduction

With the rapid development of the economy and technology, energy consumption in large public buildings has always been a focal point of energy conservation and emissions reduction. Industrial energy consumption is the primary source of carbon emissions, followed by transportation and buildings. According to McKinsey, the building sector presents the best opportunity for cost-effective emissions reduction through the widespread adoption of energy-saving technologies in buildings [1].

In 2021, among public buildings, urban residential buildings, and rural residential buildings, public buildings, consumed 42% of the energy and contributed 41% of the carbon emissions despite consisting of the total building area [2]. Therefore, public buildings are the primary source of energy consumption and carbon emissions from buildings. Recently, countries have actively developed green and low-carbon buildings to reduce consumption and improve efficiency in the construction industry. Building energy consumption covers energy usage throughout the entire life cycle, including heating, air conditioning, and lighting, as well as domestic water, electricity, and gas consumption. In traditional building energy consumption analysis, static algorithms are adopted but they fail to fully consider the dynamic nature of energy consumption of buildings, resulting in significant discrepancies between analysis results and actual operational data.

Building energy consumption is affected by multiple factors, including building design, the operation of the HVAC system, occupant behavior patterns, and climate change [3]. These factors influence the overall energy consumption of a building. On-site measurements are time-consuming and costly with much labor. Thus, computer-based dynamic simulation is regarded as an ideal approach [4]. As a tool for evaluating building energy consumption, computer simulation is used to predict and assess the energy consumption to provide energy-saving solutions for buildings. Energy consumption for buildings is analyzed to identify high-energy-consuming areas and implement cost-effective energy-saving retrofitting measures [5,6].

Software used for building energy analysis includes DOE-2 (developed by the U.S. Department of Energy), BLAST (developed by the U.S. Department of Defense), EnergyPlus (U.S.), ESP-r (U.K.), DeST, TRNSYS, and TASE. eQUEST is a software program used for simulating building energy consumption. It operates by predicting a building's energy consumption based on building information, climate data, and mathematical models through simulation calculations. This software encompasses various aspects, including building shape design, load calculation, HVAC system design, and energy consumption assessment. By analyzing and optimizing building design schemes, eQUEST helps designers, engineers, and owners better understand building energy consumption from the design stage and formulate energy-efficient and environmentally friendly plans to achieve sustainable development goals [7] .

Integrating Building Information Modeling (BIM) with building energy simulation (BES) allows for a comprehensive analysis and visualization of building energy performance, offering quantitative and interpretative interoperability tools [8]. This interoperability allows designers to evaluate and optimize building energy performance by simulating different energy-saving measures, such as passive cooling strategies [9,10], digital twins [2], and energy-efficient HVAC systems [7]. Furthermore, the use of simulation-based optimization has proven effective in achieving cost-optimal analysis for nearly zero-energy buildings [11], while comparative analyses of energy simulation tools highlight the importance of appropriate software for architectural research [6,12]. Retrofitting measures for existing buildings, particularly in arid climates are adopted to improve building envelopes, cool and green roofs, and sunshades to reduce cooling requirements [4,13,14].

This study aims to review energy consumption reduction strategies in public buildings using eQUEST simulation software. We explore the application of various energy-efficient technologies, including BIM integration, passive cooling strategies, and optimal HVAC system design, for constructing sustainable and low-carbon buildings. Using eQUEST improves building energy efficiency, reduces energy waste, lowers operating costs, and supports green building certification. Previous studies focus on how to reduce energy consumption in existing buildings by employing various modeling tools and techniques, such as energy audits, Artificial Neural Networks (ANN), and BIM/ BES integration. These studies present information on climate-specific energy-saving strategies. Table 1 summarizes the articles, highlighting their research focus, region, methods/tools used, and innovations.

Table 1. Building energy consumption and simulation review.

Region	Research Focus	Methods/Tools & Innovation	References
Toronto, Canada	Reducing energy consumption in two multi-unit residential buildings (MURBs)	- Energy audit - Energy modeling Practical strategies for reducing energy consumption in multi-unit buildings	[1]
Lebanon	Predicting energy consumption using Artificial Neural Network (ANN) as a digital twin	- Artificial Neural Network (ANN) - Digital twin modeling Digital twin modeling of residential buildings for climate change impact	[2]
Global	Integrating Building Information Modeling (BIM) and Building Energy Simulation (BES)	- Building Information Modeling (BIM) - Building Energy Simulation (BES) - Interoperability analysis Quantitative and interpretative interoperability analysis of BIM and BES	[3]
Saudi Arabia	Reducing cooling requirements in arid climates via passive energy-saving measures	- Building envelope retrofitting - Energy simulation (EnergyPlus) Retrofitting measures in arid climate for passive cooling	[4]
Turkey	Optimal decision-making in energy efficiency retrofitting projects	- Energy efficiency modeling - Decision-making model Decision-making framework for optimal retrofitting strategies	[5]
Global	Comparing energy simulation applications used in green buildings	- Comparative analysis of simulation tools Comparative analysis of various green building simulation tools	[6]
China	Energy efficiency design of building thermal and HVAC systems	- BIM-based energy efficiency analysis - HVAC optimization BIM-based HVAC optimization based on Chinese standards	[7]
Spain	Enhancing interoperability between BIM and BEM for energy modeling	- BIM-BEM interoperability analysis - Simulation and data exchange Improving data exchange between BIM and BEM	[8]
Saudi Arabia	Comparative analysis of energy simulation tools	- Comparative analysis - Case study analysis Comparative analysis of simulation tools specific to Saudi Arabia	[12]

Sri Lanka	Applicability of green BIM for existing green buildings	- Green BIM assessment - Applicability analysis Applicability framework for green BIM	[15]
Global	Investigating BIM to BES interoperability and simulation results	- BIM-BES interoperability analysis - Simulation results analysis Insights on BIM-BES interoperability challenges and opportunities	[14]
Tropical countries	Improving thermal insulation in temporary shelters for disaster management	- Thermal insulation simulation - Energy analysis (EnergyPlus) Thermal insulation strategies in tropical post-disaster shelters	[16]
Global	BIM 6D methodology for energy efficiency and sustainability in hospitals	- BIM 6D methodology - Hospital energy modeling BIM 6D methodology application in hospitals	[17]
Global	Comparative study on new technologies for understanding building energy performance	- Comparative study - New technology analysis Comparative study on emerging technologies for energy performance	[18]
Brazil	Achieving net-zero energy buildings in Brazilian mid-rise offices	- NZEB control strategy - Desk fans and set point temperature Innovative control strategy for NZEB mid-rise offices	[19]
France	Developing a thermal simulation tool interoperable with BIM platforms	- Thermal simulation tool - BIM interoperability Interoperable thermal simulation tool through BIM platforms	[20]
Bahrain	Systematic methodology for optimizing energy performance in office buildings	- Optimization methodology - Office building energy analysis Systematic optimization of office energy performance	[21]
Bahrain	Comparing accuracy of building energy analysis using different weather data	- Comparative accuracy analysis - Weather data variability Comparing weather data impact on energy analysis accuracy	[22]
Saudi Arabia	Developing sustainable residential buildings in Saudi Arabia	- Sustainable building development - Case study analysis Sustainable development strategies for Saudi Arabia	[10]
UAE	Passive cooling strategies for thermal performance and energy reduction	- Passive cooling strategies - Residential building analysis Improving Residential Thermal Performance in UAE	[9]
Italy	Experimental validation of dynamic simulation tool using real test room	- Dynamic simulation tool - Experimental validation Experimental validation of in-house simulation tool	[23]
Global	Simulation-based optimization for cost-optimal analysis of nearly zero energy buildings	- Simulation-based optimization - NZEB cost analysis Cost-optimal analysis of NZEB via simulation-based optimization	[11]
Lebanon	Natural ventilation strategies for residential buildings in Beirut	- Natural ventilation strategies - Residential building analysis Extending comfort hours with natural ventilation	[24]
Saudi Arabia	Cool and green roof strategies for energy saving and outdoor cooling in hot climates	- Cool and green roof strategies - Numerical simulation (EnergyPlus) Evaluating the pedestrian-level cooling impact of cool and green roofs	[13]

2. Materials and Methods

2.1. Materials and Case Study

In this study, we modeled a "U"-shaped theater building. The building has an area of 3530 m², with a single floor, measuring 79.2 m in length, 49.5 m in width, and 4.6 m in height. The roof is covered with 150 mm thick reinforced concrete and steel composite panels, while the exterior walls are 200 mm thick with reinforced concrete. The windows are installed with clear glass without external sunshades. Located in a subtropical monsoon climate, these conditions were input into the eQUEST simulation software for energy consumption analysis. The building model's floor plan and 3D diagram were generated as shown in Figs. 1 and 2. Following the simulation, the analysis result was reviewed, and the annual electricity consumption and consumption ratio for the building was obtained (Figs. 3 and 4).

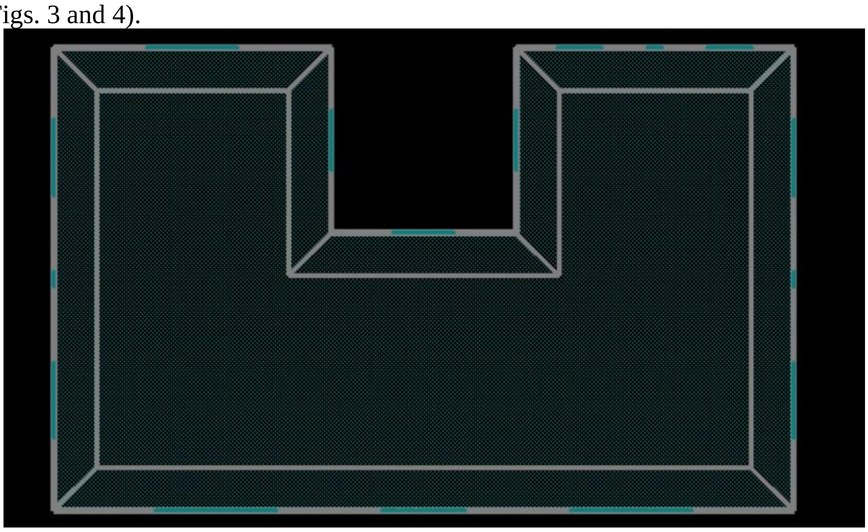

Fig. 1. Structure of the architectural model.

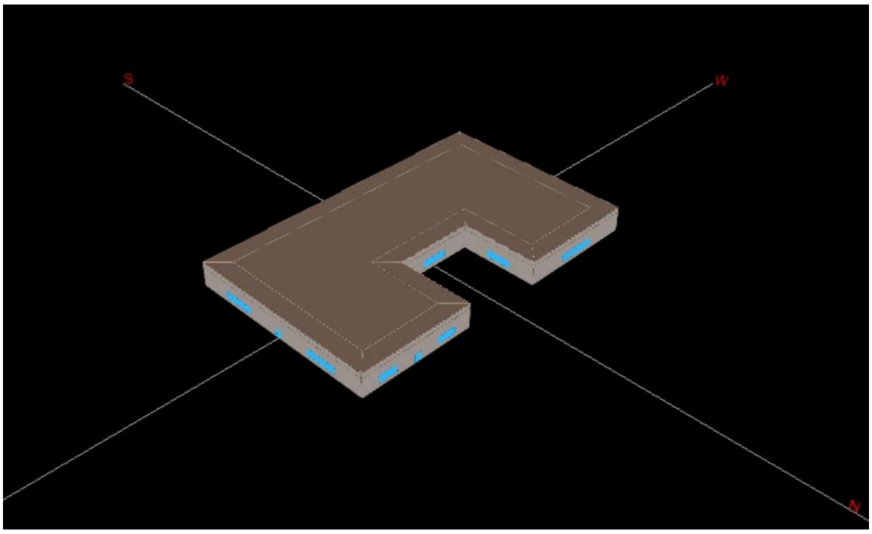

Fig. 2. 3D diagram of building model establishment.

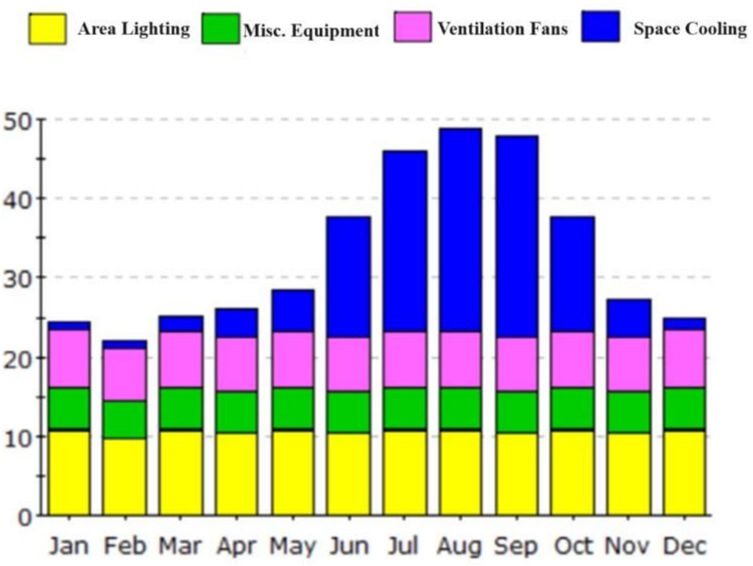

Fig. **3.** The power consumption diagram obtained by simulating of building.

The building's electricity consumption from June to October was significantly higher than in other months to supply space cooling amid hot weather, and high temperatures (Fig. 1). Annual electricity consumption was estimated as regional lighting (32%), space cooling (31%), fans (22%), and miscellaneous equipment 16% (Fig. 4).

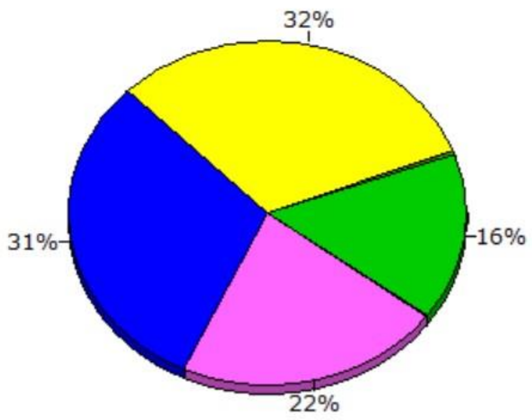

Fig. 4. Electricity consumption proportion diagram derived from simulated buildings.

3. Results

3.1. Roof

When simulating with eQUEST, all other parameters were kept constant except for the roof material to observe annual variations in energy consumption. The cost of commercial electricity is approximately CNY 0.15/kWh, and burning one ton of standard coal to generate 3200 kWh of electricity emits 2.62 tons of carbon dioxide (Table 2).

Table 2. Energy saving and carbon reduction after roof material conversion

Parameter / Material	Energy consumption (kWh ×1000)	Priority after conversion	Improve efficiency (%)	Cost saved (CNY)	Reduced carbon emissions (ton)
c	396.11				
Aluminum	393.39	2	0.69	3264	2.23
Glass,spander	398.41	6	-0.58	-2760	-1.88
Film,Mylar aluminized	388.94	1	1.81	8604	5.87
Marble	397.52	5	-0.36	-1692	-1.15

Galvanized steel (bright)	394.23	3	0.47	2256	1.54
Weathered asphalt pavement	399.92	7	-0.96	-4572	-3.12
Clay tile	396.73	4	-0.16	-744	-0.51

A comparison of the simulated values revealed that the total annual electricity consumption of the steel-roof building was 396,110 kWh. When the roof material was changed to aluminum, the total electricity consumption became 393,390 kWh; with polyester film, it became 388,940 kWh; and with steel, it became 394,230 kWh. Polyester film was the most energy-efficient, with an improvement efficiency of 1.81%, while steel was the worst. The energy-saving effectiveness was in the order of polyester film > aluminum > steel > steel composite panel > tile > marble > glass > asphalt. Compared to steel, polyester film, aluminum, and steel roofs saved CNY 8,604, 3,264, and 2,256 annually, which is equivalent to carbon emissions of 5.87 tons, 2.23 tons, and 1.54 tons, respectively (Table 2). All other materials have worse energy-saving effects than polyester film.

3.2. External Wall

The total electricity consumption of a building with exterior walls of reinforced concrete in a thickness of 200 mm was 396,110 kWh. When the wall material was changed to polyester film, the total electricity consumption decreased to 394,470 kWh with an improvement efficiency of 0.41%. Aluminum resulted in total electricity consumption of 395,330 kWh with an improvement efficiency of 0.2%. Steel had a total electricity consumption of 395,540 kWh with an improvement efficiency of 0.14%. All other materials except for reinforced concrete saved electricity. The energy-saving effectiveness ranked as polyester film > aluminum > steel > reinforced concrete > marble > glass > asphalt. Using polyester film saves CNY 1,968, equivalent to a reduction of 1.31 tons of carbon. Aluminum saves CNY 936 per year, reducing carbon emissions by 0.64 tons. Steel saved CNY 684 per year, reducing carbon emissions by 0.47 tons (Table 3).

Table 3 Energy saving and carbon reduction after exterior wall material conversion

Parameter / Material	Energy consumption (kWh ×1000)	Priority after conversion	Improve efficiency (%)	Cost saved (CNY)	Reduced carbon emissions (ton)
Wood/Plywood (6 in Conerete)	396.11				
Aluminum	395.33	2	0.2	936	0.64
Glass,spander	396.35	5	-0.06	-288	-0.20
Film,Mylar aluminized	394.47	1	0.41	1968	1.34
Marble	396.21	4	-0.03	-120	-0.08
Galvanized steel (bright)	395.54	3	0.14	684	0.47
Weathered asphalt pavement	396.42	6	-0.08	-372	-0.25
Clay tile					

3.3. Simulation Results for Window

A building with windows of clear glass showed a total electricity consumption of 396,110 kWh. When changed to low-emissivity glass, the total electricity consumption decreased to 393,980 kWh, resulting in an improvement in efficiency of 0.54%. This change saves CNY 2,556 per year and reduces carbon emissions by 1.74 tons. Coated glass showed the best energy-saving effect, with a total electricity consumption of 373,350 kWh and an improvement efficiency of 5.75% saving CNY 27,312 and reducing carbon emissions of 18.63 tons. Ultra-clear glass increases electricity consumption compared to clear glass, providing no energy-saving effect. With electroplated glass, the total electricity consumption was 395,490 kWh, resulting in an improvement efficiency of 0.16%, saving CNY 744 and reducing carbon emissions by 0.51 tons. Pilkington glass resulted in total electricity consumption of 380,040 kWh, achieving an improvement efficiency of 3.78%, saving CNY 17,976 per year and reducing carbon emissions by 12.26 tons (Table 4). The windows of coated glass and Pilkington glass presented the most significant energy-saving effects.

Table 4. Energy saving and carbon reduction after window glass material conversion.

Material \ Parameter	Energy consumption (kWh ×1000)	Priority after conversion	Improve efficiency (%)	Cost saved (CNY)	Reduced carbon emissions (ton)
Clear/Tinted glass	396.11				
Low-emissivity glass	393.98	3	0.54	2556	1.74
Reflective glass	373.35	1	5.75	27312	18.63
Ultraclear glass	397.54	5	-0.36	-1716	-1.17
Electroplated glass	395.49	4	0.16	744	0.51
Pilkington glass	381.13	2	3.78	17976	12.26

3.4. Building Envelope Combination

when the sunshade was extended by 0.3 m, 395,850 kWh was consumed, saving CNY 312 and reducing carbon emissions by 0.21 tons. When the sunshade was extended by 0.9 m, the total annual electricity consumption decreased to 395,530 kWh, saving CNY 696 and reducing carbon emissions by 0.47 tons. With a 1.5-meter extension, the total annual electricity consumption decreased to CNY 924 with a reduced carbon emissions of 0.63 tons. An extension by 2.1 m showed a total annual electricity consumption of 395,230 kWh, saving CNY 1,056 and reducing carbon emissions by 0.72 tons. When the sunshade is extended by 2.7 m, the total annual electricity consumption is reduced to 395,160 kWh, saving CNY 1,140 and reducing carbon emissions by 0.78 tons (Table 5). The larger the sunshade size, the better the energy-saving effect.

Table 5. Installation of different sun visors

Window shade \ Parameter	Energy consumption (kWh ×1000)	Priority after conversion	Improve efficiency (%)	Cost saved (CNY)	Reduced carbon emissions (ton)
none	396.11				
0.3 m	395.85	5	0.07	312	0.21
0.9 m	395.53	4	0.15	696	0.47
1.5 m	395.34	3	0.19	924	0.63
2.1 m	395.23	2	0.22	1056	0.72
2.7 m	395.16	1	0.24	1140	0.78

3.5. Energy Model of Smart Building

Based on the simulation results, the optimal results were found for a roof with polyester film, exterior walls with polyester film, windows of coated glass, and sunshades extended 2.7 m. Figure 5 and Table 6 illustrate that the original building design consumed a total of 396,110 kWh annually. By replacing the roof material, exterior wall material, window glass material, and sunshade size in an optimal combination, the annual total electricity consumption was reduced to 364,530 kWh. This change saved CNY 37,896 and reduced carbon emissions by 25.86 tons, achieving an improvement efficiency of 7.97%.

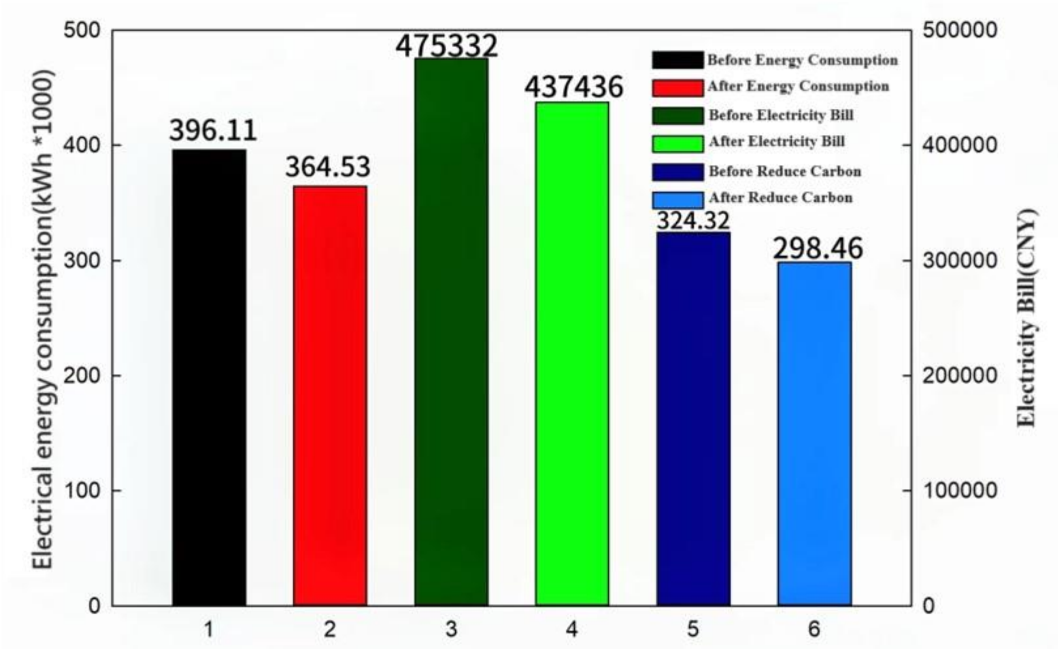

Fig. 5. Difference in energy consumption after installing energy-saving materials.

Table 6. Best energy saving and carbon reduction after conversion.

RUN / Combination	Energy consumption (kWh × 1000)	Improve efficiency (%)	Cost saved (CNY)	Reduced carbon emissions (ton)
Original comibination	396.11			
Optimal combination	364.53	7.97	37896	25.86

4. Conclusions

We built a model to save energy for a large public building using eQUEST. By changing the roof material, exterior wall material, window glass, and sunshade length, the building's energy consumption was simulated to evaluate energy-saving and carbon reduction improvements. According to the eQUEST simulation, steel, polyester film, or aluminum for the roof reduced building energy consumption in the order of polyester film > aluminum > steel. Installing sunshades on the building reduced energy consumption, and the longer the sunshade size, the better the shading effect. Replacing the roof material, exterior wall material, window glass type, and sunshade size with optimal conditions showed the best results for saving energy.

Author Contributions: C.-F.H.: Writing—original draft; D.-X.H.: Formal analysis, Investigation, Software; T.Y.: Data curation; X.-J.C.: Data curation; A.-C.H. and T.-J.W.: Supervision, Conceptualization, Methodology. All authors have read and agreed to the published version of the manuscript.

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

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