

Article

Zero-Carbon Building: Rule-Based Design and Scheduling Adapting to Seasonal Time-of-Use Electricity Prices

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Abstract

Against the backdrop of the global advancement of carbon neutrality goals and the energy transition in the building sector, zero-carbon buildings have emerged as pivotal enablers for achieving carbon neutrality in the construction industry. The rule-based scheduling of energy storage systems (ESS) is critical to enhancing energy efficiency and economic performance of buildings. This study takes the Jinan Zero-Carbon Operation Center Project in Shandong Province as the research object, developing a comprehensive technical framework covering the entire process from design to operation, and investigates the rule-based design and ESS scheduling strategies in response to Shandong's newly implemented seasonal time-of-use (TOU) electricity pricing policy. First, core performance indicators are defined in accordance with national evaluation standards for zero-carbon buildings. Hourly building energy loads and photovoltaic (PV) generation profiles are simulated over a full year, which serves as the basis for determining the optimal PV installed capacity and ESS sizing. Second, an ESS scheduling strategy integrating PV generation forecasting and the seasonal TOU electricity price structure is formulated, with clear charging and discharging logic defined. Finally, the operational and economic performance of different scheduling modes are evaluated and compared through case studies. The results show that the annual PV generation ratio reaches 101.38%, with a self-consumption rate of 73% and a self-sufficiency rate of 72%, all meeting the core requirements for zero-carbon buildings. Compared with the conventional real-time scheduling mode (Mode 1), the proposed optimized mode (Mode 2) that incorporates TOU pricing and PV forecasting achieves an annual operational cost saving of 367,349 CNY, corresponding to a reduction of 47.02%. Distinct seasonal variations in core indicators are also observed: the PV generation ratio is lower in summer and winter but the self-consumption rate is higher, with the opposite trend in spring and autumn. The proposed technical framework and scheduling strategy provide practical guidance for the design and operational optimization of zero-carbon buildings and offer decision-making support for ESS operation under TOU electricity pricing policies.

Keywords: zero-carbon building; energy design; photovoltaic generation; energy optimization

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1. Introduction

Against the backdrop of global climate change mitigation and the pursuit of carbon neutrality, the building sector has emerged as a critical focal point for energy transition

and emission reduction. Globally, buildings account for approximately 30% of final energy consumption and 26% of energy-related emissions [1]. In response, many countries have set ambitious targets to decarbonize their building stock, with regulations increasingly mandating new constructions to be nearly or net-zero-energy buildings [2,3]. As a pivotal enabler of these targets, zero-carbon buildings (ZCBs) are characterized by on-site renewable energy self-sufficiency and lifecycle carbon neutrality. They integrate photovoltaic (PV) systems, energy storage systems (ESS), and advanced energy-saving technologies to realize low-carbon operation and energy autonomy [4,5].

The technological pathway for ZCBs is multifaceted, involving both passive and active strategies. A significant body of research has focused on building-integrated photovoltaic (BIPV) technologies, which have demonstrated substantial potential. For instance, studies in China's Hainan Province show that rooftop PV alone could supply 86.9% of the province's electricity demand, with a payback period of approximately 6.3 years [6]. Similarly, a case study in India on a 42 kWp rooftop PV plant reported an internal rate of return of about 21% and a CO₂ mitigation of 1199 tons over its lifetime [7]. The performance of BIPV systems is highly dependent on factors such as building orientation, tilt angle, and urban layout, which influence shading and thus power generation [8,9]. Advanced glazing technologies like Heat Insulation Solar Glass (HISG) have been developed to not only generate power but also provide superior thermal insulation and self-cleaning functions, offering a U-value as low as 1.10 W/m²K [10].

Beyond power generation, the operational energy management of ZCBs is crucial for achieving both carbon reduction and economic efficiency. This involves optimizing the complex interaction between the building's load, renewable generation, and energy storage, often described as "source-grid-load-storage" coordination [11,12]. Many studies have developed optimal scheduling models using various objective functions, such as minimizing operational costs, reducing grid loss, or flattening the load profile [13,14]. For peak load shaving, particle swarm optimization and genetic algorithms have been applied to determine the optimal location and capacity of ESS, demonstrating significant improvements in load factor and economic benefits [15]. Furthermore, Li [16] presents an integrated framework combining field measurements and multi-scenario simulations to quantify residential air conditioning flexibility across seasons and control strategies. Wu [17] considered the coordinated optimization of active and passive energy conservation from a cost perspective; compared to a method that considers only active energy conservation, this approach can reduce costs by approximately 2.2–3.4%.

However, the inherent uncertainty of on-site PV generation and building loads poses a significant challenge to real-world energy management [18]. Day-ahead scheduling strategies, while common, can be overly conservative or fail to adapt to intraday fluctuations caused by cloud cover or occupancy changes [19]. To address this, researchers have explored multi-timescale optimization, combining day-ahead planning with intraday rolling optimization to correct deviations based on real-time data [20,21]. For instance, a day-ahead flexible planning and intraday rolling optimization algorithm applied to a ZCB in Beijing increased the PV self-absorption rate by 7.13% [21,22]. Other studies have tackled uncertainty by employing fuzzy chance-constrained programming, which models source-load forecast errors and allows decision-makers to balance operational risk against thermal comfort objectives with an adjustable confidence level [23,24].

Although many studies have focused separately on the optimal design of zero-carbon buildings (ZCBs) or the scheduling of their energy systems, a comprehensive framework capable of seamlessly integrating ZCB design principles with operational scheduling—and explicitly adapting to dynamic and seasonal energy pricing mechanisms—has yet to be fully developed. The introduction of complex pricing mechanisms, such as China's seasonal

time-of-use electricity pricing policy, creates new opportunities for economic optimization that are rarely considered in current design practices. Most existing studies either assume fixed electricity prices or fail to utilize price differences across seasons and time periods as core drivers for system sizing and operational logic. This oversight may result in designs that are technically compliant but economically suboptimal.

To bridge this research gap, this study takes the Jinan Zero-Carbon Operation Center in Shandong Province as an empirical case and proposes a novel integrated technical framework for zero-carbon buildings (ZCBs). The main innovations of this study are threefold:

- (1) A rule-based integrated design-operation methodology is proposed, which takes the three core performance indicators of zero-carbon buildings (PV generation ratio, PV self-consumption rate, and PV self-sufficiency rate) as constraints and conducts full-year hourly simulations of building energy load and PV power output.
- (2) A predictive scheduling strategy for energy storage systems (ESS) considering time-of-use (TOU) electricity prices is constructed. By incorporating day-ahead PV generation and building load forecasting to formulate scheduling plans, the strategy prioritizes grid power purchase and charging during deep off-peak periods and reserves stored energy for discharge during top peak periods, so as to maximize electricity price arbitrage under Shandong's five-tier seasonal TOU pricing policy.
- (3) A two-dimensional comparative analysis covering technical compliance and economic performance is carried out between the zero-carbon rule-based scheduling mode and the conventional real-time passive scheduling mode. This dual assessment reveals significant seasonal variations in core indicators and quantifies the considerable cost-saving benefits of the proposed intelligent strategy, providing practical and implementable guidance for the design and operational optimization of future zero-carbon buildings.

2. Research Technical Route and Theoretical Formulas

2.1. Technical Roadmap

This study establishes a step-by-step implementation pathway from zero-carbon building design to energy storage system operation and scheduling, incorporating seasonal TOU electricity prices and key performance indicators. The technical roadmap is illustrated in Figure 1.

The first step involves the design of zero-carbon buildings, where core performance indicators are defined in accordance with the Assessment standard for carbon-neutral building (T/CECS 1555-2024) [25], including: (1) the annual PV generation ratio is no less than 100%; (2) the PV self-consumption rate is no less than 55%; and (3) the PV self-sufficiency rate is no less than 60%. Based on relevant design standards and building energy simulation tools, hourly energy loads and PV generation profiles of the building are simulated over a full year, which are then used to determine the optimal PV installed capacity and ESS capacity.

The second step focuses on the development of an ESS operation and scheduling strategy for zero-carbon buildings. Building on the design outcomes, a scheduling approach integrating TOU pricing and PV generation forecasting is formulated. By predicting the hourly building load and PV output for the next day, the system prioritizes on-site PV consumption and calculates the expected surplus PV power available for storage. Through multi-step logical decision-making, the strategy determines whether grid charging is required during deep off-peak/off-peak periods and schedules discharging during peak/top peak periods, thus establishing a comprehensive control logic. This optimized strategy is benchmarked against the conventional real-time scheduling mode.

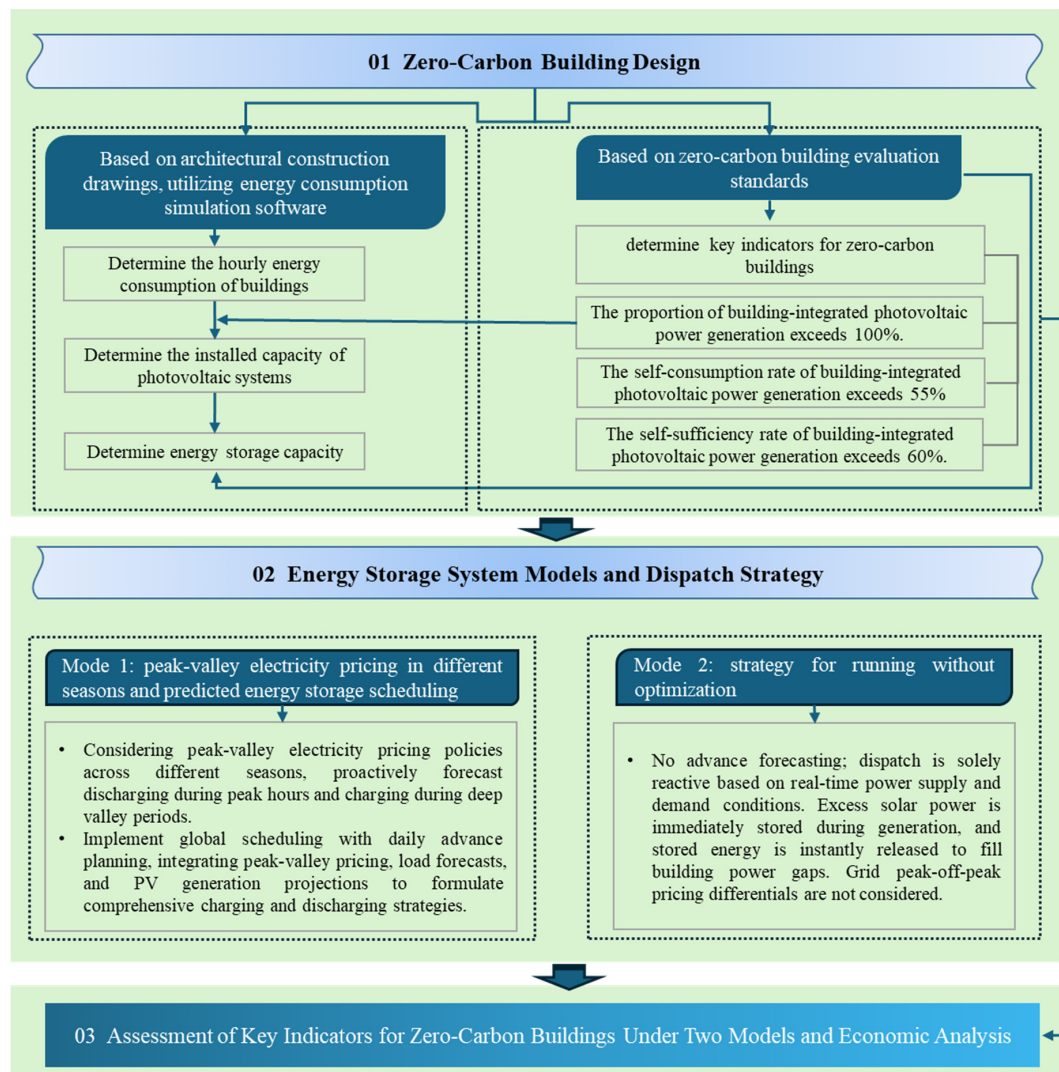


Figure 1. Technical roadmap of the study.

The third step conducts a comparative analysis under Shandong Province’s newly implemented seasonal TOU pricing policy (covering spring, summer, autumn, and winter). The evaluation includes both technical indicators (PV generation ratio, self-consumption rate, and self-sufficiency rate) and economic performance (cost savings achieved by the optimized scheduling strategy). This dual-assessment approach verifies whether the proposed strategy can simultaneously meet zero-carbon objectives and enhance economic feasibility.

2.2. Core Performance Indicators

In accordance with the national standards [25], three core indicators are adopted to evaluate the performance of zero-carbon buildings, with their calculation formulas as follows:

PV generation ratio (η_1): the ratio of the annual PV generation to the annual building electricity consumption, calculated as:

$$\eta_1 = \frac{E_{pv,year}}{E_{load,year}} \times 100\% \quad (1)$$

where $E_{pv,year}$ is the annual PV generation (kWh), and $E_{load,year}$ is the annual building electricity consumption (kWh).

PV self-consumption ratio (η_2): the ratio of the on-site PV power directly consumed by the building to the annual PV generation, calculated as:

$$\eta_2 = \frac{E_{pv,use}}{E_{pv,year}} \times 100\% \quad (2)$$

where $E_{pv,use}$ is the annual on-site PV consumption (kWh).

PV self-sufficiency ratio (η_3): the ratio of the on-site PV power consumed by the building to the annual building electricity consumption, calculated as:

$$\eta_3 = \frac{E_{pv,use}}{E_{load,year}} \times 100\% \quad (3)$$

2.3. Scheduling Strategies for Ess in Zero-Carbon Buildings

2.3.1. Seasonal Tou Periods and Electricity Prices

To promote the stable operation of the power grid, Shandong Province has taken the lead in implementing a five-tier seasonal TOU electricity pricing policy [26], which encourages energy-consuming entities to optimize their electricity consumption behavior by leveraging TOU price differentials. Table 1 presents the latest time period division and corresponding electricity prices of the tiered seasonal TOU pricing policy in Shandong Province. In accordance with national regulations, the PV grid-connected electricity price is implemented based on the local benchmark price of coal-fired power generation, with the annual PV grid-connected electricity price in Shandong Province set at 0.3949 CNY/kWh [27].

Table 1. Time period distribution of seasonal TOU electricity prices in Shandong province.

Time Period	Spring (Mar–May) Type	Price	Summer (Jun–Aug) Type	Price	Autumn (Sep–Nov) Type	Price	Winter (Dec–Feb) Type	Price
00:00–01:00	Shoulder	0.69	Off-peak	0.33	Shoulder	0.69	Shoulder	0.69
01:00–02:00	Shoulder	0.69	Off-peak	0.33	Shoulder	0.69	Shoulder	0.69
02:00–03:00	Shoulder	0.69	Off-peak	0.33	Shoulder	0.69	Shoulder	0.69
03:00–04:00	Shoulder	0.69	Off-peak	0.33	Shoulder	0.69	Shoulder	0.69
04:00–05:00	Shoulder	0.69	Off-peak	0.33	Shoulder	0.69	Shoulder	0.69
05:00–06:00	Shoulder	0.69	Off-peak	0.33	Shoulder	0.69	Shoulder	0.69
06:00–07:00	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69
07:00–08:00	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69
08:00–09:00	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69
09:00–10:00	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69
10:00–11:00	Off-peak	0.33	Shoulder	0.69	Off-peak	0.33	Off-peak	0.33
11:00–12:00	Deep off-peak	0.23	Shoulder	0.69	Deep off-peak	0.23	Deep off-peak	0.23
12:00–13:00	Deep off-peak	0.23	Shoulder	0.69	Deep off-peak	0.23	Deep off-peak	0.23
13:00–14:00	Deep off-peak	0.23	Shoulder	0.69	Deep off-peak	0.23	Deep off-peak	0.23
14:00–15:00	Off-peak	0.33	Shoulder	0.69	Off-peak	0.33	Off-peak	0.33
15:00–16:00	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69
16:00–17:00	Shoulder	0.69	Peak	1.04	Peak	1.04	Top peak	1.19
17:00–18:00	Top peak	1.19	Top peak	1.19	Top peak	1.19	Top peak	1.19
18:00–19:00	Top peak	1.19	Top peak	1.19	Top peak	1.19	Top peak	1.19
19:00–20:00	Top peak	1.19	Top peak	1.19	Peak	1.04	Peak	1.04
20:00–21:00	Peak	1.04	Top peak	1.19	Peak	1.04	Peak	1.04
21:00–22:00	Peak	1.04	Top peak	1.19	Shoulder	0.69	Shoulder	0.69
22:00–23:00	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69
23:00–24:00	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69	Shoulder	0.69

2.3.2. Mode 1: Real-Time Passive Scheduling

Mode 1 operates without day-ahead planning and only responds to real-time power supply–demand imbalances. Surplus PV power is stored immediately, and any power shortfall is compensated by ESS discharging or grid electricity purchase. This mode does

not take TOU price differentials into consideration, and its operational logic is shown in Figure 2.

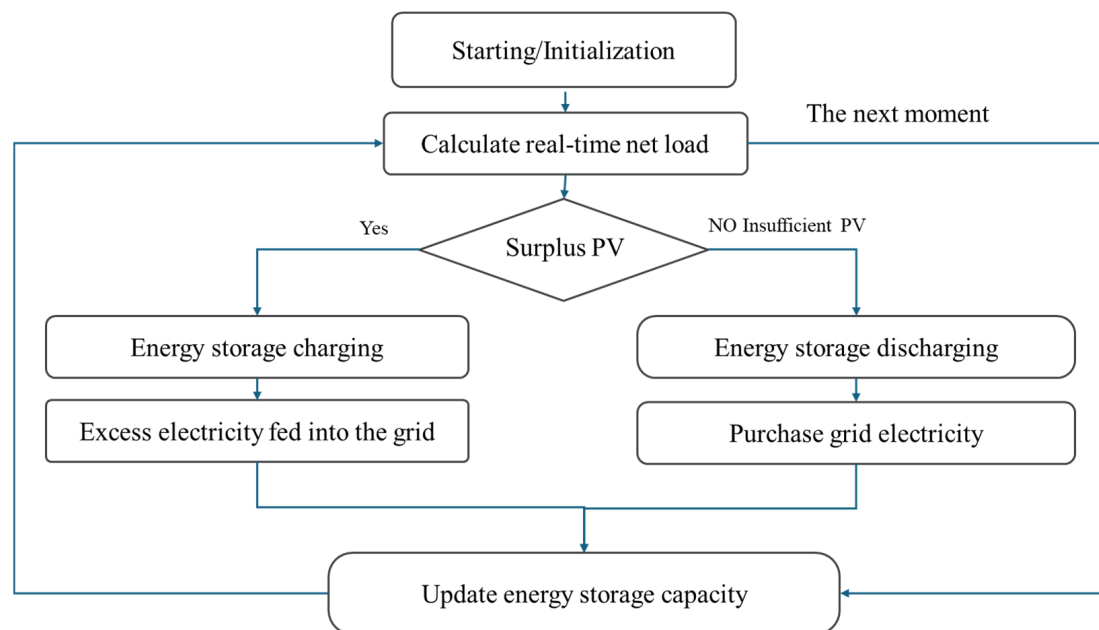


Figure 2. Model 1: real-time passive scheduling based on instantaneous supply–demand balance.

(1) Surplus PV scenario

Surplus PV power is prioritized for storage in the ESS, with the charging power not exceeding the remaining available capacity of the battery. The excess power beyond the battery capacity is fed into the grid, generating only power sales revenue with no electricity purchase expenditure.

$$P_{charge}(t) = \min(|P_{net}(t)|, E_{cap} - E_{bat}(t - 1)) \quad (4)$$

$$P_{sell}(t) = |P_{net}(t)| - P_{charge}(t) \quad (5)$$

where $P_{charge}(t)$ is the charging power of the ESS at time t (kW); $P_{net}(t)$ is the net load at time t (kW); E_{cap} is the rated capacity of the ESS (kWh); $E_{bat}(t)$ is the remaining capacity of the ESS at time t (kWh); and $P_{sell}(t)$ is the electricity fed into the grid at time t (kW).

(2) Insufficient PV scenario

The stored power in the ESS is prioritized to compensate for the power shortfall, with the discharging power not exceeding the current remaining capacity of the battery. The unmet shortfall is supplemented by grid electricity purchase, resulting in only electricity purchase expenditure.

$$P_{discharge}(t) = \min(P_{net}(t), E_{bat}(t - 1)) \quad (6)$$

$$P_{buy}(t) = P_{net}(t) - P_{discharge}(t) \quad (7)$$

where $P_{discharge}(t)$ is the discharging power of the ESS at time t (kW), $P_{buy}(t)$ is the grid electricity purchase power at time t (kW).

(3) Real-time update of energy storage power

The remaining capacity of the ESS is updated on an hourly basis according to the actual charging and discharging power, with the calculation formula as:

$$E_{bat}(t) = E_{bat}(t-1) + P_{charge}(t) - P_{discharge}(t) \quad (8)$$

2.3.3. Mode 2: Tou-Aware Predictive Scheduling

Taking the maximization of profits from TOU price differentials as the core objective, this study constructs an ESS rule-based scheduling control logic that combines next-day PV generation forecasting and building load forecasting. This mode adopts day-ahead planning and scheduling on a natural day (d) basis, with the core goal of reducing operational costs by utilizing grid TOU price differentials: the ESS is fully charged during low-price periods and the stored power is reserved for discharging during high-price (especially top peak) periods to realize arbitrage through price differentials, making it an active scheduling strategy. Its operational logic is shown in Figure 3.

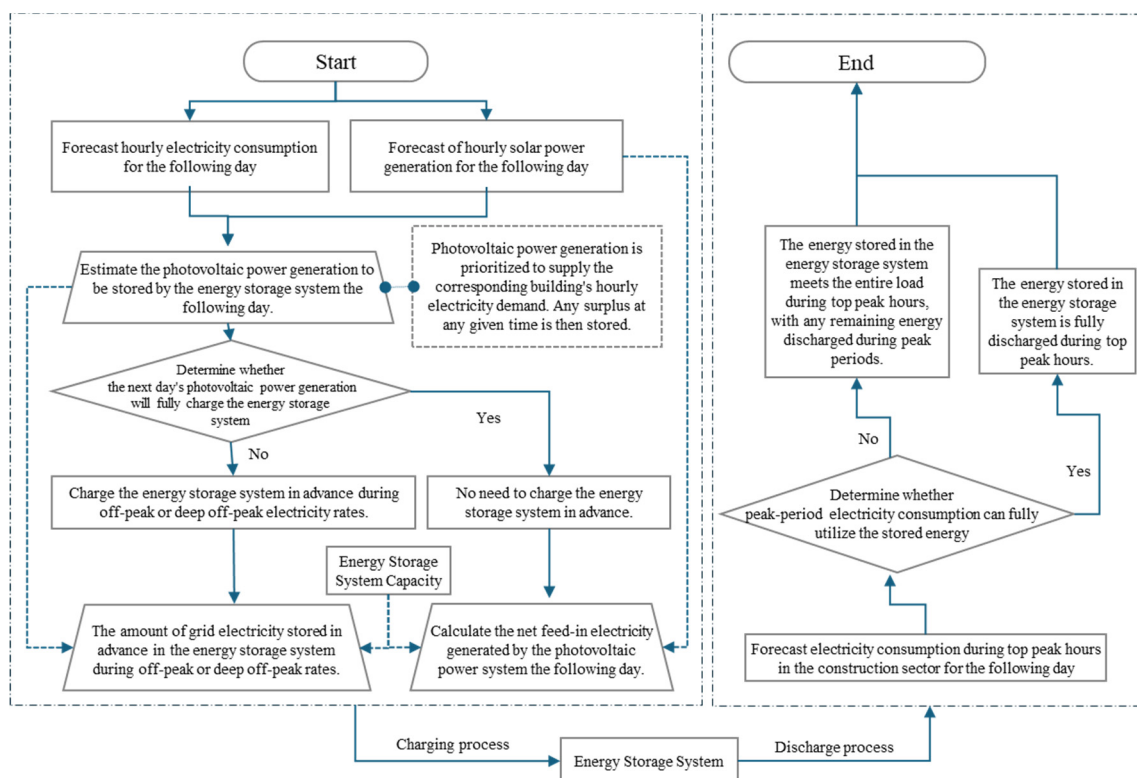


Figure 3. Mode 2: Predictive scheduling incorporating TOU pricing and generation forecasting.

(1) Day-ahead planning

At 00:00 every day, the system formulates the charging plan and discharge limit based on the predicted PV generation and building load data for the day. The specific steps and calculation formulas are as follows:

Prediction of daily photovoltaic power generation: Based on the standards [28], the calculation formula for daily photovoltaic power generation is shown in Equation (9):

$$E_{P,pv}^{(d)} = H_A \cdot \frac{P_{AZ}}{E_s} \cdot K \quad (9)$$

where $E_{P,pv}^{(d)}$ is daily photovoltaic power generation, H_A is the total horizontal solar irradiance of the day, P_{AZ} is the installed capacity of photovoltaic modules, E_s is the irradiance under standard test conditions, and K is the comprehensive efficiency correction coefficient.

This coefficient integrates multiple correction factors, including: photovoltaic module type correction coefficient, inclination and azimuth correction coefficients of the photovoltaic array, availability factor of the photovoltaic power generation system, light utilization efficiency, inverter efficiency, deviation coefficient of photovoltaic module output power from peak value, string matching loss, photovoltaic module attenuation coefficient, collection line power loss, step-up transformer power loss, surface contamination correction coefficient of photovoltaic modules, conversion efficiency correction coefficient of photovoltaic modules, and auxiliary power consumption rate of the power station, etc.

Prediction of total surplus PV power: The total surplus PV power, where PV generation exceeds building load in all periods of the day, is calculated as:

$$E_{surplus,pv}^{(d)} = \sum_{t \in d} \max(0, P_{pv}(t) - P_{load}(t)) \quad (10)$$

where $E_{surplus,pv}^{(d)}$ is the surplus self-generated PV power on the d-th day (kWh), $P_{pv}(t)$ is the PV generation in hour t (kWh), $P_{load}(t)$ is the building electricity consumption in hour t (kWh).

Calculation of grid-supplemented charging power: To achieve full charging and discharging of the ESS on the day, the power shortfall after deducting the surplus PV power is supplemented by grid electricity purchase, calculated as:

$$E_{req,charge}^{(d)} = \max(0, E_{cap} - E_{bat}(0) - E_{surplus,pv}^{(d)}) \quad (11)$$

where $E_{req,charge}^{(d)}$ is the grid-supplemented charging power on the d-th day (kWh); $E_{bat}(0)$ is the remaining power of the energy storage system at the initial moment of the d-th day (kWh).

Formulation of off-peak charging strategy: The deep off-peak periods of the day are prioritized as the planned charging periods; if there are no deep off-peak periods in the month, off-peak periods are selected instead. The required grid-supplemented charging power is evenly allocated to each planned charging hour, calculated as:

$$P_{pre,charge}(t) = \frac{E_{req,charge}^{(d)}}{N_{charge}} \quad (12)$$

where $P_{pre,charge}(t)$ is the planned charging power in the t-th hour during the planned charging period on the d-th day (kW); N_{charge} is the number of planned charging hours on the d-th day.

Predict the reserve limit of electricity shortage during top peak periods: To ensure the priority of discharging during top peak periods, the total power shortfall during all top peak periods of the day is pre-calculated as the basis for reserving ESS capacity, calculated as:

$$E_{req,top\ peak\ periods}^{(d)} = \sum_{t \in \text{top peak periods}} \max(0, P_{load}(t) - P_{pv}(t)) \quad (13)$$

where $E_{req,top\ peak\ periods}^{(d)}$ is the total electricity shortage during all the top peak periods of the day.

(2) Hourly real-time scheduling execution

In accordance with the day-ahead plan, real-time power scheduling is implemented for each hour t, which consists of two core links: grid power supplement and load satisfaction. The specific rules and calculation formulas are as follows:

Grid power supplement link: If the current time t falls within the planned deep off-peak/off-peak charging period, grid electricity is purchased as planned to charge the ESS. The formulas for electricity purchase power and the update of ESS remaining capacity are:

$$P_{buy}(t) = P_{pre,charge}(t) \quad (14)$$

$$E_{bat}(t) = E_{bat}(t-1) + P_{buy}(t) \times 1 \quad (15)$$

Load satisfaction link: Based on the real-time net load status and combined with the division of TOU periods, a differentiated scheduling strategy is implemented. The rules and formulas for different scenarios are as follows:

Surplus power is prioritized to be charged into the energy storage system, and the part exceeding the battery capacity is sold to the power grid, with the formulas:

$$P_{charge}(t) = \min(|P_{net}(t)|, E_{cap} - E_{bat}(t-1)) \quad (16)$$

$$P_{sell}(t) = |P_{net}(t)| - P_{charge}(t) \quad (17)$$

$$E_{bat}(t) = E_{bat}(t-1) + P_{charge}(t) \quad (18)$$

Combined with the TOU attribute of the current period, discharging is carried out in a differentiated manner according to priority, and the electricity shortage that cannot be met after energy storage discharging is supplemented by purchasing power from the power grid. The discharging rules and formulas for each period are as follows:

Top peak periods: Unrestricted discharging to maximize the offset of high electricity price purchase costs, with the formulas:

$$P_{discharge}(t) = \min(P_{net}(t), E_{bat}(t-1)) \quad (19)$$

$$E_{req,jianfeng}^{(d)}(t) = E_{req,jianfeng}^{(d)}(t-1) - P_{discharge}(t) \quad (20)$$

Peak periods: Restricted discharging, with sufficient power reserved to cope with the electricity shortage during the uncured top peak periods of the day, with the formulas:

$$P_{allow} = \max(0, E_{bat}(t-1) - E_{req,jianfeng}^{(d)}(t-1)) \quad (21)$$

$$P_{discharge}(t) = \min(P_{net}(t), E_{bat}(t-1), P_{allow}) \quad (22)$$

where P_{allow} is the maximum allowable discharging power of the energy storage system in the t -th hour (kW).

Shoulder, off-peak and deep off-peak periods: Discharging is prohibited, $P_{discharge}(t) = 0$, and the electricity shortage in this period is fully supplemented by purchasing power from the power grid.

Grid supplementary electricity purchase: In any of the above scenarios, the unmet power shortfall after ESS discharging is supplemented by grid electricity purchase:

$$P_{extra,buy}(t) = P_{net}(t) - P_{discharge}(t) \quad (23)$$

where $P_{extra,buy}(t)$ is the grid supplementary purchased electricity quantity in the t -th period.

(3) Update of ESS remaining capacity

$$E_{bat}(t) = E_{bat}(t-1) - P_{discharge}(t) \quad (24)$$

2.4. Economic Analysis

2.4.1. Operation Cost

The main research scope and boundary of this paper focus on a comparative analysis of operational costs under two distinct operation modes. Although factors such as the capital investment cost, service life degradation, charge–discharge cycle loss, and operation and maintenance cost of the energy storage system may affect the actual economic evaluation, these parameters remain identical in both operation modes and exert a negligible impact on the operational cost difference. Accordingly, they are not included in the analytical scope.

The operational costs under the two modes include the hourly expenditure of planned charging electricity purchase and load shortfall supplementary electricity purchase, as well as the revenue from grid-connected surplus PV power. The formula for calculating the net electricity cost in a certain period is:

$$Cost(t) = [P_{buy}(t) + P_{extra,buy}(t)] \times Price_{in}(t) - P_{sell}(t) \times Price_{out}(t) \quad (25)$$

where $Cost(t)$ is the net electricity cost at hour t ; a positive value indicates an electricity expenditure in the hour, while a negative value indicates an electricity revenue in the hour; $Price_{in}(t)$ is the grid electricity purchase price at hour t ; $Price_{out}(t)$ is the PV grid-connected price.

2.4.2. Investment Payback Period and Net Present Value (NPV) Analysis

The static investment payback period refers to the time required for the annual net cash inflow (annual operating cost savings) to recover the total initial investment of the PV-ESS system, without considering the time value of money. Net present value is the sum of the present value of the annual net cash flow of the PV-ESS system throughout the lifecycle, which reflects the total profit of the project after considering the time value of money.

$$PBP = \frac{I_{total}}{C_{annual}} \quad (26)$$

$$PV = I_{total} + \sum_{t=1}^n \frac{C_{annual}}{(1+i)^t} \quad (27)$$

where PBP is the static investment payback period, I_{total} is the total initial investment of PV power generation system and energy storage system, C_{annual} is the annual net operating cost savings. NPV is the net present value of the project, i is the benchmark discount rate, and n is the service life of the PV-ESS system.

3. Case Application

3.1. Project Overview

This study selects the Jinan Zero-Carbon Operation Center Project in Jinan City, Shandong Province, as the case study object. The project has a total construction area of 72,431 m², including an above-ground area of 48,053 m² and an underground area of 24,378 m². To enhance the energy-saving and carbon reduction effects, the project is designed and certified in accordance with China's Assessment standard for carbon-neutral building, Evaluation Standard for Green Buildings, the US LEED Building Standard and the US WELL Building Standard and has obtained the corresponding certifications.

In terms of carbon emission reduction, a polycrystalline silicon PV generation system is installed on the project's roof, and a cadmium telluride PV generation curtain wall is installed on the building facade. To improve the carbon sink capacity of vegetation, a large number of green plants are planted both inside and outside the building, as shown in Figure 4.

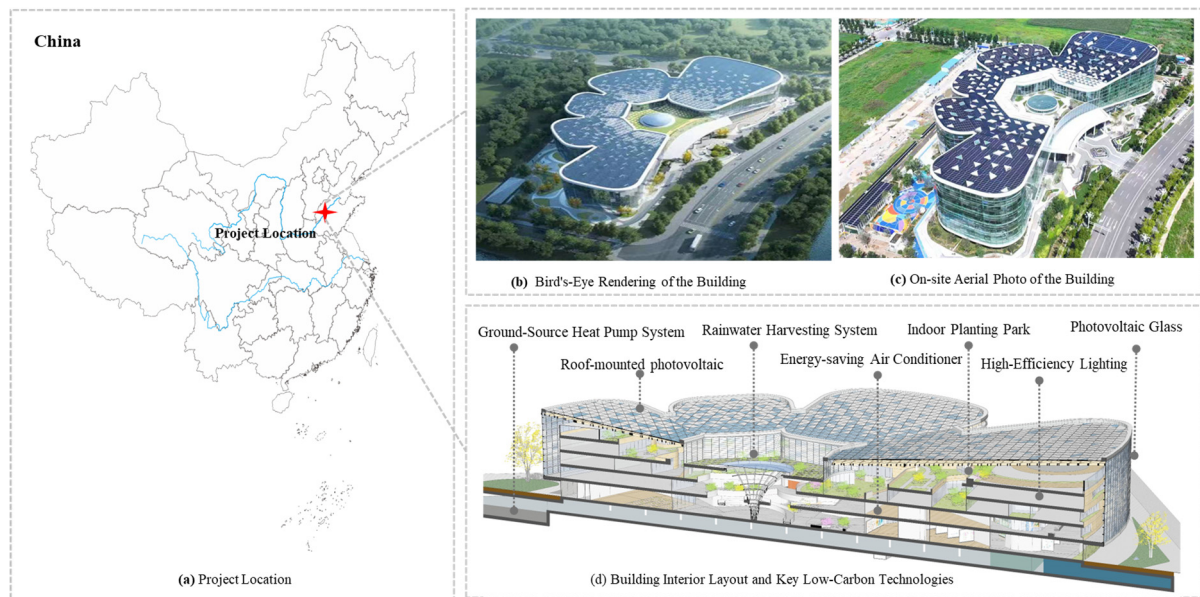


Figure 4. Project location, renderings, site photos, and key low-carbon technologies.

3.2. Design of Zero-Carbon Buildings and Analysis of Key Indicators

3.2.1. Design of Pv Installed Capacity and Ess Capacity

To meet the requirements of the core evaluation indicators for zero-carbon buildings, combined with the project's building layout, solar radiation conditions, and the measured hourly energy load and PV generation data, the optimal capacity configuration of the PV generation system and ESS for the project is determined: the total installed capacity of the PV generation system is 5364.12 kW, and the capacity of the ESS is 4000 kWh.

The PV generation system consists of three subsystems, with their installed capacities and layout locations as follows: (1) a building facade curtain wall PV generation system with an installed capacity of 40.27 kW, which is integrated with the building facade glass curtain wall, realizing the integration of building skin and renewable energy generation; (2) a building roof PV generation system with an installed capacity of 819.85 kW, which is centrally arranged on the idle roof space and serves as the core of the building's distributed PV generation; (3) a centralized PV generation system on the west side of the project site with an installed capacity of 4504 kW, which is the main PV generation system of the project and ensures the sufficiency of total PV generation.

3.2.2. Calculation of Hourly Building Electricity Consumption and Hourly Pv Generation

The building energy consumption of the project covers heating, cooling, lighting, elevator operation, and other office electrical equipment consumption, which is the core scope for measuring the building energy load. Based on the project's building thermal parameters, equipment selection parameters and actual operating conditions, combined with the building energy consumption simulation software BESI 2024 and the theoretical calculation formulas for building energy consumption, the hourly electricity consumption of the building over the full year (8760 h) is measured, and the results are shown in Figure 5.

From the perspective of seasonal distribution, the building energy load exhibits significant seasonal differences: the load is the highest in summer, followed by winter, and relatively stable and low in spring and autumn. The core reason is that Jinan has a warm temperate semi-humid monsoon climate with a long and hot summer. The project adopts a large area of glass curtain walls on the roof and facade, resulting in a high building heat transfer coefficient, which leads to a substantial increase in air conditioning cooling load—the main component of summer energy consumption. In winter, the low temperature

leads to an increase in the proportion of building heating load, making the energy load the second highest. Spring and autumn are transition seasons without central heating and cooling systems, and the building energy consumption is mainly the basic load of office equipment, lighting, and elevators, resulting in a stable and low energy consumption level.

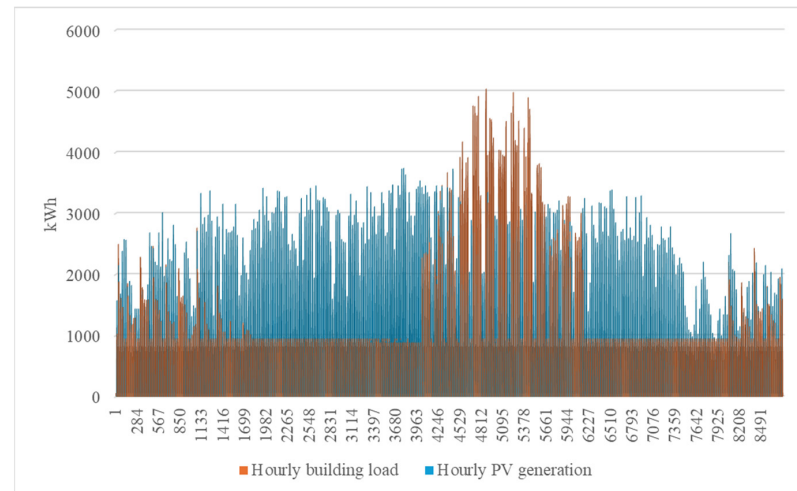


Figure 5. Hourly building load and hourly PV generation over the full year (8760 h).

Based on the total installed capacity of the PV generation system and the layout parameters of each subsystem, combined with the theoretical calculation formulas for PV generation, the hourly PV generation of the project over the full year (8760 h) is measured. Statistical results show that the cumulative annual PV generation of the project reaches 6,251,598.15 kWh, providing sufficient renewable energy support for the building to achieve zero-carbon operation.

3.2.3. Analysis of Key Indicators of Zero-Carbon Buildings

(1) Compliance analysis of key indicators

Based on the ESS charging and discharging strategy proposed in Section 2.3.3, the annual hourly electricity consumption and PV generation data (Section 3.2.2) are substituted into the core indicator calculation formulas (Section 2.2) to measure the core indicators of the project. The results show that all three core indicators meet the requirements of the Assessment standard for carbon-neutral building, with the specific values shown in Table 2.

Table 2. Compliance judgment of key indicators of zero-carbon buildings.

Indicator Name	Operation Mode	Project Indicator Value	Zero-Carbon Building Requirement	Compliance
Annual PV Generation ratio	Mode 1	101.38%	$\geq 100\%$	Yes
	Mode 2	101.38%		Yes
PV Generation self-sufficiency rate	Mode 1	72.74%	$\geq 60\%$	Yes
	Mode 2	72.21%		Yes
PV Generation self-consumption rate	Mode 1	73.74%	$\geq 55\%$	Yes
	Mode 2	73.21%		Yes

(2) Analysis of temporal variation characteristics of key indicators

Based on the hourly building load and PV generation data, the daily and monthly variations in the core indicators are further calculated to conduct an in-depth analysis of

their seasonal distribution characteristics, providing a basis for the seasonal scheduling optimization of the ESS.

PV generation ratio: The daily and monthly variation trends of the PV generation ratio under Mode 1 and Mode 2 exhibit significant reverse seasonal characteristics (Figures 6 and 7). The ratio is relatively low in summer and winter, with some months below 100% and a minimum value of 60.49%; it is significantly higher in spring and autumn, with most months above 100% and a maximum value of 184.02%. The core reason is that the high building energy load in summer and winter makes it difficult for PV generation to fully cover the building's electricity demand, leading to a low generation ratio; while in spring and autumn, the low building energy load and sufficient solar radiation result in PV generation far exceeding the building's electricity consumption, leading to a high generation ratio.

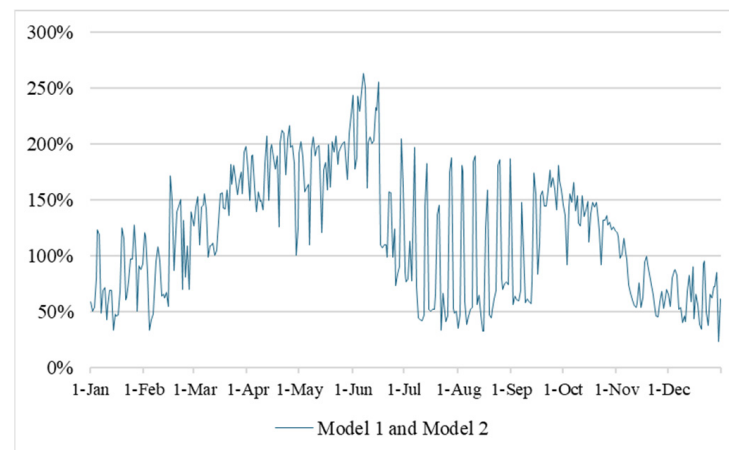


Figure 6. PV generation ratio.

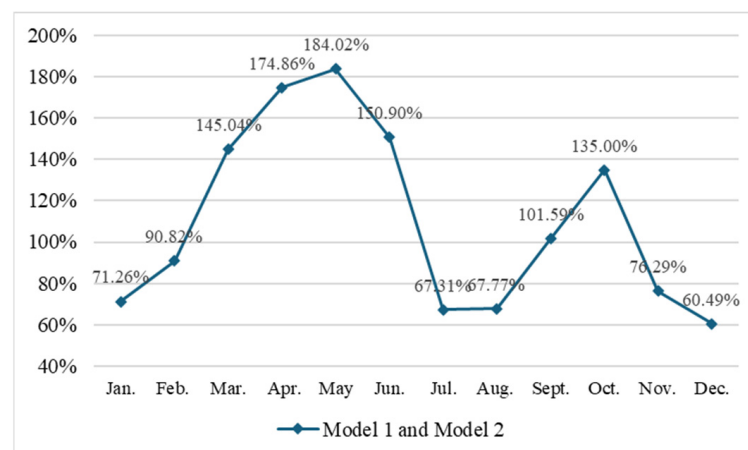


Figure 7. Monthly PV generation ratio.

PV self-consumption ratio: The daily and monthly variations in the PV self-consumption ratio show opposite seasonal characteristics to the PV generation ratio (Figures 8 and 9). The self-consumption ratio is relatively high in summer and winter, with most months above 90% and a maximum value of 98.38%; it is relatively low in spring and autumn, with most months below 70%. The reason is that the large building energy load in summer and winter enables the building to consume most of the PV generation in real time with little surplus, resulting in a high self-consumption ratio; while the small building energy load in spring and autumn leads to PV generation far exceeding the real-time electricity demand, with a large amount of surplus PV power fed into the grid, resulting in

a low real-time self-consumption ratio. In addition, the PV self-consumption ratio under Mode 1 is slightly higher than that under Mode 2 in some months (e.g., 53.46% for Mode 1 and 51.81% for Mode 2 in May).

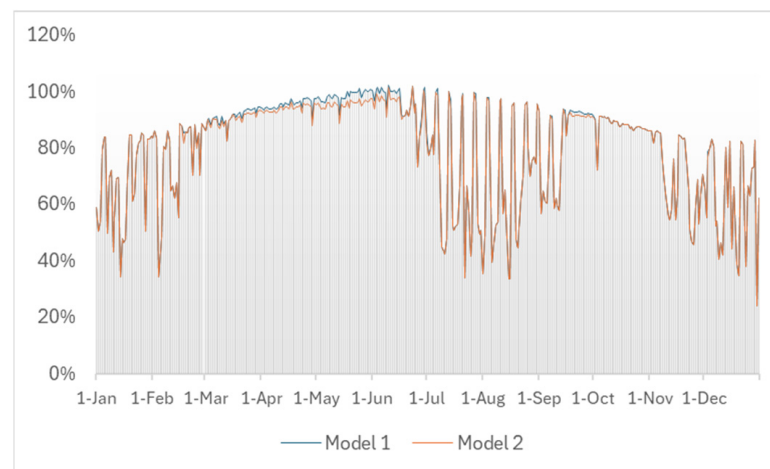


Figure 8. Daily PV self-consumption ratio.

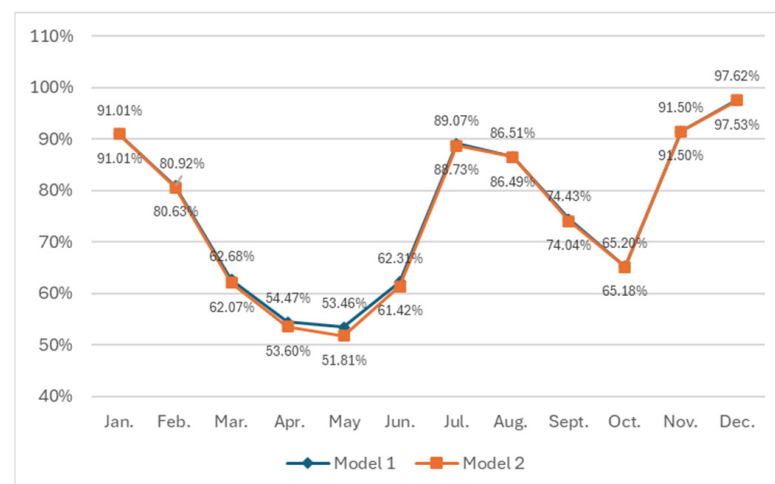


Figure 9. Monthly PV self-consumption ratio.

PV self-sufficiency ratio: The daily and monthly variations in the PV self-sufficiency ratio are opposite to the PV self-consumption ratio and similar to the PV generation ratio (Figures 10 and 11). The self-sufficiency ratio is relatively low in winter and summer, with most months below 70% and a minimum value of 58.63%; it is relatively high in spring and autumn, with most months above 70% and a maximum value of 95.34%. The core reason is that the large electricity demand in summer and winter results in a low proportion of PV generation in the total building electricity consumption despite the relatively high PV generation, leading to a low self-sufficiency ratio; while in spring and autumn, the small electricity demand enables PV generation to fully meet the building's electricity demand with a high proportion in the total consumption, thus resulting in a high self-sufficiency ratio. Similarly, the PV self-sufficiency ratio under Mode 1 is slightly higher than that under Mode 2 in some months (e.g., 95.38% for Mode 1 and 95.34% for Mode 2 in May).

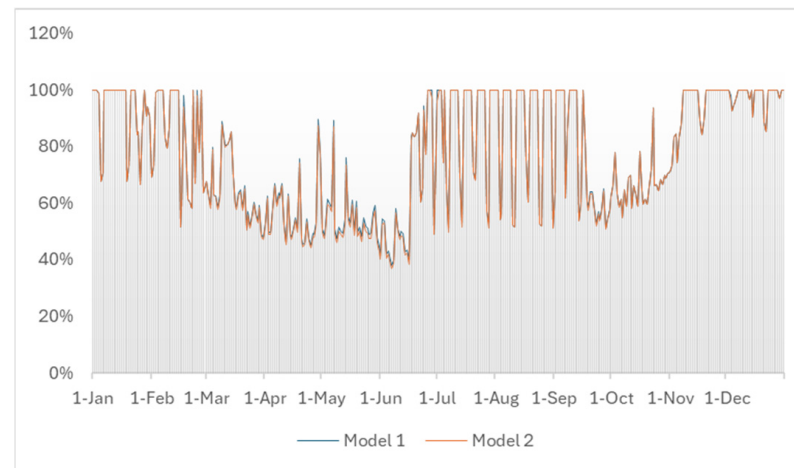


Figure 10. Daily PV self-sufficiency ratio.

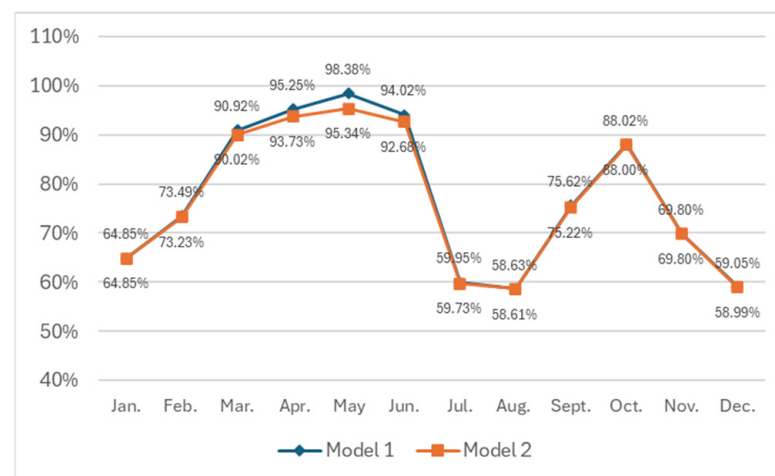


Figure 11. Monthly PV self-sufficiency ratio.

4. Discussion

Based on the above case measurement and analysis, the zero-carbon building design scheme and ESS charging–discharging scheduling strategy adopted in this project can effectively meet the requirements of the core indicators specified in the Assessment standard for carbon-neutral building and achieve the zero-carbon operation goal of the building. The core indicator values under Mode 1 are slightly higher than those under Mode 2, because Mode 2 adopts refined scheduling of “discharging during top peak/peak periods and charging during deep off-peak periods”, which reduces the real-time PV consumption by the ESS; while Mode 1 adopts a passive real-time generation-consumption scheduling mode without considering grid power supplement, which effectively improves the PV consumption capacity of the ESS.

On this basis, this section conducts an in-depth analysis from the perspective of an operational economy and compares the operational cost differences between the two modes. The core of economic analysis in the building operation stage is the measurement of net operational cost, where net operational cost = total grid electricity purchase cost–total revenue from grid-connected surplus PV power. A lower net operational cost indicates better economic performance of the building. Under the same PV installed capacity, ESS capacity and building energy consumption data, the daily and monthly revenue from grid-connected surplus PV power, total grid electricity purchase cost and net operational cost of the building under the two modes are measured, respectively, with the results as follows.

4.1. Revenue from Grid-Connected and Grid Electricity Purchase Cost

Figures 12 and 13 show the daily and monthly revenue from grid-connected surplus PV power, respectively. The temporal variations indicate that the difference in grid-connected revenue between Mode 1 and Mode 2 is small, with the cumulative annual grid-connected revenue reaching 673,010 CNY and 685,988 CNY. The grid-connected revenue for Mode 2 is 12,978 CNY higher than that of Mode 1. Revenue from grid connection was highest in June, exceeding 120,000 CNY, while it was lowest in December, falling short of 30,000 CNY.

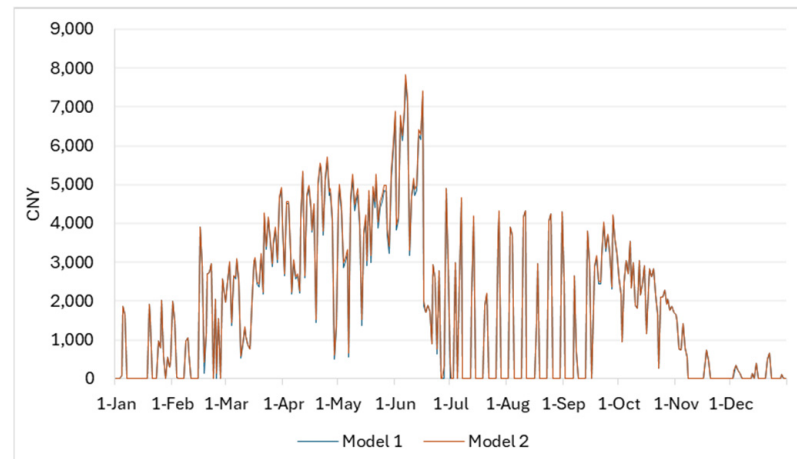


Figure 12. Daily grid-connected surplus PV revenue.

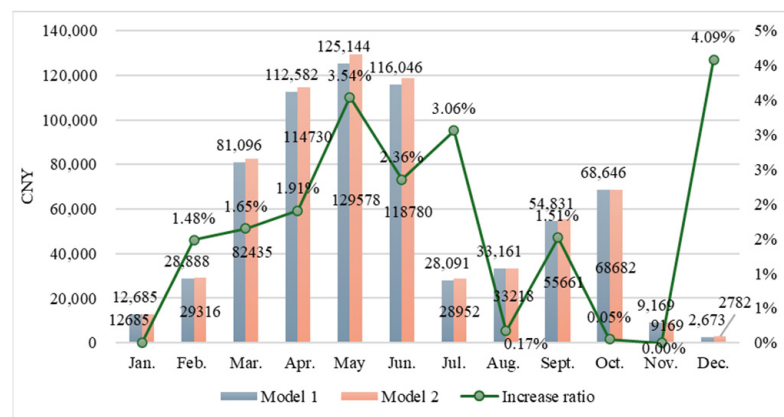


Figure 13. Monthly grid-connected surplus PV revenue.

Figures 14 and 15 show the daily and monthly grid electricity purchase costs, respectively. The highest daily electricity purchase costs ranged from 7000 to 8000 CNY, with the peak occurring in July. The temporal variations indicate that the grid electricity purchase cost under Mode 1 is consistently higher than that under Mode 2, except for in April and May; the lower purchase cost under Mode 1 in these two months is attributed to its better PV consumption capacity, which reduces the grid electricity purchase volume. Modes 1 and 2 had the highest grid electricity purchase costs in July and August, at 348,162 CNY and 292,390 CNY, respectively. The annual cumulative grid electricity purchase cost for Mode 1 reached 1,454,201 CNY, while that for Mode 2 was 1,099,830 CNY.

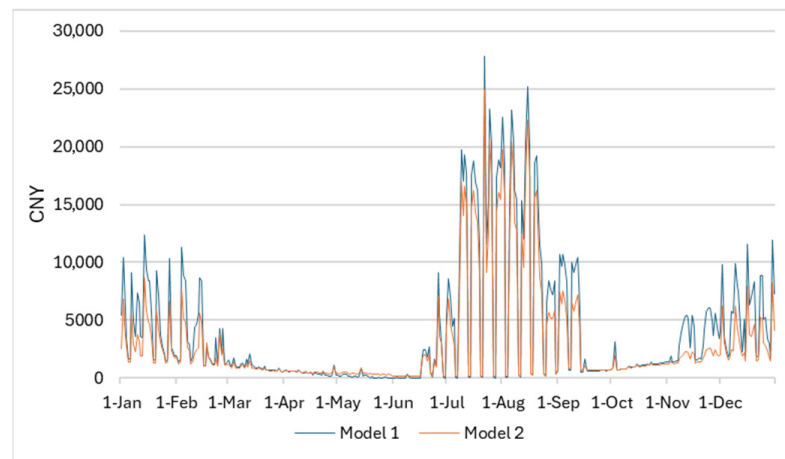


Figure 14. Daily grid electricity purchase costs.

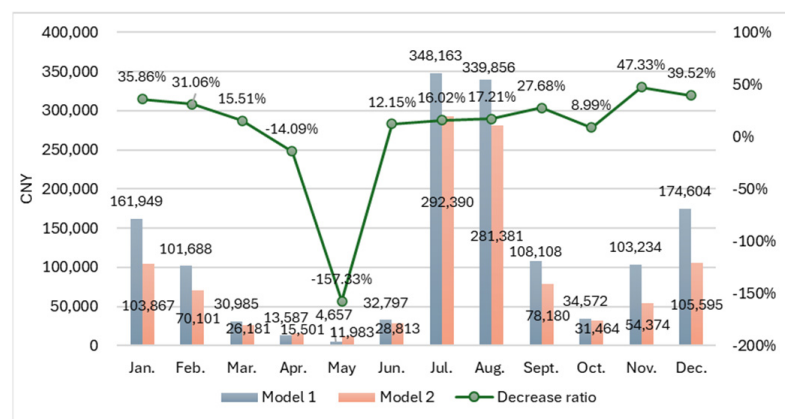


Figure 15. Monthly grid electricity purchase costs.

4.2. Net Operating Cost

Figures 16 and 17 show the daily and monthly net operating costs, respectively. Their variation over time exhibits a consistent seasonal pattern: net operating costs are positive in seven months (January, February, July, August, September, November, and December), indicating that in these months, the cost of purchasing electricity exceeded the revenue from surplus grid-connected PV power, and the building incurred certain electricity costs. The cumulative electricity purchase costs for Model 1 and Model 2 were 1,168,104 CNY and 814,104 CNY. In the remaining five months, net operating costs are negative, indicating that revenue from surplus grid-connected PV power exceeds the cost of purchased electricity, and the building thus generates electricity revenue. The cumulative grid-connected electricity revenue for Model 1 and Model 2 is −386,914 CNY and −400,262 CNY, respectively. After deducting grid-connected revenue, the annual cumulative cost of purchased electricity for Model 1 and Model 2 is 781,190 CNY and 413,842 CNY, respectively.

In terms of cumulative annual economic performance, the net operational cost under Mode 1 is 781,190 CNY, while that under Mode 2 is 413,842 CNY. Calculations show that Mode 2 achieves an annual operational cost saving of 367,349 CNY compared with Mode 1, with a cost saving rate of approximately 47.02%. This fully verifies the economic advantages of the optimized ESS scheduling strategy constructed in this study, which takes into account seasonal TOU pricing and PV forecasting. The core reason for this economic advantage is that the optimized scheduling strategy makes full use of the seasonal TOU price differentials in Shandong Province. Through refined scheduling of “purchasing power for charging during deep off-peak/off-peak periods at low prices and discharging

during top peak/peak periods at high prices”, the strategy minimizes the grid electricity purchase of the building during high-price periods and maximizes the profits from TOU price differentials. In contrast, the conventional scheduling strategy fails to fully combine price differentials and PV forecasting, and the timing and capacity of ESS charging and discharging lack optimization, leading to a large volume of grid electricity purchase during high-price periods and a corresponding increase in operational costs.

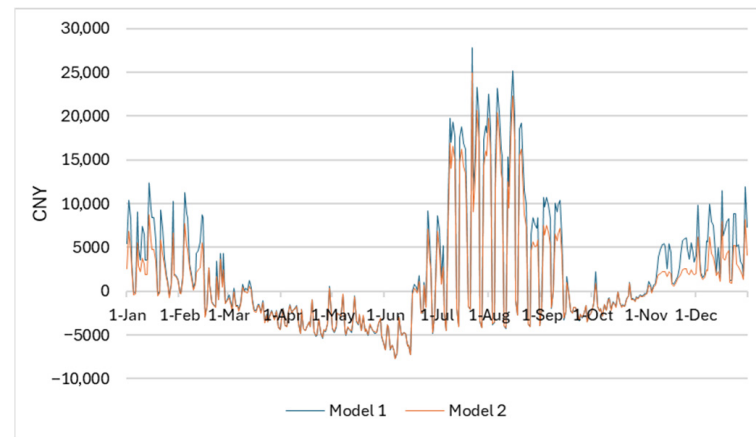


Figure 16. Daily net operation cost.

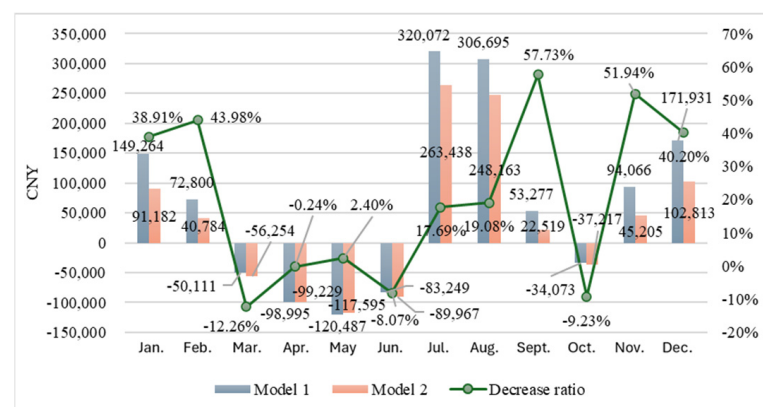


Figure 17. Monthly net operation cost.

4.3. Payback Period and Net Present Value

In the analysis of payback period and net present value (NPV) under different operation modes, the electricity price is assumed to be constant at the current level. Without PV and energy storage systems, the project incurs no equipment operation and maintenance (O&M) costs, and the only operating expense is the electricity purchase cost, calculated at 4,449,766 CNY per year.

Both Mode 1 and Mode 2 share the same initial capital investment. According to the project design documents, the total initial investment for PV and energy storage systems is 25 million CNY. The service life of photovoltaic systems and energy storage systems is set at 20 years, with no account taken of degradation. The benchmark discount rate is set at 8%. The annual equipment O&M cost for PV and energy storage systems is 150,000 CNY [29] for both Mode 1 and Mode 2. The annual electricity purchase costs are 781,190.37 CNY for Mode 1 and 413,841.71 CNY for Mode 2, respectively.

Substituting the above data into Equations (26) and (27) yields the project's payback period and NPV, as shown in Table 3. The payback periods are 7.1 years for Mode 1 and 6.4 years for Mode 2, representing a 0.7-year reduction for Mode 2 compared with Mode 1.

The NPVs are 34,142,566.00 CNY for Mode 1 and 30,535,882.00 CNY for Mode 2, meaning the NPV of Mode 1 is 3,606,684.00 CNY higher than that of Mode 2.

Table 3. Payback period and net present value of Model 1 and Model 2.

Name	Model 1	Model 2	The Difference Between Model 1 and Model 2
Payback Period	7.11 years	6.43 years	0.7 years
Net Present Value	34,142,566 CNY	30,535,882 CNY	3,606,684 CNY

5. Conclusions

Taking the Jinan Zero-Carbon Operation Center Project as a case study, this paper constructs a technical system for the design of zero-carbon buildings and the rule-based scheduling of ESS, adapting to Shandong Province’s seasonal TOU electricity pricing policy. Through simulation measurement and comparative analysis, the feasibility and economic efficiency of the design scheme and scheduling strategy are verified, and the following core conclusions are drawn:

- (1) The optimized PV-ESS configuration (5364.12 kW PV, 4000 kWh ESS) meets the requirements of T/CECS 1555-2024, with an annual PV generation ratio of 101.38%, self-consumption rate of 73.21% and self-sufficiency rate of 72.21%, realizing stable zero-carbon operation.
- (2) Core indicators show distinct seasonal variations: PV generation ratio and self-sufficiency rate are higher in spring and autumn, lower in summer and winter; self-consumption rate presents the opposite trend, which is dominated by seasonal load and solar radiation.
- (3) The TOU-aware predictive scheduling (Mode 2) reduces annual net operation cost by 367,349 CNY (47.02%) compared with conventional real-time scheduling (Mode 1), owing to low-price charging in deep off-peak periods and high-price discharging in top peak periods.
- (4) The integrated design-operation framework balances technical compliance and economic efficiency, providing a replicable solution for zero-carbon public buildings in Shandong and regions with similar climates and tariff policies.

6. Research Prospects

Zero-carbon buildings are the core carrier of carbon neutrality in the construction industry, and the rule-based scheduling of ESS is the key to improving the energy efficiency and economic benefits of zero-carbon buildings. In the future, with the continuous improvement of China’s TOU electricity pricing policy and the iteration and upgrading of renewable energy technologies, refined ESS scheduling strategies combined with artificial intelligence and big data will become the development trend of zero-carbon building operation, which will help the construction industry achieve a higher-quality energy transition and carbon neutrality goals. Although this paper constructs a technical system for zero-carbon building design and ESS scheduling under seasonal TOU electricity pricing and verifies its effectiveness through an actual case study, there are still some limitations, and further research can be carried out from the following aspects:

- (1) Introduce PV and load forecasting error correction and intraday rolling optimization to enhance scheduling robustness under real-world uncertainties.
- (2) Expand the analysis to the whole building lifecycle, covering initial investment, ESS degradation, operation and demolition, for multi-objective techno-economic carbon optimization.

- (3) Conduct comparative studies across climate zones and tariff systems to establish region-adaptive scheduling templates and improve universality.
- (4) Integrate AI and big data to upgrade rule-based scheduling to intelligent dynamic control, coordinating flexible loads and multi-energy systems for higher efficiency and economy.

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