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Energy management strategy for a dormitory building PV-storage microgrid based on time-of-use pricing and state-of-charge constraints

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Abstract. Against the background of China's dual-carbon goals and refined energy management on the building side, university dormitory buildings have become typical scenarios for the coordinated application of rooftop photovoltaics and electrochemical energy storage. This paper takes Dormitory Building No. 9 at the University of Science and Technology Beijing, constructing a grid-connected microgrid with rooftop Photovoltaics (PV), lithium iron phosphate storage, loads, and the grid. Using Beijing's time-of-use industrial/commercial tariff and typical summer/winter days, a 24-hour linear optimal scheduling model minimizes daily operating cost (power purchase cost plus PV curtailment penalty) under constraints like power balance, State-of-Charge (SOC), charge/discharge limits, and grid interaction. The results show that, under the boundary condition of no power export to the grid, the energy storage system reconstructs the grid purchase curve through "off-peak charging, high-price discharging, and midday absorption of surplus PV power." The daily operating costs in the typical summer and winter scenarios decrease by 16.41% and 18.59%, respectively; PV curtailment is reduced to zero in both scenarios; and the PV self-consumption rate increases to 100%. Sensitivity analysis indicates that increasing the storage capacity can further reduce operating cost, but the marginal benefit declines gradually, providing a quantitative reference for sizing energy storage in dormitory buildings.

Keywords: microgrid, time-of-use pricing, dormitory building, photovoltaic energy storage, energy management system, optimal scheduling

1. Introduction

As distributed photovoltaics, energy storage, and related technologies advance, microgrids offer an important approach to improving building energy efficiency and renewable energy integration. University dormitory loads are relatively concentrated, with high evening electricity demand, and therefore represent typical scenarios for building-side microgrid studies. Under Beijing's industrial and commercial electricity tariff and time-of-use pricing mechanism, the deployment of rooftop photovoltaics and energy storage can optimize the power purchase structure and reduce operating costs. Therefore, studying the scheduling of PV-storage

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microgrids in dormitory buildings offers a reference for building-side microgrid scheduling under time-varying pricing.

Research on microgrids has shifted from conceptual and structural design toward control strategies, optimal scheduling, and multi-scenario applications, both in China and abroad. Existing studies mainly focus on two themes: safe and stable system operation and economically efficient scheduling. Hierarchical control theory provides the basic framework for microgrid operation. As the fluctuation of distributed generation increases and electricity pricing mechanisms improve, research emphasis has further shifted toward energy management systems and energy storage optimization. Energy storage plays a prominent role in peak shaving and valley filling, smoothing PV fluctuations, and improving renewable energy integration, though efficiency losses and lifetime degradation should also be accounted for in modeling. For campus dormitory buildings, where load patterns are relatively clear and rooftop PV resources are concentrated, PV-storage microgrid research is particularly suitable. Therefore, this paper constructs an intra-day optimal scheduling model for a dormitory building by incorporating time-of-use pricing, PV output, and storage SOC constraints.

The construction and optimal scheduling of a PV-storage microgrid for Dormitory Building No. 9 of the University of Science and Technology Beijing are investigated. With Beijing's time-of-use pricing mechanism and the State-of-Charge (SOC) constraints of energy storage as the core, an optimization model for typical daily operation is established.

The study focuses on the coordination among PV generation, energy storage charging/discharging, and grid power purchase based on dormitory load characteristics, rooftop PV installation conditions, and storage operation rules. MATLAB is used to solve the intra-day scheduling problem. On this basis, system performance is evaluated in terms of operating cost, power purchase structure, PV curtailment, and PV self-consumption rate, thereby verifying the feasibility and economic benefits of PV-storage microgrid deployment and scheduling in dormitory building scenarios.

2. PV-storage microgrid system and parameter settings for dormitory building No. 9

2.1. Research object and load characteristics

Dormitory Building No. 9 of the University of Science and Technology Beijing serves as the research object. Its annual electricity consumption is approximately 700,000 kWh, and its peak load is approximately 0.4 MW (400 kW). The dormitory load exhibits typical residential electricity-use patterns. Evening lighting, hot water, mobile phone and computer charging, air conditioning or fans, and other uses are the main sources of the evening peak load. From the perspective of daily load distribution, the dormitory load shows a curve characterized by relatively low demand at midday and relatively high demand in the evening. This natural mismatch between dormitory electricity demand and rooftop PV output further highlights the need for energy storage to shift electricity across time periods [1-3].

Two typical daily load scenarios are constructed for optimal scheduling: a summer scenario and a winter scenario. Both load curves are subject to the engineering constraint that the peak load of Dormitory Building No. 9 is about 400 kW, and remain consistent with the magnitude of the annual electricity consumption [4].

2.2. Analysis of rooftop PV construction potential

The rooftop projected area of Dormitory Building No. 9 is set to 1,200 m² as the basis. Considering equipment rooms, maintenance areas, fire passages, and other requirements, the usable rooftop area is reduced to about

70%, resulting in an effective installation area of about 840 m². Based on an installation density of 0.20 kW/m², the estimated PV capacity is about 168 kW. For the convenience of subsequent modeling and equipment selection, the PV installed capacity is rounded to 170 kW [3, 5].

The Haidian District of Beijing has favorable annual sunshine conditions. According to public data from China Weather Network, the annual sunshine duration is about 2,662 hours, suitable for rooftop distributed PV applications. The distributed PV project implemented on the library building of the University of Science and Technology Beijing also provides a practical basis for selecting a PV installed capacity of 170 kW in this study [4, 5].

The rooftop PV installed capacity of a dormitory building needs to be selected reasonably. If the installed capacity is too small, its effect in replacing power purchases during high-price periods will be limited; if the installed capacity is too large and lacks storage support, the probability of PV curtailment will increase. This paper adopts a 170 kW PV system with 500 kWh of storage to reflect the coordinated relationship among rooftop resource utilization, midday surplus absorption, and nighttime load support. In summary, the main parameters of the PV-storage microgrid for Dormitory Building No. 9 are shown in Table 1.

Table 1. Main parameters of the PV-storage microgrid for Dormitory Building No. 9

Parameter	Value
Annual electricity consumption of dormitory building	About 700,000 kWh
Peak load of dormitory building	About 400 kW
Rooftop projected area	About 1,200 m2
Usable area	About 840 m2
PV installed capacity	170 kW
Energy storage type	Lithium iron phosphate battery
Rated storage capacity	500 kWh
Maximum charging/discharging power of storage	250 kW
SOC operating range	20%-90%
Charging/discharging efficiency	95%
PV curtailment penalty coefficient	0.20 yuan/kWh

2.3. Time-of-use pricing mechanism and scenario boundary

This paper adopts a general industrial and commercial time-of-use electricity tariff as a hypothetical pricing scenario. The time periods and adopted prices are shown in Table 2. The system only purchases electricity from the grid, with no export allowed. The mechanism in which the critical-peak price is raised above the peak price provides a clear economic signal for energy storage to "purchase electricity at low prices and replace grid purchases at high prices" [6]. It should be noted that there are currently multiple pricing models for electricity in university dormitories in Beijing. This study assumes a general industrial and commercial time-of-use electricity price with a flat rate of 0.5003 yuan/kWh as the basis for modeling, rather than claiming it as the actual billing category of the studied dormitory.

Based on the publicly disclosed electricity purchase unit price of the university library building PV project, the flat-period electricity price is set to 0.5003 yuan/kWh. On this basis, the peak, valley, and critical-peak prices are constructed as 0.9005 yuan/kWh, 0.1501 yuan/kWh, and 1.0806 yuan/kWh, respectively. This treatment adopts a pricing structure consistent with Beijing's general industrial and commercial TOU tariff, providing a clear peak–valley price spread for the scheduling model. Since this paper focuses on intra-day operation optimization, more complex market factors such as demand charges, capacity tariffs, and spot-market deviation assessment are not further discussed; the research boundary is limited to the most critical electricity energy cost component of a typical building microgrid [5-7].

In terms of scenario boundary, this paper considers only a grid-connected PV-storage microgrid for a dormitory building. Power export and electricity sales revenue are excluded, and the grid mainly serves as a supplementary power source in the model. Reverse power flow control, transformer expansion, and distribution network power-flow calculation are also not considered. Although this means that the model is simplified relative to real engineering practice, the treatment still preserves the core problem of dormitory building microgrid operation, namely how to optimize grid power purchase behavior under given load, PV, and storage conditions. Hence the research focus is clear [2, 8, 9].

Table 2. Beijing industrial and commercial TOU periods and adopted prices

Period type	Time period	Adopted price (yuan/kWh)
Valley	23:00-next day 7:00	0.1501
Flat	7:00-10:00; 13:00-17:00; 22:00-23:00	0.5003
Peak	10:00-13:00; 17:00-22:00	0.9005
Summer critical peak	11:00-13:00; 16:00-17:00	1.0806
Winter critical peak	18:00-21:00	1.0806

2.4. System structure and operation mechanism of the PV-storage microgrid

The PV-storage microgrid constructed for Dormitory Building No. 9 consists of the dormitory load, rooftop PV system, lithium iron phosphate energy storage system, AC bus, and public grid. The system topology is shown in Figure 1. The operating rules are as follows: PV output first supplies the local load; any surplus PV power then charges the energy storage system; once the storage reaches its SOC upper limit, further surplus PV power is curtailed. Conversely, when PV output is insufficient to meet load demand, the system can be supplied by storage discharge or the grid according to the optimal scheduling result [2, 10].

This paper focuses on the tertiary control layer of the microgrid, namely the energy management decision-making layer oriented toward economic operation. This layer uses time-of-use prices, load forecasts, and renewable energy forecasts as inputs, and an optimization algorithm determines the charging/discharging power of storage and grid purchase power in each period. In this way, operating cost minimization is achieved under safety constraints. The scheduling time scale is hourly typical-day scheduling [9, 10].

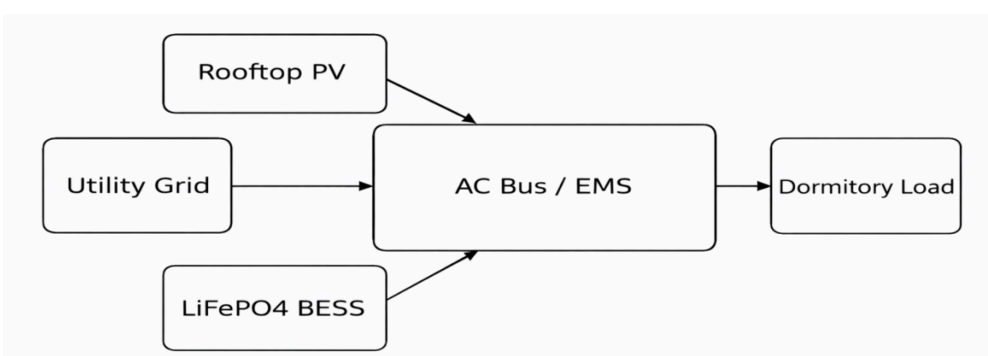

Figure 1. System topology of the PV-storage microgrid for Dormitory Building No. 9

2.5. Construction of typical daily scenarios

Two types of scenarios are considered: a typical summer day and a typical winter day. In the summer scenario, the total daily load is 5,145 kWh and the peak reaches about 400 kW at 20:00; the typical daily generation of the 170 kW rooftop PV system is 1,280 kWh, with midday output close to the rated value. In the winter scenario, the total daily load is 3,891 kWh and the peak reaches about 320 kW at 20:00; the typical daily PV generation is 803 kWh, lower than that in summer overall [4, 5].

Sample days are constructed around the most representative seasonal operating states of the dormitory building. On the one hand, this approach highlights core issues such as the mismatch between PV output and load and the response to time-of-use pricing. On the other hand, it avoids excessive model complexity when complete measured data are unavailable [9, 11].

Load and PV output curves for the typical summer and winter days are shown in Figure 2. Both scenarios have the common feature that PV output is relatively high at midday while load is relatively low, whereas evening load rises significantly when PV output is absent. Without energy storage or optimal scheduling, this would lead to "daytime PV curtailment and nighttime high-price electricity purchase" [4, 9].

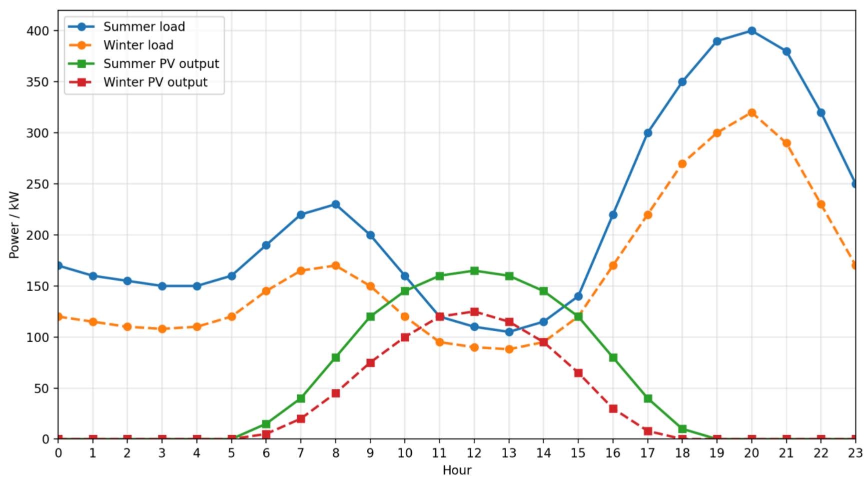

Figure 2. Load and PV output curves for typical summer and winter days

3. Energy management model for the pv-storage microgrid

3.1. Basic modeling assumptions

To capture the core trade-off in the energy management problem of the dormitory building microgrid while keeping the model tractable, the following basic assumptions are made. The study period is divided into 24 discrete time intervals, each with a duration of 1 h. The load power and PV output in each interval are treated as known constants, and intra-interval fluctuations are not considered. The grid is used only as an external power purchase source; reverse power export to the grid is not permitted. The charging and discharging efficiencies of the energy storage system are fixed, and self-discharge as well as the influence of ambient temperature on storage performance are ignored. The initial SOC of the energy storage system is kept equal to the terminal SOC at the end of the day to ensure the sustainable cycling of intra-day scheduling results.

Common treatments in existing Energy Management System (EMS) research are followed: an hourly discretized scheduling strategy is adopted, and modeling and optimization analysis are conducted based on typical daily load and PV output data [12].

3.2. Objective function

The optimization objective is to minimize the daily operating cost, including electricity purchase cost and PV curtailment penalty [13]:

$$minF = \sum_{t=1}^{24}(c_t P_g(t)\Delta t) + \lambda \sum_{t=1}^{24}(P_{cur}(t)\Delta t) \tag{1}$$

where c_t is the electricity price in period t, $P_g(t)$ is the grid purchase power, $P_{cur}(t)$ is the PV curtailment power, and lambda is the PV curtailment penalty coefficient. In this paper, lambda is set to 0.20 yuan/kWh.

3.3. Constraints

Power balance:

$$minF = \sum t = 124(ctPg(t)\Delta t) + \lambda \sum t = 124(Pcur(t)\Delta t)Pg(t) + Pdis(t) + Ppv(t) - Pcur(t) = PL(t) + Pch(t) \tag{2}$$

In Equation (2), $P_g(t)$ denotes the grid purchase power in period t; $P_{dis}(t)$ and $P_{ch}(t)$ denote storage discharging and charging power, respectively; $P_{pv}(t)$ denotes PV output; $P_{cur}(t)$ denotes PV curtailment power; and $P_L(t)$ denotes dormitory load power. This equation reflects the basic energy-flow relationship of the system and serve as the core constraint for subsequent scheduling [9].

SOC update of the energy storage system:

$$SOC_t = SOC_{t-1} + \frac{\eta_{ch} P_{ch}(t)\Delta t}{E_B} - \frac{P_{dis}(t)\Delta t}{\eta_{dis} E_B} \tag{3}$$

where E_B is the rated capacity of the energy storage system, and η_{ch} and η_{dis} are the charging and discharging efficiencies, respectively.

SOC limits:

$$SOC_{min} \leq SOC_t \leq SOC_{max} \tag{4}$$

In this paper, $SOC_{min} = 0.2, SOC_{max} = 0.9$.

The initial and terminal states are set equal to ensure daily-cycle sustainability:

$$SOC_{24} = SOC_0 \tag{5}$$

Charging and discharging power constraints are:

$$\begin{gathered} 0 \leq P_{ch}(t) \leq P_{ch}^{max} \\ 0 \leq P_{dis}(t) \leq P_{dis}^{max} \end{gathered} \tag{6}$$

where:

$$P_{ch}^{max} = P_{dis}^{max} = 250kW \tag{7}$$

For the grid purchase constraint and PV curtailment constraint:

$$0 \leq P_g(t) \leq P_g^{max} \tag{8}$$

In this paper, $P_g^{max} = 400kW$.

The PV curtailment power satisfies:

$$0 \leq P_{cur}(t) \leq P_{pv}(t) \tag{9}$$

3.4. Evaluation indicators

To comprehensively evaluate the optimal scheduling effect, the following indicators are set. Daily operating cost, namely the sum of electricity purchase cost and PV curtailment penalty. Daily electricity purchase, used to measure the system's dependence on the external grid. Electricity purchased during high-price periods, used to reflect how energy storage utilizes the peak-flat-valley price difference. PV curtailment and PV self-consumption rate, used to evaluate the local utilization level of renewable energy. Maximum grid purchase power, used to analyze the impact of the system on the building-side net load curve.

These indicators together constitute the quantitative basis for the result analysis [3, 6, 9].

$$\eta_{pv} = \frac{\sum P_{pv}(t)\Delta t - \sum P_{cur}(t)\Delta t}{\sum P_{pv}(t)\Delta t} \times 100\% \tag{10}$$

$$\eta_{pv} = \frac{\sum P_{pv}(t)\Delta t - \sum P_{cur}(t)\Delta t}{\sum P_{pv}(t)\Delta t} \times 100\% \tag{11}$$

The PV self-consumption rate refers to the proportion of total PV generation that is actually absorbed by local load and energy storage. Electricity purchased during high-price periods is calculated by combining the peak and critical-peak periods. By comparing the differences between the "operation without storage coordination" and "optimal scheduling operation" schemes with respect to the above indicators, the sources of cost change can be analyzed [6, 9].

4. MATLAB simulation and result analysis

4.1. Simulation parameter settings

This paper does not consider stochastic forecast errors or equipment failures, but only compares the operating differences between two schemes under the same load, PV output, and price conditions. From the modeling results above, the typical daily input parameters and basic results are shown in Table 3. The relevant input curves and optimization outputs are shown in Figures 3 to 6; and the main results are summarized in Table 4 to 6.

Table 3. Typical daily input parameters and basic results

Scenario	Daily load energy/kWh	Daily PV generation/kWh	PV curtailment without storage/kWh
Typical summer day	5,145	1,280	180.00
Typical winter day	3,891	803	87.00

4.2. Optimization results for the typical summer day

As shown in Figure 3, the system charges the energy storage system at 6:00 and 23:00 using the valley electricity price, and discharges during high-price periods such as 16:00 and 21:00.

Table 4 presents the results for the typical summer-day scenario. The daily operating cost of the scheme without storage is 2,375.54 yuan, compared to 1,985.70 yuan for the optimized scheme, a decrease of 16.41%. Daily electricity purchase drops by 126.53 kWh, and electricity purchased during high-price periods falls by 347.50 kWh. PV curtailment goes down from 180.00 kWh to 0, and the PV self-consumption rate increases from 85.94% to 100%.

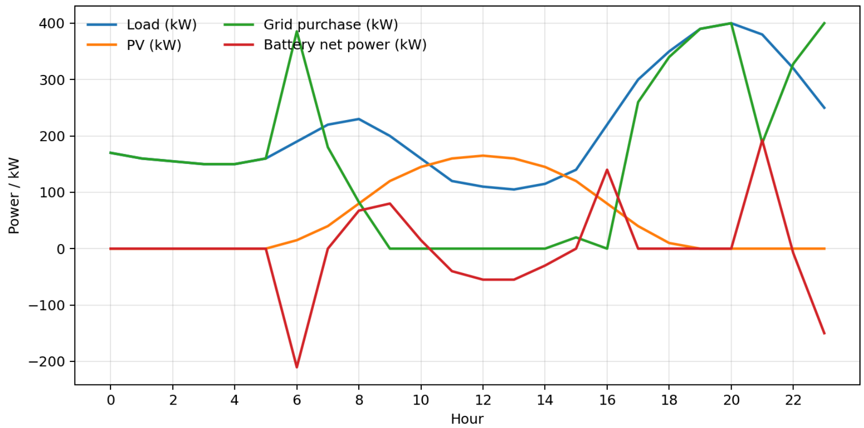

Figure 3. Power allocation results of optimal scheduling for the typical summer day

Table 4. Comparison between the no-storage scheme and optimized scheme for the typical summer day

Indicator	No-storage Scheme	Optimized Scheme	Change
Daily operating cost/yuan	2,375.54	1,985.70	-16.41%
Daily electricity purchase/kWh	4,045.00	3,918.47	-126.53
Electricity purchase in high-price periods/kWh	1,925.00	1,577.50	-347.50
PV curtailment/kWh	180.00	0.00	Reduced to 0
PV self-consumption rate/%	85.94	100.00	+14.06

4.3. Optimization results for the typical winter day

In the typical winter-day scenario, the total daily load of the dormitory building is 3,891 kWh, and the daily PV generation is 803 kWh. In the no-storage scheme, PV curtailment is 87 kWh. In the optimized scheduling scheme, the storage system absorbs all surplus PV power and releases it during the evening critical-peak period, reducing PV curtailment to 0. As seen in Figure 4 and 5, the SOC trajectory in the winter scenario is smoother than that in the summer scenario, while the discharge action during 18:00-21:00 is more concentrated.

As shown in Table 5, the daily operating cost of the winter no-storage scheme is 1,983.48 yuan, compared to 1,614.79 yuan for the optimized scheme, a reduction of 18.59%. Daily electricity purchase drops from 3,175.00 kWh to 3,132.40 kWh, electricity purchased during high-price periods falls from 1,412.00 kWh to 1,059.50 kWh, and the PV self-consumption rate rises from 89.17% to 100%.

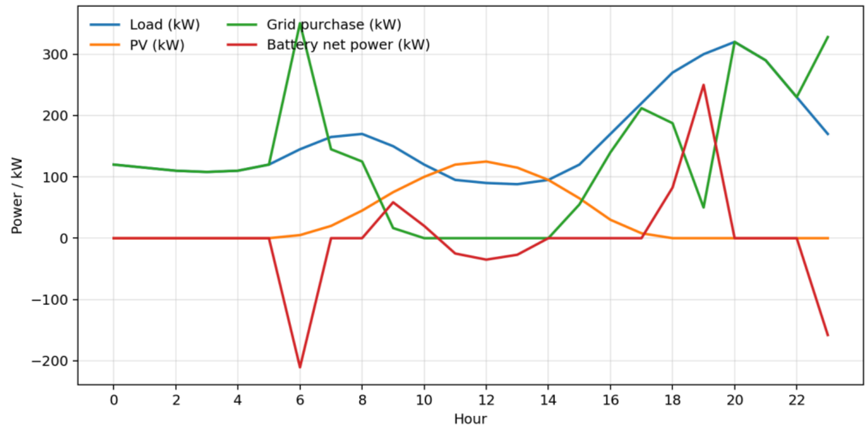

Figure 4. Power allocation results of optimal scheduling for the typical winter day

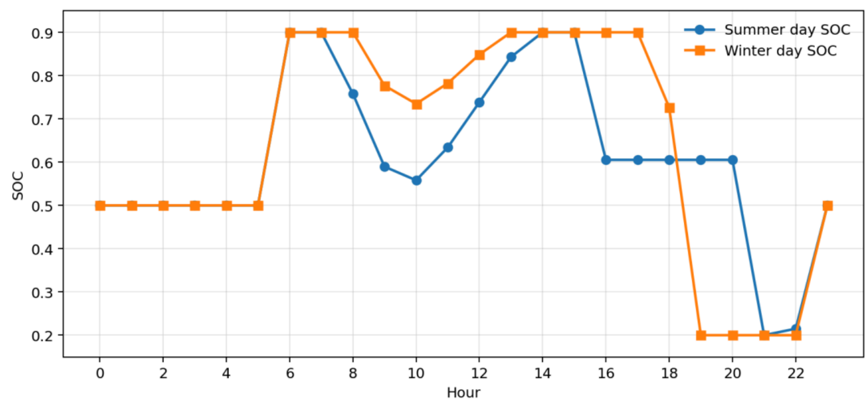

Figure 5. SOC variation curves of energy storage for typical summer and winter days

Table 5. Comparison between the no-storage scheme and optimized scheme for the typical winter day

Indicator	No-storage scheme	Optimized scheme	Change
Daily operating cost/yuan	1,983.48	1,614.79	-18.59%
Daily electricity purchase/kWh	3,175.00	3,132.40	-42.60
Electricity purchase in high-price periods/kWh	1,412.00	1,059.50	-352.50
PV curtailment/kWh	87.00	0.00	Reduced to 0
PV self-consumption rate/%	89.17	100.00	+10.83

4.4. Sensitivity analysis

As seen in Table 6, under the typical summer-day condition, as the storage capacity increases from 300 kWh to 700 kWh, the optimized daily operating cost decreases from 2,080.58 yuan to 1,910.17 yuan, and the reduction relative to the no-storage scheme increases from 12.42% to 19.59%.

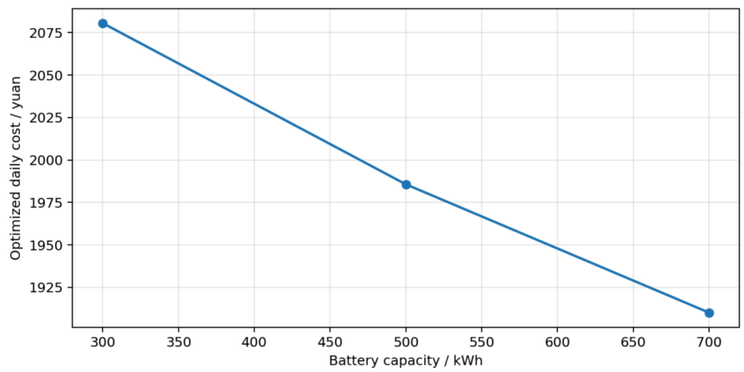

Figure 6. Effect of storage capacity variation on optimized daily operating cost

Table 6. Sensitivity analysis results for storage capacity on the typical summer day

Storage capacity/kWh	Optimized daily operating cost/yuan	Reduction relative to no-storage scheme/%
300	2,080.58	12.42
500	1,985.70	16.41
700	1,910.17	19.59

The effect of PV installed capacity on the optimized results for the typical summer day is shown in Table 7. As the PV installed capacity increases from 120 kW to 220 kW, PV curtailment without storage rises from 14.41 kWh to 408.24 kWh, while the optimized daily operating cost decreases from 2,182.52 yuan to 1,812.70 yuan.

Table 7. Sensitivity analysis results for PV installed capacity on the typical summer day

PV installed capacity/kW	PV curtailment without storage/kWh	Optimized daily operating cost/yuan	Reduction relative to no-storage scheme/%
120	14.41	2,182.52	12.25
170	180.00	1,985.70	16.41
220	408.24	1,812.70	21.97

5. Discussion

5.1. Findings

Compared with the no-storage scheme, the storage scheme offers the core advantage of alleviating the temporal mismatch between PV output and load demand, reducing PV curtailment, decreasing electricity purchases during high-price periods, and improving PV self-consumption and the system's operating efficiency. Although the no-storage scheme is simpler, it has clear shortcomings in integrating renewable energy and optimizing peak-valley dynamics. Therefore, introducing energy storage is of practical significance and optimization value in the dormitory building PV-storage microgrid scenario.

In addition, with a small storage capacity, the added capacity is first used to absorb otherwise curtailed PV power and to replace electricity purchases during the most expensive periods. In fact, the benefits increase rapidly. However, once the capacity exceeds the total midday surplus PV and the energy required for the typical evening peak, further capacity expansion offers limited additional flexibility. The benefits then mainly come from minor time-shifting, with declining marginal returns. For dormitory buildings, this means that storage configuration should not blindly pursue a "larger is better" approach, but should be determined comprehensively based on the load peak-valley difference, surplus PV power, and electricity price differences.

The maximum grid purchase power does not decrease significantly mainly because the optimization objective in this paper focuses on electricity purchase cost and PV curtailment suppression, without separately incorporating the maximum grid purchase power into the objective function or constraints. Meanwhile, the peak load of the dormitory building occurs mostly in the evening, when PV output is low. Given storage capacity, discharge power, and SOC constraints, energy storage can reduce part of the electricity purchased during high-price periods, but its effect on reducing instantaneous peak grid purchase power is limited.

5.2. Practical implications

For typical building loads, such as dormitory buildings, the coordinated integration of photovoltaics and energy storage can effectively mitigate the temporal mismatch between load and PV output, improve renewable energy integration, and reduce electricity purchase costs during high-priced periods under a time-of-use pricing mechanism. This points to the practical feasibility of constructing building-side microgrids in universities. At the same time, the use of hourly discretization and typical-day modeling also provides a reference implementation path for energy management research and preliminary engineering design in similar scenario.

5.3. Limitations

Several limitations remain in this study. First, the typical daily data are constructed through engineering estimation and pattern abstraction, and full-year measured data have not yet been introduced. Second, stochastic factors such as load forecast errors, weather uncertainty, and equipment failures are not considered. Third, the objective function lacks demand charges, storage degradation costs, or carbon-emission reduction benefits. Fourth, islanded operation and outage backup capability are not analyzed further.

Future work could address the following aspects. First, multiple typical days or full-year hourly data can be introduced to conduct longer-term economic evaluations [7-9]. Second, battery aging models, demand response, and carbon trading parameters can be incorporated to form a multi-objective optimization framework [12]. Third, capacity configuration and resilience analysis can be conducted in conjunction with the university's actual distribution system, thereby expanding the study from single-building scheduling to a campus-integrated energy system [13].

6. Conclusion

Taking Dormitory Building No. 9 of the University of Science and Technology Beijing as a case study, this paper establishes an intra-day optimal scheduling model for a grid-connected PV-storage microgrid based on the coupling relationship among time-of-use pricing, PV generation, energy storage, and dormitory load. The results show that, under the conditions of a peak load of about 400 kW, a PV installed capacity of 170 kW, and an energy storage configuration of 500 kWh/250 kW for Dormitory Building No. 9, the energy storage system can reconstruct power purchase behavior through valley-period charging, daytime absorption of surplus PV power, and high-price-period discharging. Compared with the no-storage scheme, daily operating cost decreases by 16.41% in the typical summer scenario and 18.59% in the typical winter scenario. PV curtailment falls from a positive value to zero in both cases, and the PV self-consumption rate reaches 100%. This indicates that, in the dormitory load scenario, the value of energy storage is mainly reflected in time shifting and improved PV consumption.

Sensitivity analysis further shows that increasing storage capacity can continuously improve economic performance, but the marginal benefit gradually decreases. Therefore, storage capacity should be reasonably configured based on building load characteristics and surplus PV levels, rather than simply pursuing a larger capacity. Overall, this paper presents a modeling, solution, and evaluation framework for PV-storage microgrids in university dormitory buildings, offering a reference for campus energy-saving renovation and distributed energy applications.

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