

Optimal Operation Model of a PV–ESS–EV Microgrid Toward the Net-Zero Target

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Abstract — Currently, in Vietnam and worldwide, the Zero Energy Building (ZEB) concept is receiving increasing attention as a promising solution to reduce energy consumption and carbon emissions in the building sector. ZEBs integrate renewable energy sources, energy storage systems, and advanced energy management strategies to enhance energy autonomy and lower operating costs. In this context, this study proposes an optimal operational model for an office building microgrid that includes photovoltaic (PV) generation, an energy storage system (ESS), and electric vehicles (EVs) providing Vehicle-to-Building (V2B) services. The coordinated operation of these distributed energy resources aims to achieve energy balance while minimizing electricity costs and maximizing the utilization of renewable energy. The proposed optimization model is formulated as a mixed-integer linear programming (MILP) problem and solved using GAMS software with the CPLEX solver. Several scenarios are analyzed, including variations in electricity purchase and sale prices and different operating modes of the ESS, to comprehensively evaluate the model's effectiveness and its potential contribution to the development of sustainable and energy-efficient buildings.

Keywords: *Energy storage system, Optimal operation, Renewable energy, Vehicle-to-building, Zero energy building.*



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INTRODUCTION

In recent years, issues such as resource depletion, air pollution, and global warming have become increasingly pressing and have drawn considerable global attention. Consequently, Vietnam together with many other countries has been seeking comprehensive and practical solutions to reduce the use of conventional energy sources and curb greenhouse gas emissions. Among the available approaches, the Zero Energy Building (ZEB) concept has emerged as a particularly effective pathway. ZEBs not only mitigate environmental impacts but also promote the transition toward cleaner, decentralized, and more sustainable energy systems that can be readily applied to both residential and commercial buildings [1]. A ZEB is generally defined as a building capable of producing sufficient renewable energy to meet its

own annual consumption. From the perspective of power system operation, a ZEB can be characterized as a building whose electricity drawn from the grid is less than or equal to the renewable energy it exports over a year [2]-[4]. Such buildings contribute to grid stability by reducing reliance on centralized power generation and by increasing the share of renewables in overall energy consumption. According to [5], the ZEB concept represents a promising approach capable of simultaneously addressing multiple global challenges, including energy security, sustainable resource management, and climate change mitigation. Furthermore, the study in [6] shows that ZEB technologies and applications have been widely studied and implemented in countries such as the United States, Spain, Italy, China, and Japan. That study also highlights the increasing prevalence of ZEBs that employ photovoltaic (PV) systems as their primary renewable energy source, emphasizing the central role of solar energy in building decarbonization. Nevertheless, the intermittent and unpredictable nature of PV generation presents significant challenges for energy management in ZEBs. Variations in solar radiation cause fluctuations in output, making it difficult to maintain a consistent balance between generation and consumption particularly during peak demand or low-insolation periods. Consequently, the effective utilization of PV systems often remains below their available power output. To overcome this limitation, most ZEBs integrate energy storage systems (ESS) to store surplus energy for later use when demand exceeds generation. Moreover, the rapid development of electric vehicle (EV) technology has enabled EVs to serve as flexible energy assets that can supply electricity back to the grid (Vehicle-to-Grid, V2G) or directly to buildings (Vehicle-to-Building, V2B) [7], [8]. The V2B concept is especially promising because vehicles typically remain parked for extended periods, allowing them to deliver supplementary power to buildings during idle hours. In this context, EVs can function as mobile, temporary storage units that absorb excess PV generation or perform load-shifting operations to enhance overall energy management efficiency [9], [10].

This study proposes an optimal operation model for a building-level microgrid that integrates PV generation, an ESS, and EVs providing V2B services. The model aims to achieve ZEB objectives by maintaining energy balance and minimizing electricity costs. Various ESS operating strategies, along with different electricity purchase and sale price scenarios, are analyzed to evaluate the model's performance and adaptability under changing market and environmental conditions. The optimization problem is formulated as a mixed-integer linear programming (MILP) model and solved using the GAMS platform with the CPLEX solver [11]. Simulation results indicate that, beyond the installation of PV systems, coordinated operation between the ESS and EVs plays a vital role in enhancing self-sufficiency and economic efficiency, thereby facilitating the realization of ZEB goals. The remainder of this paper is organized as follows. Section 1 introduces the theoretical background and reviews related literature. Section 2 presents the proposed optimization model for a microgrid integrating PV, ESS, and EV systems. Section 3 applies the model to a representative case study and provides detailed analysis of the results under various scenarios. Finally, Section 4 summarizes the key findings and offers concluding remarks on the applicability and future research directions of ZEB-based microgrids for buildings.

METHOD

This study focuses on optimizing the operational scheduling of an office building microgrid toward achieving the Zero Energy Building (ZEB) target. The building is equipped with a photovoltaic (PV) system whose available generation for a representative week has been forecast in advance, an Energy Storage System (ESS) for long-term energy storage, and a parking lot where Electric Vehicles (EVs) participate in providing Vehicle-to-Building (V2B) services (referred to as EV-V2B). The operation of the building microgrid follows a hierarchical energy management strategy that prioritizes the utilization of PV power. When the PV generation is insufficient to meet the building's electricity demand, the remaining demand is supplied by the ESS, EV-V2B, and power purchased from the grid. Conversely,

when PV generation exceeds the building load, the surplus power is either exported to the electricity market or stored in the ESS for later use Figure 1. It is assumed that the EVs belong to employees working in the building. These EVs are charged overnight at residential charging stations under a Time-of-Use (ToU) electricity tariff. During working hours, from 7:00 to 18:00, Monday through Friday, the EVs are parked at the office building and provide V2B services. Because the nighttime ToU charging price is generally lower than the rate at which the building purchases electricity through the V2B service, EV owners can obtain a profit by participating in V2B operations. This profit should be sufficient to offset the potential degradation in battery lifetime resulting from frequent charging and discharging cycles. For the building, the use of V2B services enhances its energy autonomy and helps move it closer to the goal of becoming a Zero Energy Building.

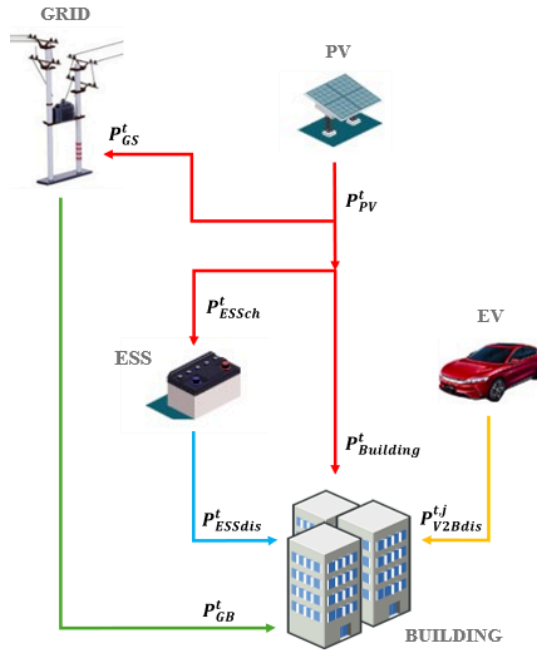


Figure 1. ZEB's operating model

A. Objective Function

The optimal operation model of the building microgrid aims to minimize its total operating cost over a one-week period, from 00:00 on Monday to 24:00 on Sunday, corresponding to 168 hours, as expressed in equation (1).

$$\text{Min} \sum_{t=1}^{168} DA_B^t + DA_{V2B}^t - DA_S^t \quad (1)$$

where DA_B^t , DA_S^t , and DA_{V2B}^t represent, respectively, the electricity purchase cost, the revenue from selling electricity to the market, and the payment for V2B services at time t . These components are defined by equations (2)-(4) below.

$$DA_B^t = \sum_{t=1}^{168} P_{GB}^t \cdot C_{GB}^t \quad (2)$$

$$DA_s^t = \sum_{t=1}^{168} P_{GS}^t \cdot C_{GS}^t \quad (3)$$

$$DA_{V2B}^t = C_{V2B} \cdot \sum_{t=1}^{168} \sum_{j=1}^{N_{EV}} P_{V2Bdis}^t \quad (4)$$

In the above equations, C_B^t , C_S^t , and C_{V2B}^t denote the electricity purchase price, the electricity selling price to the market, and the payment rate for the V2B service, respectively. Similarly, P_B^t , P_S^t , and P_{V2B}^t represent the purchased power, the power sold to the market, and the discharging power from EVs at time t . N_{EV} denotes the number of EVs participating in the V2B service under contract. In equation (4), the electricity price paid by the building for V2B service is assumed to be fixed, and the number of participating EVs is also assumed to remain constant during the scheduling period.

B. Constraints

ESS Operating Constraints

The energy storage system in the building is used to store surplus energy generated by the PV system and to provide power support when the building load demand is high. Equations (5) and (6) ensure that the charging and discharging power of the ESS remain within their permissible limits. The binary variable u_{ESS}^t is introduced to ensure that the ESS can either charge or discharge at any given time, but not both simultaneously.

$$0 \leq P_{ESSdis}^t \leq u_{ESS}^t \cdot P_{ESS}^{max} \quad (5)$$

$$0 \leq P_{ESSch}^t \leq (1 - u_{ESS}^t) \cdot P_{ESS}^{max} \quad (6)$$

In these equations, P_{ESSch}^t and P_{ESSdis}^t denote the charging and discharging power of the ESS at hour t , respectively, while P_{ESS}^{max} represents the maximum charging/discharging capacity of the ESS. The stored energy level of the ESS at any given time depends on the charging and discharging efficiencies, as described in equations (7)-(9). Equation (9) ensures that, after one week of operation, the energy level of the ESS returns to its initial state so that the system is ready for the next operational cycle.

$$E_{ESS}^t = E_{ESS}^{t-1} + \left(\eta_{ESS} P_{ESSch}^t - \frac{P_{ESSdis}^t}{\eta_{ESS}} \right) \Delta t \quad (7)$$

$$0.2E_{ESS}^{max} \leq E_{ESS}^t \leq 0.8E_{ESS}^{max} \quad (8)$$

$$E_{ESS}^0 = E_{ESS}^{168} \quad (9)$$

In these equations, E_{ESS}^t represents the energy stored in the ESS at the end of hour t ; E_{ESS}^0 and E_{ESS}^{168} denote the stored energy levels of the ESS at the beginning and at the end of the week, respectively; E_{ESS}^{max} the maximum storage capacity of the ESS; η_{ESS} denotes the

charging/discharging efficiency; and Δt is the duration of each time interval, which is set to 1 hour in this study.

EVs Operating Constraints

In the operating model, the EVs are assumed to be charged at home or at nearby residential charging stations during nighttime. While parked at the office building during daytime hours, these EVs do not charge but can discharge power when requested to supply electricity to the building. It is assumed that all EVs arrive at the office at 7:00 am and depart at 6:00 pm, from Monday to Friday. This study further assumes that each EV participating in the V2B service discharges at a fixed power level P_{EV}^{max} . This relationship is expressed in equation (10), where

$u_{V2Bdis}^{(t,j)}$ is a binary variable equal to 1 if EV j is discharging at time t , and 0 otherwise.

$$0 \leq P_{V2Bdis}^{t,j} = u_{V2Bdis}^{t,j} \cdot P_{EVmax} \quad (10)$$

Equations (11) and (12) constrain the EVs from discharging when their remaining energy falls below the allowable limit. This condition ensures that each EV retains sufficient energy to return home after the working day. In addition, equation (13) specifies that the energy level of each EV, $E_{V2B}^{(t,j)}$, must remain within its permissible range.

$$E_{V2B}^{t-1,j} - P_{EV}^{max} \cdot \Delta t \geq u_{V2Bdis}^{t,j} \cdot EV_{minlevel} \cdot E_{V2B}^{max}, \quad (11)$$

$$\forall 24 \times (i - 1) + 9 \leq t \leq 24 \times (i - 1) + 18, \forall i = \{1, 2, \dots, 5\}$$

$$SOC_{EV} \cdot E_{V2B}^{max} - P_{EV}^{max} \cdot \Delta t \geq u_{V2Bdis}^{t,j} \cdot EV_{minlevel} \cdot E_{V2B}^{max}, \quad (12)$$

$$\forall t = 24 \times (i - 1) + 8, \forall i = \{1, 2, \dots, 5\}$$

$$0 \leq E_{V2B}^{t,j} \leq E_{V2B}^{max} \quad (13)$$

In these equations, E_{V2B}^{max} represents the maximum battery capacity of an EV; $EV_{minlevel}$ denotes the minimum allowable state of charge (expressed as a percentage) required for participation in V2B operations; SOC_{EV} is the state of charge (in percentage) of the EV upon arrival at the building; and i is the day index of the week, where $i = 1$ to 5 correspond to weekdays from Monday to Friday. Equations (14) and (15) describe the variation of the stored energy level in each EV after every time step t of day i , where η_{EV} represents the discharging efficiency of the EV battery.

$$E_{V2B}^{t,j} = E_{V2B}^{t-1,j} - \frac{P_{V2Bdis}^{t,j}}{\eta_{EV}} \Delta t, \quad (14)$$

$$\forall 24 \times (i - 1) + 9 \leq t \leq 24 \times (i - 1) + 18, \forall i = \{1, 2, \dots, 5\}$$

$$E_{V2B}^{t,j} = SOC_{EV} \cdot E_{V2B}^{max} - \frac{P_{V2Bdis}^{t,j}}{\eta_{EV}} \Delta t \quad (15)$$

$$\forall t = 24 \times (i - 1) + 8, \forall i = \{1, 2, \dots, 5\}$$

Equation (16) defines the actual output power limit of the PV system at hour t .

$$0 \leq P_{PV}^t \leq P_{PVfc}^t \quad (16)$$

In this equation, P_{PV}^t and P_{PVfc}^t represent the actual output power and the forecasted available power of the PV system at time t , respectively. This constraint aims to limit the power purchased from or sold to the electricity market to meet the building's demand.

$$0 \leq P_{GB}^t \leq u_{Grid}^t \cdot M \quad (17)$$

$$0 \leq P_{GS}^t \leq (1 - u_{Grid}^t) \cdot M \quad (18)$$

In these equations, the binary variable u_{Grid}^t indicates the power exchange state with the grid, where a value of 1 represents power purchase from the grid and 0 indicates power sale to the grid. M is a sufficiently large constant. Equation (19) represents the power balance at time t . It describes how the building meets its electricity demand P_{Loads}^t using different energy sources.

$$P_{Loads}^t = \sum_{j=1}^{N_{EV}} P_{V2Bdis}^{t,j} + P_{ESSdis}^t + P_{GB}^t - (P_{ESSch}^t + P_{GS}^t) \quad (19)$$

RESULT AND DISCUSSION

A. Case Study

The optimal operation model presented in method is applied to an office building in Hanoi, Vietnam, which is equipped with a photovoltaic (PV) system, an energy storage system (ESS), and electric vehicles (EVs). It is assumed that ten employee-owned EVs are parked at the building during working hours and participate in providing Vehicle-to-Building (V2B) services. Each EV is capable of discharging at a rated power of 12 kW. The ESS has a rated capacity of 200 kW/500 kWh, with a charging/discharging efficiency of 95%. The forecasted PV generation and the building's electricity demand over one week are illustrated in Figure 2 under two scenarios: PV surplus and PV shortage. The data in Figure 2 indicate that the building load is relatively high during normal working hours, reaching over 170 kW at peak periods. In contrast, outside office hours and during weekends, the building load remains low, typically between 40 kW and 55 kW. In the PV surplus scenario, PV generation is available from 6:00 am to 6:00 pm on most days, with a peak output exceeding 350 kWh approximately twice the building load. On Thursday, PV generation slightly decreases but can still meet 100% of the load demand between 8:00 am and 3:00 pm. Conversely, in the PV shortage scenario, the PV output is considerably lower (ranging from 3 kW to 65 kW), meeting only about 21% of the weekday energy demand.

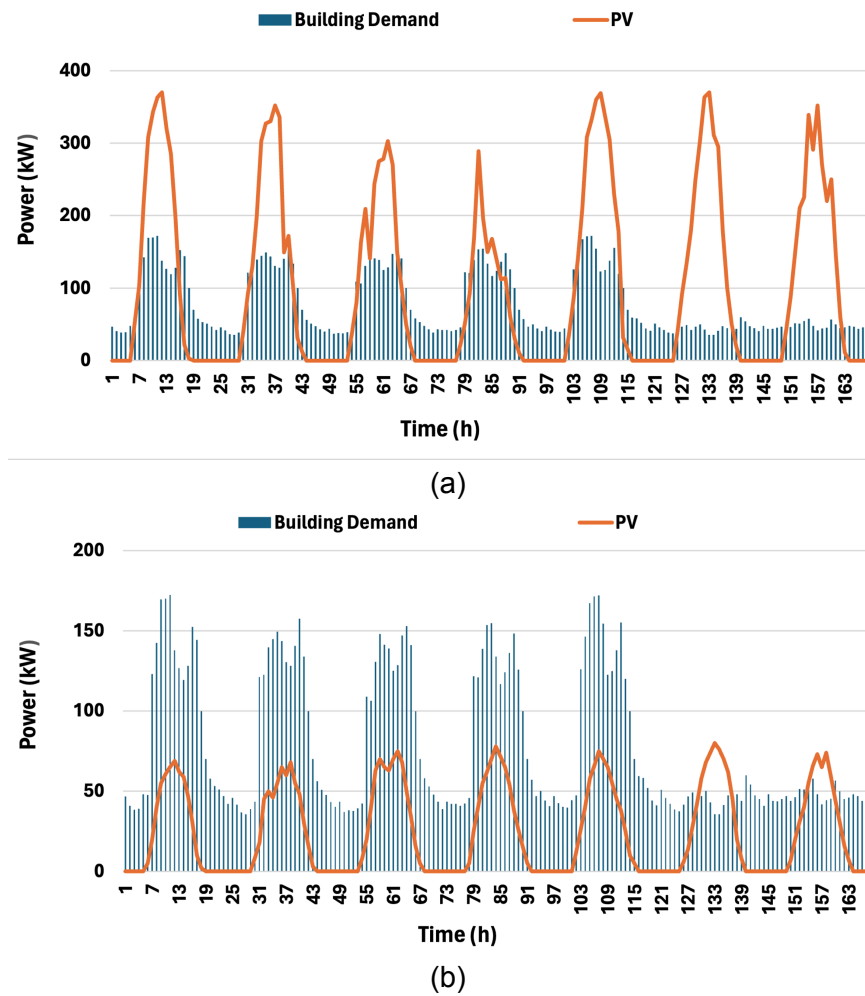


Figure 2. Forecasted PV power output and demand for (a) PV surplus and (b) PV shortage

During weekends, since the building is an office facility, the load is significantly reduced compared to weekdays. Under these conditions, PV generation can meet the building's demand only during the period from 10:00 a.m. to 3:00 p.m.; outside this time window, the ESS must supply additional power or electricity must be purchased from the grid. Table 1 presents the electricity tariffs in Vietnam, which are applied to the building for purchasing power from the grid, and the payment rate for EVs providing V2B services. Two grid purchase tariff options are considered: (1) a commercial Time-of-Use (ToU) tariff, and (2) a fixed electricity price. Surplus electricity generated by the building is sold back to the grid at a rate of 2,100 VND/kWh. EVs are assumed to be charged overnight at the off-peak ToU price of 1,465 VND/kWh [12], and later provide V2B services to the building at a rate of 2,200 VND/kWh. The difference between these two prices creates an economic incentive for EV owners to participate in V2B operations.

Table 1. Electricity purchase/sale price

Time Frame	Purchase Price (VND/kWh)		Sale Price (VND/kWh)	V2B Price (VND/kWh)
	Tariff for Business	Fixed Tariff		
Peak	4575	3151	2100	2200
Regular	2629	3151	2100	2200
Off-peak	1465	3151	2100	2200

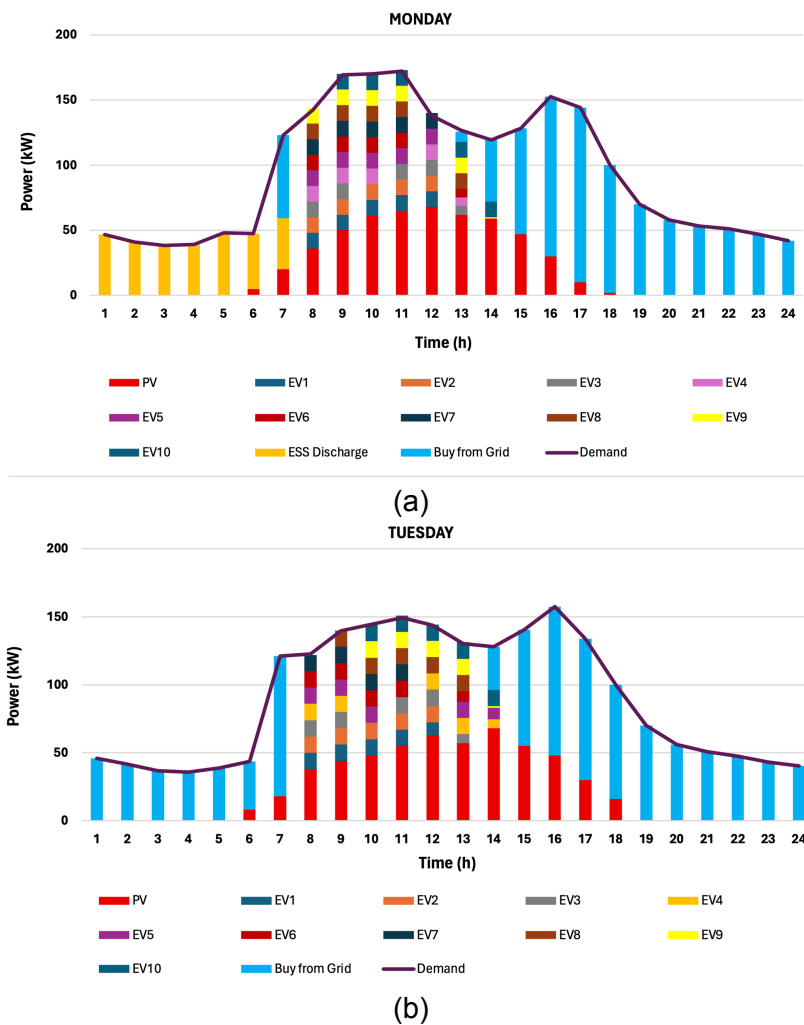
The authors perform an operational scheduling analysis under the commercial electricity tariff, considering two ESS operation scenarios as described below. The optimization

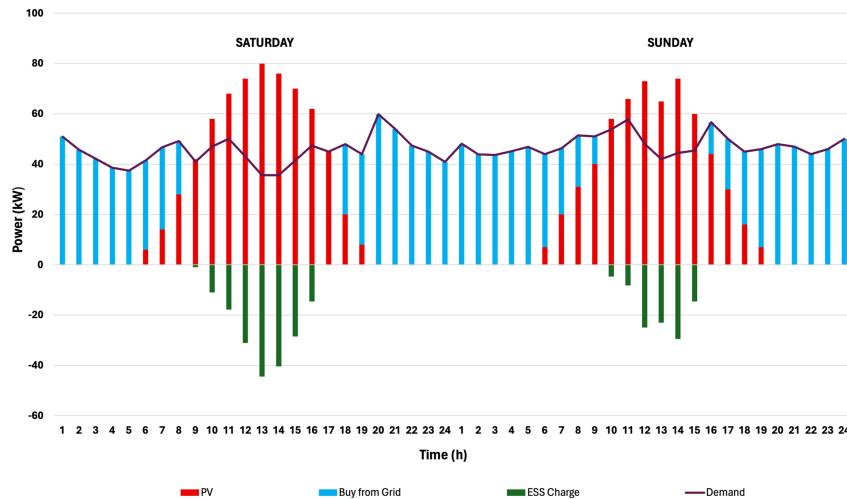
problem is solved using GAMS and CPLEX

- Scenario 1: The ESS is allowed to charge only during weekends, when the building load is relatively low and PV generation is significantly surplus.
- Scenario 2: The ESS is allowed to charge and discharge freely throughout the week.

B. Operational Scheduling under Different Scenarios

In this case, EVs act as mobile energy storage units that support the PV system during peak hours, from 7:00 am to 6:00 pm, when PV generation alone cannot fully meet the building load demand. Each EV can discharge up to 12 kWh, and the initial energy level is assumed to remain high (85–95%), as the EV owners prepare their vehicles by charging them overnight before arriving at the office in the morning. Figure 3 illustrates the operation of the building microgrid on Monday, Tuesday, and during the weekend.





(c)

Figure 3. ZEB operating schedule under PV shortage:(a) Monday, (b) Tuesday, and (c) Weekend days

In this scenario, the ESS is charged only on weekends and discharges during weekdays. Given its moderate capacity (200 kW/500 kWh), the ESS can supply power to the building only until around 7:00 am. on Monday morning Figure 3(a). At that time, the load demand is 122.92 kW, while the PV generation is only 20 kW insufficient to meet the demand thus 65.77 kW must be purchased from the grid. At 7:00 am. (i.e., the 8th hour of the day), ten EVs arrive with battery energy levels ranging from 87.7 to 92 kWh. The results in Figure 4a show that between the 8th and 12th hours on Monday, the EVs discharge power to compensate for the shortage, allowing the building to operate without purchasing electricity from the grid even though PV generation is insufficient. At 11:00 am, the building load reaches its peak at 170 kW, while PV generation provides only about 60 kW; at this point, nine EVs discharge simultaneously to meet the load. From then until the 14th hour, the EVs take turns discharging until their remaining energy decreases to the minimum allowable level of 30% of battery capacity. This ensures that the EVs retain sufficient energy to return home. Thanks to the contribution of EVs, the building does not need to purchase power from the grid again until after the 13th hour. From Tuesday through Friday, the EVs play a similar role as they did on Monday Figure 3(b). Figure 4 depicts the energy levels of the EVs while supporting the building load during PV shortages.

During the weekend, surplus PV power is used to charge the ESS. As shown in Figure 3(c), at time step 129 (9:00 am. on Saturday), the building load is 40.8 kW, and the PV output is 42 kW, allowing the ESS to charge at 1.2 kW. At time step 137 (5:00 pm), PV generation drops to 40 kW below the load demand so the ESS stops charging. Since it is scheduled to discharge only during weekdays, the ESS does not supply power on weekends, and all the building's electricity demand is met by grid purchases. By the end of Saturday, the ESS has stored 188.8 kWh and continues charging at time step 154 (10:00 am on Sunday) but remains idle until the start of the following week. Overall, the role of the ESS in this scenario is relatively limited. However, from the perspective of extending the ESS lifespan, reducing frequent charge discharge cycling is a reasonable strategy. Therefore, this scenario remains valuable for consideration in practical building operation.

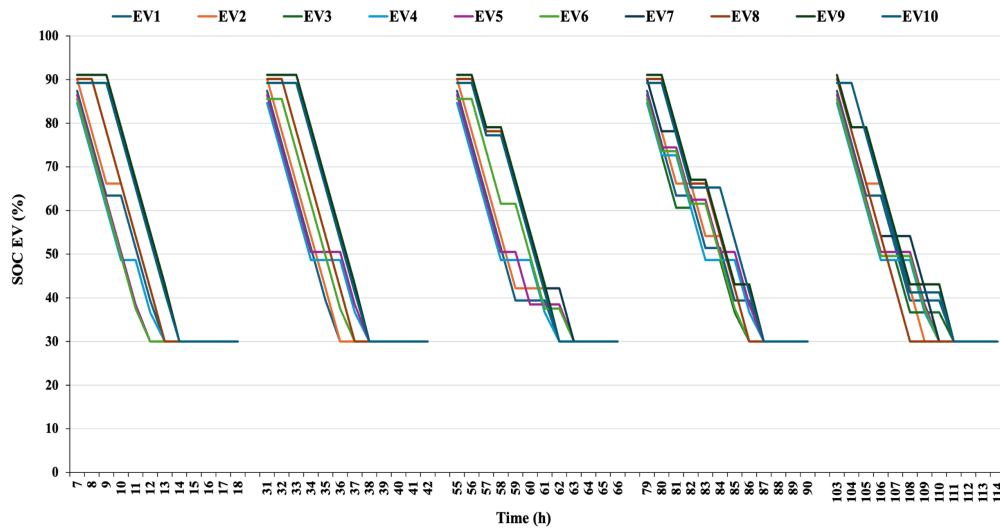


Figure 4. Energy levels of EVs connected to V2B on Monday under PV shortage

PV Generation Higher than the Building Load

Figure 5 illustrates that in the PV surplus case, the V2B contribution of the EVs becomes less significant. Specifically, from the 6th hour onward, PV generation is sufficient to supply the entire building load; therefore, the EVs do not need to discharge starting from the 7th hour. Only at the 16th hour, when the load demand reaches around 150 kW while PV generation drops to 92 kW, do the EVs begin discharging to compensate for the deficit, continuing until the 18th hour just before their departure.

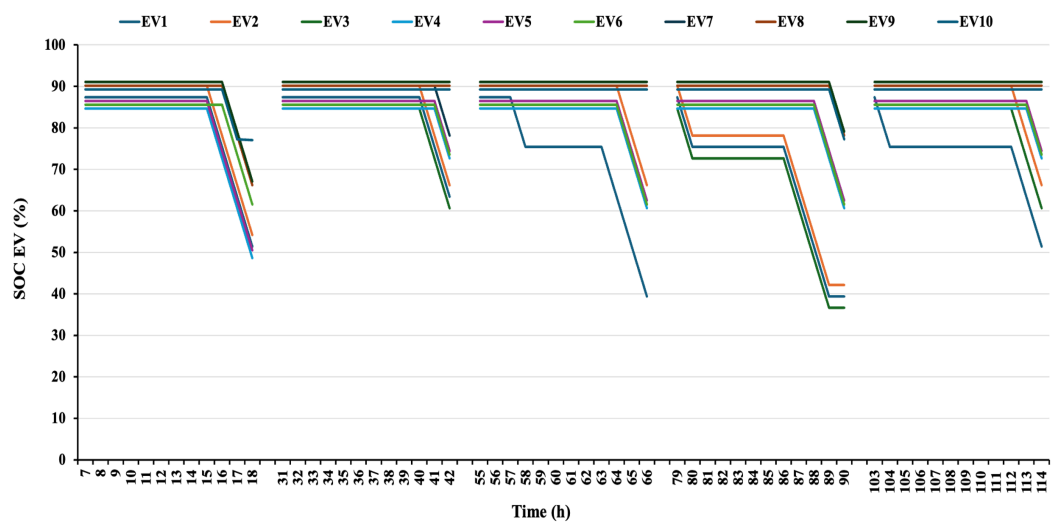


Figure 5. Energy levels of EVs connected to V2B on Monday under PV surplus

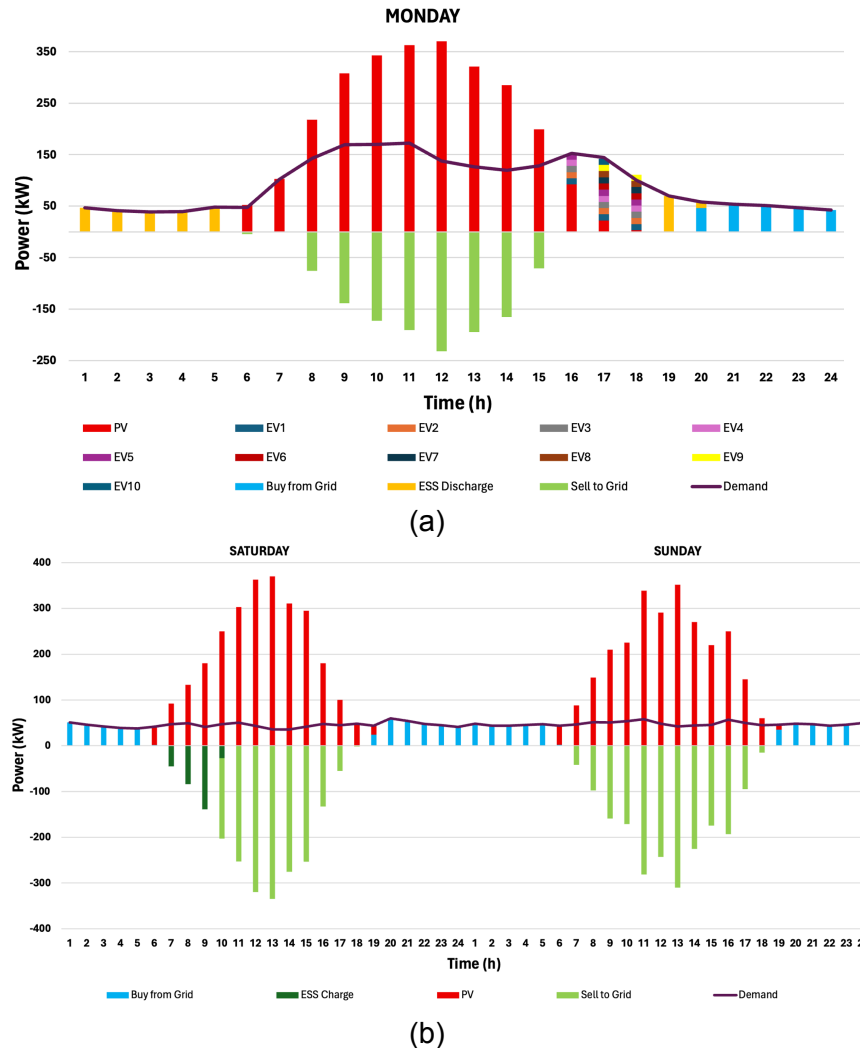


Figure 6. ZEB operating schedule under PV surplus:(a) Monday, (b) Weekend days

The surplus PV power between the 8th and 15th hours is sold back to the grid to generate additional revenue (Figure 6a). This operation pattern is repeated on other weekdays. During the weekend, as the building load decreases, part of the surplus PV power is used to charge the ESS, while the majority is exported to the grid for sale (Figure 6b).

Scenario 2 allows the ESS to charge and discharge freely throughout the week, providing greater operational flexibility compared to Scenario 1. In the PV shortage case, since the ESS capacity is relatively small, the overall operation pattern of the building microgrid does not differ significantly from that in Scenario 1. As shown in Figure 7a, the ESS supplies power to the building until 6:00 am on Monday. Subsequently, ten EVs arrive and discharge to support the load; however, the building still needs to purchase an additional 20.85 kW from the grid. During the weekend (Figure 7b), surplus PV generation is utilized to charge the ESS. In the PV surplus case, Figure 8a shows that the ESS plays a more active role in supplying electricity to the building. On Monday, the ESS discharges to support the load during the first five hours. At the 6th hour, when there is a surplus of 4.2 kW from the PV system, this energy is used to charge the ESS instead of being sold to the grid. At 10:00 am, after the ESS is fully charged, there remains 115.66 kW of surplus power, which is then sold back to the grid. At 7:00 pm, after the EVs have departed, the ESS begins discharging to supply the building load. By midnight, the ESS discharges its remaining available energy of 15.75 kWh, but since the load at that time is 42.2 kW, the building must still purchase 26.45 kW from the grid. This operational pattern repeats for the following weekdays.

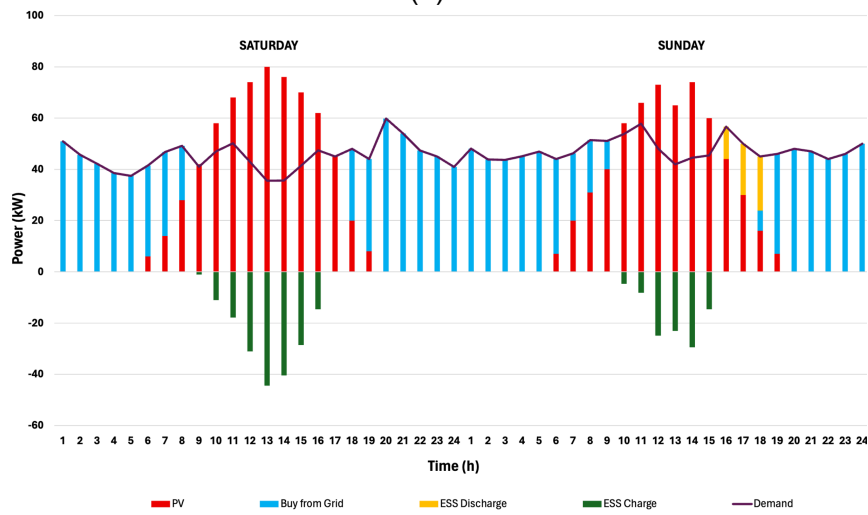
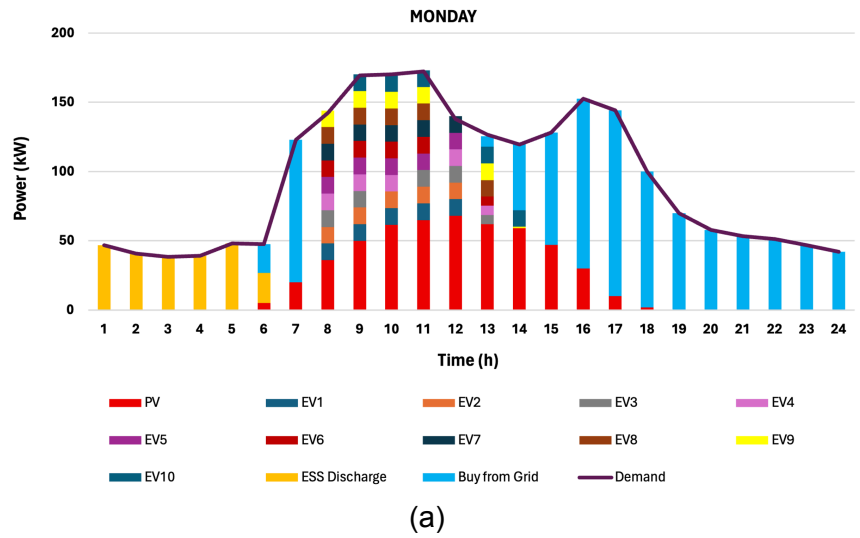
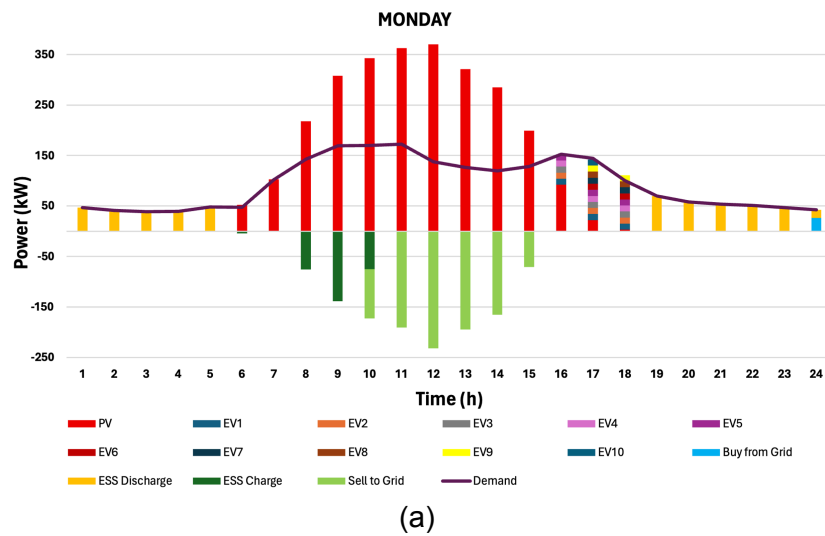


Figure 7. ZEB operating schedule under PV shortage:(a) Monday, (b) Weekend days



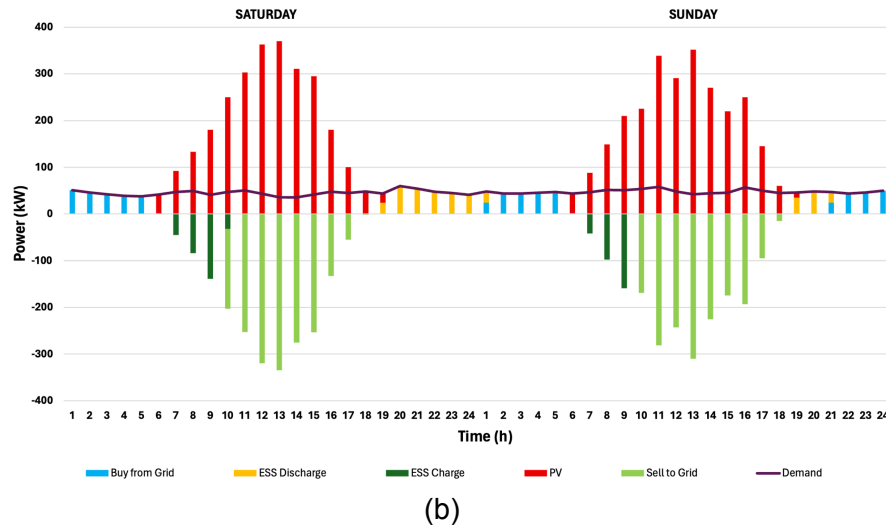


Figure 8. ZEB operating schedule under PV surplus:(a) Monday, (b) Weekend days

During the weekend, as the building load decreases, part of the PV generation is used to charge the ESS, while the remaining surplus is sold to the grid (Figure 8b). However, since the ESS becomes fully charged by 10:00 am on Sunday, it starts discharging 60 kW at 7:00 pm to prepare for the upcoming week and stops at 9:00 pm. From that point onward, all the building's electricity demand is met by purchasing from the grid. The charging/discharging behavior and energy level of the ESS under the PV surplus condition are illustrated in Figure 9.

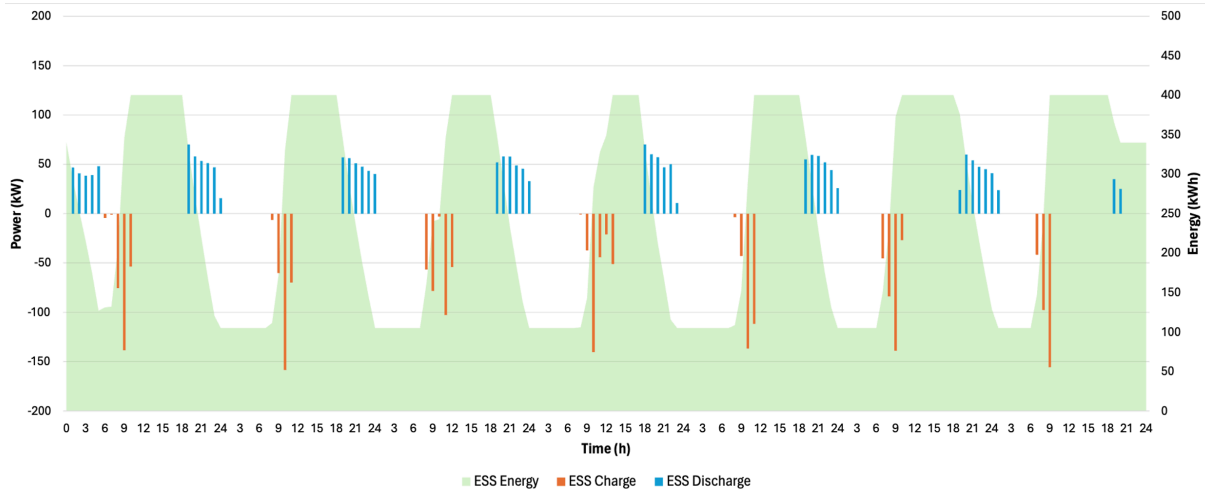


Figure 9. ESS charging/discharging power and energy level during PV surplus

C. Evaluation of the ZEB Target Considering the Operating Cost

The main objective of the optimization problem is to achieve the ZEB target, meaning that the building operates with high energy efficiency. From the perspective of grid operation, a ZEB is defined as a building whose electricity consumption from the grid is less than or equal to the amount of electricity exported back to the grid. Assuming a one-year operation consisting of 28 weeks in the dry season and 24 weeks in the rainy season (corresponding to 28 PV-surplus weeks and 24 PV-deficit weeks), the total amounts of electricity purchased from and sold to the grid are summarized in Table 2. As shown in Table 2, when the building operates under Scenario 1, the amount of self-generated energy reaches 246,889 kWh per year, which is greater than the purchased electricity of 215,034 kWh per year. Therefore,

Scenario 1 successfully achieves the ZEB objective.

Table 2. Total annual energy in each operating scenario of ESS

Energy (kWh)	Scenario 1		Scenario 2	
	Consumption	Production	Consumption	Production
PV Surplus	86254	246889	34167	191598
PV Shortage	128780	0	160547	0
Total	215034	246889	194715	191598

Assuming a one-year operation consisting of 28 weeks in the dry season and 24 weeks in the rainy season, Table 3 highlights the significant differences in operating costs between the two ESS operation scenarios under both electricity tariff options. In both scenarios, the commercial electricity tariff provides better economic performance compared to the fixed-price tariff. When considering the ESS investment cost and the number of charge/discharge cycles, Scenario 1 results in less battery degradation than Scenario 2. Combined with the ZEB objective results shown in Table 2, the optimal solution in terms of both cost efficiency and energy performance is Scenario 1 under the commercial electricity tariff.

Table 3. Annual cost in each scenario

Cost (VND)	Scenario 1		Scenario 2	
	Fixed Tariff	Tariff for Business	Fixed Tariff	Tariff for Business
PV Surplus	197007048	276380580	236355168	281635004
PV Shortage	-591693504	-517824216	-632676504	-562437000
Total	-394686456	-241443636	-396321336	-280801996

CONCLUSION

This paper has successfully developed an optimal operation model for a customer-side microgrid integrating photovoltaic (PV) generation, an energy storage system (ESS), and electric vehicles (EVs) providing Vehicle-to-Building (V2B) support for an office building. The model aims to minimize the cost of electricity purchased from the grid while enhancing the building's energy self-sufficiency. Through two ESS operation scenarios, the simulation results demonstrate that flexible utilization of distributed energy resources particularly the effective participation of EVs in the V2B scheme can significantly improve energy efficiency and reduce operating costs for the building load. The proposed model also proves its feasibility in achieving the Zero Energy Building (ZEB) objective, contributing practically to the broader Net-Zero target. The proposed optimization framework and operational strategy not only yield economic benefits but also hold strong scientific and practical significance in the context of energy transition and sustainable development. These findings can serve as a foundation for future studies on optimal operation of ZEBs and planning of distributed energy networks.

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