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Techno-Economic Optimization of a Grid-Tied Hybrid Photovoltaic–Battery System Under Vietnam Climatic Conditions

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Abstract

The rapid growth of electricity demand in Vietnam has placed increasing pressure on the national power grid, highlighting the need for efficient renewable energy utilization. This study investigates the techno-economic performance of grid-connected photovoltaic– energy storage systems (PV–BESS) under Vietnam's climatic conditions and electricity tariff structure. A detailed simulation framework is developed, incorporating PV generation, battery storage dynamics, inverter efficiency, and grid interaction. An energy management system (EMS) is implemented to coordinate power flows and evaluate three configurations: PV-only, PV+BESS, and PV+BESS with time-of-use (TOU)–based operation.

Simulation results show that integrating battery storage significantly improves renewable energy utilization, increasing the self-consumption ratio (SCR) from 0.36 to 0.62 and the self-sufficiency ratio (SSR) from 0.40 to 0.68. The TOU-based strategy enhances operational flexibility by enabling tariff-driven energy shifting; however, it may increase grid import due to scheduled charging during off-peak periods. These findings highlight the trade-off between energy efficiency and economic optimization. Overall, hybrid PV–battery systems with appropriate energy management strategies represent a technically viable and economically attractive solution for improving renewable energy utilization in Vietnam.

Keywords: Hybrid photovoltaic-battery system; Techno-economic optimization; Grid-tied system; Energy management; Vietnam

1. Introduction

The rapid growth of electricity demand driven by economic development has placed increasing pressure on power systems worldwide, particularly in developing countries such as Vietnam (Parra et al., 2017; Branker et al., 2011). Fossil-fuel-based generation still dominates the electricity mix, raising concerns regarding energy security and greenhouse gas emissions (Cucchiella et al., 2015). In response, solar PV systems have been widely promoted due to Vietnam's favorable solar irradiation conditions (Weniger et al., 2014).

Grid-connected PV systems can reduce electricity costs and emissions; however, the intermittency of solar generation and the mismatch between PV output and load demand often result in high PV energy export and low self-consumption ratios (Every et al., 2017; Han et al., 2021). BESS provides an effective solution by storing surplus PV energy and supplying electricity during periods of insufficient generation (Allwyn et al., 2022; Makhubele et al., 2025; Schmidt et al., 2017). Nevertheless, the techno-economic feasibility of PV–battery systems strongly depends on battery sizing and operational strategies (Han et al., 2021; Schmidt et al., 2017; Lai et al., 2017).

Recent studies highlight the importance of energy management strategies, particularly those incorporating time-of-use tariff structures, to achieve peak shaving and cost reduction (Mulder et al., 2013; Babacan et al., 2017; Perez et al., 2016; Khan et al., 2025). However, comprehensive analyses tailored to Vietnam's climatic conditions and electricity tariff structures remain limited (Makhubele et al., 2025; Le et al., 2025).

To address this gap, this paper proposes a techno-economic optimization framework for a grid-tied hybrid PV–battery system adapted to Vietnam's operating conditions. The framework evaluates three system configurations PV-only, PV+BESS, and PV+BESS with TOU-based operation—within a unified modeling environment.

The novelty of this study lies in the integrated evaluation of PV–battery systems under Vietnam-specific climatic conditions and electricity tariff structures. In particular, the study provides a comparative analysis of TOU-based energy management strategies, highlighting the trade-offs between energy efficiency, grid dependency, and economic performance. This approach offers new insights into the optimal operation of hybrid PV–battery systems in emerging electricity markets.

2. Methodology and System Modeling

This section describes the modeling framework of the proposed grid-connected hybrid PV–battery system. The system architecture, power balance formulation, component models, and the energy management strategy are presented in detail to evaluate the operational and economic performance of the system.

2.1. Grid-Tied Hybrid PV–Battery System Architecture

The system considered in this study is a grid-connected hybrid photovoltaic–battery (PV–Battery) system designed to operate under Vietnam's climatic conditions. The configuration integrates a photovoltaic (PV) generation unit, a battery energy storage system (BESS), power electronic converters, local AC loads, and a utility grid connection at the point of common coupling (PCC).

The PV subsystem consists of a PV array interfaced with a maximum power point tracking (MPPT) DC/DC converter to maximize solar energy extraction under varying irradiance conditions. The battery storage system is equipped with a bidirectional DC/DC converter and a battery management system (BMS), which regulates charging and discharging processes while ensuring safe operation within predefined state-of-charge (SOC) limits.

A hybrid inverter connects the DC bus to the AC bus and converts DC power from the PV array and battery storage into AC power for local consumption. The inverter operates in grid-following mode and implements active and reactive power control to maintain stable interaction with the utility grid. The AC bus supplies local loads and enables bidirectional energy exchange with the grid through a smart meter located at the PCC.

During normal operation, PV generation is prioritized to supply the local load. When PV production exceeds the instantaneous load demand, the surplus energy is stored in the battery, subject to SOC and converter constraints. Conversely, when PV generation becomes insufficient, the battery discharges to support the load demand and reduce grid import. Any remaining power imbalance is exchanged with the utility grid.

An energy management system (EMS) supervises the overall system operation by coordinating the power flows among the PV array, battery storage, and the grid interface. The EMS enforces operational constraints such as SOC limits and converter ratings while implementing control strategies aimed at maximizing PV self-consumption, reducing grid dependency, and enabling tariff-aware operation.

The overall architecture of the proposed system is illustrated in Fig. 1.

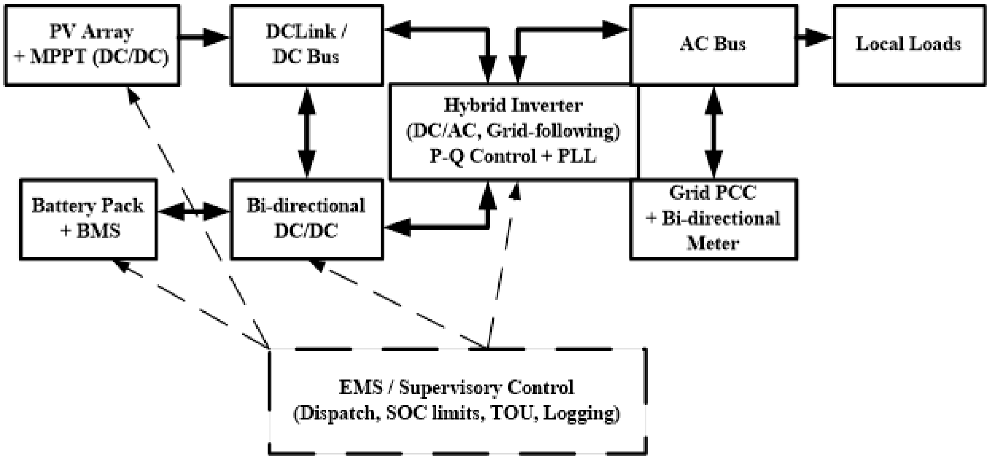

Figure 1: Architecture of the grid-connected hybrid PV–battery system with EMS and TOU-based operation

2.2. *Power Balance Formulation*

The instantaneous power balance at the AC bus is expressed as:

$$P_{pv,ac}(t)+P_{bat,ac}(t)+P_{grid}(t)=P_{load}(t) \tag{1}$$

where $P_{pv,ac}(t)$ denotes the AC-side PV power, $P_{bat,ac}(t)$ represents the battery power at the AC bus, $P_{grid}(t)$ is the power exchanged with the grid (positive for import and negative for export), and $P_{load}(t)$ is the local load demand.

This formulation ensures that the total generated and imported power equals the instantaneous load demand at each time step.

2.3. *PV Power Generation Model*

The DC output power of the PV array is modeled as a function of solar irradiance and cell temperature:

$$P_{pv,dc}(t)=P_{pv,r}\left(\frac{G(t)}{G_{STC}}\right)\left[1+\gamma(T_c(t)-T_{STC})\right] \tag{2}$$

where $P_{pv,r}$ is the rated PV capacity, $G(t)$ is the solar irradiance, G_{STC} represents the irradiance under standard test conditions, $T_c(t)$ is the PV cell temperature, T_{STC} denotes the standard test temperature, and γ is the temperature coefficient.

Considering conversion efficiencies, the AC-side PV power is expressed as:

$$P_{pv,ac}(t)=P_{pv,dc}(t).\eta_{MPPT}.\eta_{inv} \tag{3}$$

where η_{MPPT} and η_{inv} denote the efficiencies of the MPPT converter and inverter, respectively.

2.4. *Battery Model and SOC Dynamics*

The battery model considers charging and discharging efficiencies together with SOC constraints. The SOC evolution during charging and discharging modes is described as:

+ **Charging mode** ($P_{bat,dc}(t)<0$):

$$SOC(t+\Delta t)=SOC(t)+\frac{\eta_{ch}.P_{bat,dc}(t).\Delta t}{E_{bat,r}} \tag{4}$$

+ **Discharging mode** ($P_{bat,dc}(t)>0$):

$$SOC(t+\Delta t)=SOC(t)-\frac{P_{bat,dc}(t).\Delta t}{\eta_{dis}.E_{bat,r}} \tag{5}$$

where $E_{bat,r}$ denotes the nominal battery capacity, and η_{ch} and η_{dis} represent the charging and discharging efficiencies, respectively.

The battery operation is constrained within predefined SOC limits:

$$SOC_{min} \le SOC(t) \le SOC_{max} \tag{6}$$

These limits ensure safe battery operation and extend battery lifetime.

2.5. *Inverter Efficiency and Loss Model*

The inverter losses are modeled using a quadratic approximation of the output power:

$$P_{loss,inv}(t)=aP_{out}(t)^2+bP_{out}(t)+c \tag{7}$$

Accordingly, the inverter efficiency can be expressed as:

$$\eta_{inv}(t)=\frac{P_{out}(t)}{P_{out}(t)+P_{loss,inv}(t)} \tag{8}$$

This formulation enables a more realistic representation of inverter performance under varying operating conditions.

2.6. *Energy Management Strategy (EMS)*

An energy management system is implemented to coordinate the power flows among PV generation, battery storage, and grid interaction. The EMS operates at a supervisory level with a control interval of Δt.

The EMS follows a priority-based dispatch strategy:

1. PV generation is first used to supply the local load.
2. Surplus PV energy is used to charge the battery within SOC and converter limits.
3. When PV generation is insufficient, the battery discharges to support the load.
4. The grid supplies the remaining deficit or absorbs excess power.

In scenarios where time-of-use (TOU) tariffs are considered, the EMS may schedule battery charging during off-peak tariff periods to enable peak shaving during high-price periods.

Through this coordinated operation, the EMS enhances PV energy utilization, reduces grid dependency, and improves the overall techno-economic performance of the system.

The EMS decision logic can be summarized as follows:

- If Ppv > Pload: charge battery or export excess energy
- If Ppv < Pload: discharge battery or import from grid
- Under TOU: charge during off-peak and discharge during peak periods

3. Performance Indicators

To evaluate the technical and economic performance of the proposed PV–battery system, several key performance indicators are considered, including the self-consumption ratio, self-sufficiency ratio, peak reduction, and the levelized cost of energy. These indicators allow a comprehensive evaluation of energy utilization efficiency, grid dependency, and economic performance of the considered system configurations.

3.1. Self-Consumption Ratio

The self-consumption ratio (SCR) measures the fraction of the generated PV energy that is utilized locally rather than exported to the grid. It is defined as:

$$SCR = \frac{E_{pv} - E_{grid,\exp}}{E_{pv}} \tag{9}$$

3.2. Self-Sufficiency Ratio

The self-sufficiency ratio (SSR) indicates the extent to which the local electricity demand is supplied by on-site PV generation and battery storage instead of the utility grid. It can be expressed as:

$$SSR = \frac{E_{load} - E_{grid,imp}}{E_{load}} \tag{10}$$

3.3. Peak Reduction

Peak reduction evaluates the effectiveness of the energy management strategy in reducing the maximum grid import power compared to a reference configuration. The grid import power is defined as:

$$P_{imp}(t) = \max(P_{grid}(t), 0)$$

The peak reduction ratio is calculated as:

$$PR(\%) = \frac{\max_t P_{imp,ref}(t) - \max_t P_{imp}(t)}{\max_t P_{imp,ref}(t)} .100 \tag{11}$$

3.4. Levelized Cost of Energy

The levelized cost of energy (LCOE) is used to evaluate the long-term economic performance of the system by considering the total discounted costs and the total energy served over the project lifetime. It is calculated as:

$$LCOE = \frac{C_{cap} + \sum_{y=1}^{N} \frac{C_{O\&M}(y) + C_{rep}(y)}{(1+r)^y}}{\sum_{y=1}^{N} \frac{E_{served}(y)}{(1+r)^y}} . \frac{1}{k} \tag{12}$$

3.5. Simulation Scenarios

The simulation scenarios considered in this study are summarized in table 1, including three system configurations: PV-only, PV+BESS, and PV+BESS with TOU-based energy management. Each scenario represents a different operational strategy for evaluating the impact of battery storage and tariff-aware control on system performance.

Table 1: Simulation scenarios considered in this study

Case	**Configuration**	**EMS strategy**	**Grid interaction**	**Objective**
PV-only	PV + grid	MPPT only	Import/export	Baseline
PV + BESS	PV + battery	Self-consumption priority	Limited export	Increase SCR & SSR
PV + BESS + TOU	PV + battery	TOU-based EMS	Peak shaving	Cost reduction

4. Results and Discussion

4.1. System Power Flow Characteristics

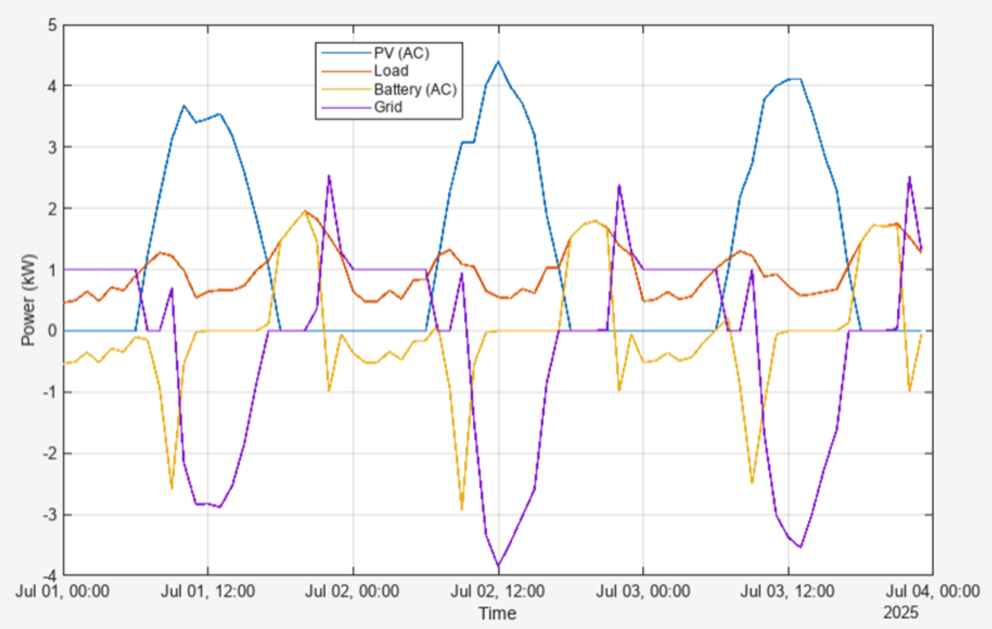

Figure 2: Typical daily power profiles of the grid-tied PV–Battery system showing PV generation, load demand, battery operation, and grid power exchange

Figure 2 illustrates the typical daily power profiles of the grid-tied PV–battery system under representative operating conditions. PV generation follows the solar irradiation pattern and reaches its peak during midday hours, while the load demand exhibits typical morning and evening peaks.

During periods of high PV generation, the local load is primarily supplied by PV power. Excess PV energy is stored in the battery or exported to the grid, depending on the battery state of charge (SOC). When PV generation decreases during evening hours, the battery discharges to compensate for the deficit, thereby reducing grid import.

These results demonstrate that the proposed EMS effectively coordinates power flows among PV generation, battery storage, and the grid while maintaining SOC within predefined operating limits.

4.2. Battery SOC Evolution and Operational Behavior

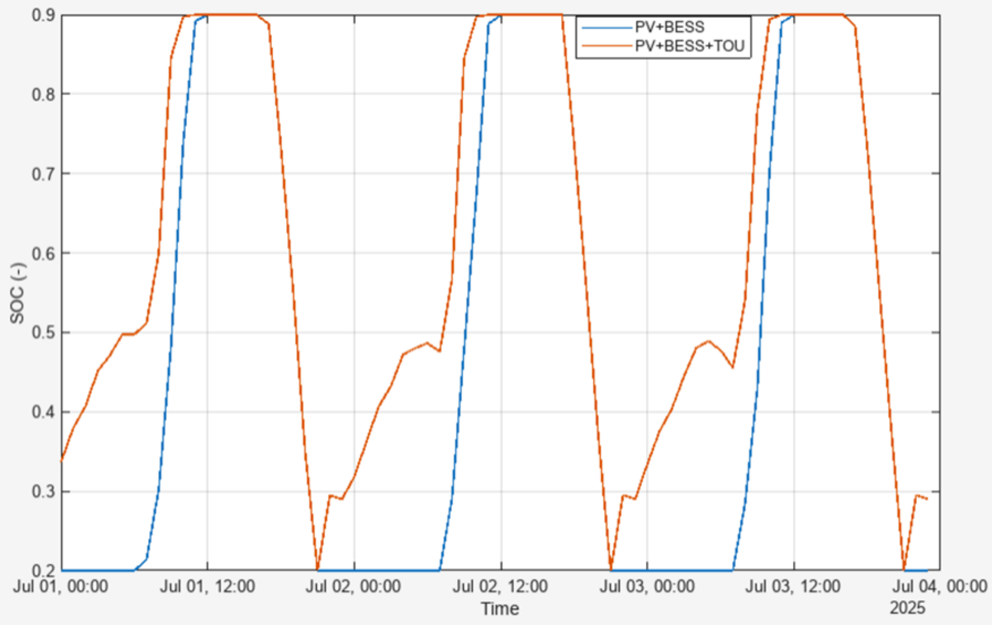

Figure 3: Battery state-of-charge (SOC) trajectories for the PV+BESS and PV+BESS+TOU configurations

Figure 3 presents the SOC trajectories for the PV+BESS and PV+BESS+TOU configurations. In the PV+BESS case, the battery is mainly charged by surplus PV energy during daytime and discharged during evening peak demand periods.

Under the PV+BESS+TOU strategy, a different operational pattern is observed. The battery is partially charged from the grid during off-peak tariff periods, resulting in higher SOC levels before peak tariff intervals. Consequently, deeper battery discharge occurs during high-price periods, which effectively reduces grid import.

In all scenarios, the SOC remains within the defined operating limits, confirming that the EMS ensures safe battery operation while enabling flexible energy shifting

4.3. Comparison of Self-Consumption and Self-Sufficiency

Table 2: Self-Consumption Ratio and Self-Sufficiency Ratio for the Three Simulation Scenarios

Case	SCR	SSR	PR pct	E_PV kWh	E_Export kWh	E_Import kWh	E_Load kWh
PV-only	0.36	0.40	0.00	9695.40	6172.20	5296.90	8820.10
PV+BESS	0.62	0.68	16.87	9695.40	3482.80	2848.00	8820.10
PV+BESS+TOU	0.63	0.69	-28.28	9695.40	4801.60	4395.30	8820.10

Table 2 summarizes the self-consumption ratio (SCR) and self-sufficiency ratio (SSR) for the three simulation scenarios.

In the PV-only configuration, the absence of storage leads to significant PV energy export, resulting in relatively low SCR (0.36) and SSR (0.40). Integrating battery storage (PV+BESS) substantially improves local utilization of PV generation, increasing SCR and SSR to 0.62 and 0.68, respectively.

The PV+BESS+TOU configuration achieves slightly higher SCR and SSR values compared to the PV+BESS case. However, the peak reduction value is negative (-28.28%), indicating that peak grid import increases due to tariff-driven charging during off-peak periods. This reflects a trade-off between peak reduction and economic optimization.

4.4. Grid Import Reduction and Peak Shaving Effect

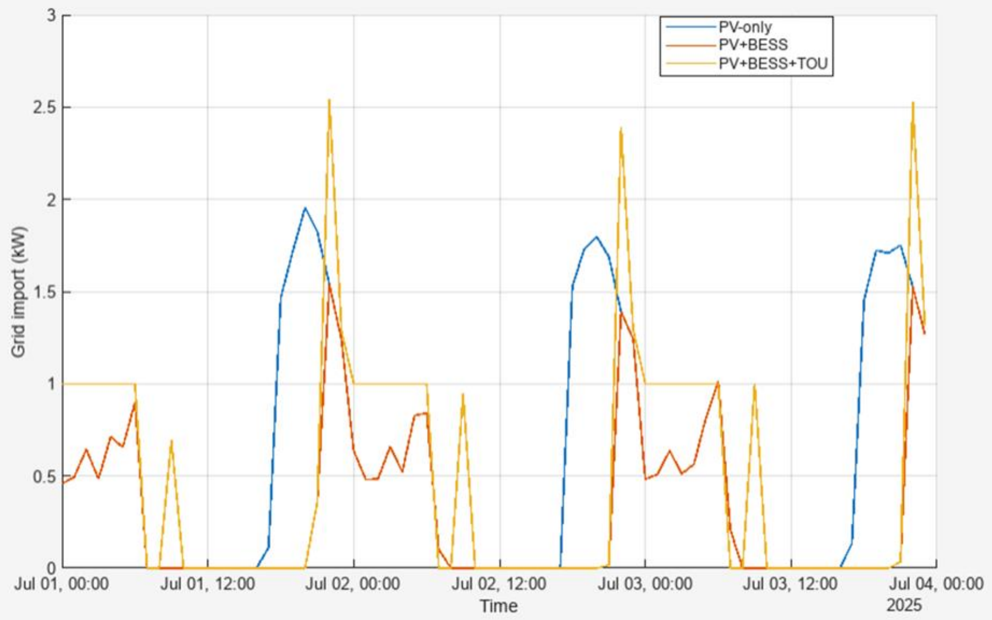

Figure 4: Hourly grid imports power profiles for the PV-only, PV+BESS, and PV+BESS+TOU configurations

Figure 4 presents the hourly grid import power profiles for the three configurations over a representative period. The PV-only case exhibits the highest grid import during evening hours when PV generation is unavailable.

The PV+BESS configuration reduces both the magnitude and duration of these peaks by discharging the battery during high-demand intervals. In contrast, the PV+BESS+TOU configuration modifies the import profile through tariff-aware operation, allowing the battery to charge during off-peak periods and discharge during peak demand intervals.

Overall, the results indicate that integrating battery storage significantly reduces grid dependency and contributes to peak-shaving capability in grid-connected PV systems.

4.5. Techno-Economic Performance and LCOE Analysis

Table 3: Techno-Economic Performance Indicators of the Three System Configurations

Case	**CAPEX** (VND)	**LCOE_net** (USD/kWh)	**SCR**	**SSR**	**Grid Import** (kWh)	**Payback** (years)
PV-only	100,500,000	0.05	0.36	0.4	5303.4	–
PV+BESS	169,050,000	0.06	0.62	0.68	2854.1	6.88
PV+BESS+TOU	169,050,000	0.07	0.63	0.69	4406.9	8.83

Table 3 summarizes the key techno-economic indicators for the three system configurations.

The PV-only system requires the lowest capital investment but exhibits limited renewable energy utilization, with SCR and SSR values of 0.36 and 0.40, respectively. Consequently, the system remains highly dependent on grid electricity.

With battery integration, the PV+BESS configuration significantly improves on-site energy utilization. SCR and SSR increase to 0.62 and 0.68, while annual grid import decreases substantially.

The PV+BESS+TOU configuration enhances operational flexibility through tariff-aware energy management. However, it does not reduce grid import compared to the PV+BESS configuration. Instead, grid import increases due to charging during off-peak periods. This strategy reflects a trade-off between economic optimization and energy independence, where cost savings may be achieved at the expense of increased grid reliance.

An exchange rate of 1 USD = 24,000 VND is used for all economic calculations.

4.6. Discussion and Practical Implications

The results reveal a fundamental trade-off between energy autonomy and economic optimization. While battery storage significantly improves SCR and SSR by increasing local energy utilization, the integration of TOU-based strategies introduces additional grid dependency due to tariff-driven charging behavior. This indicates that optimal system design should consider both technical and economic objectives simultaneously rather than focusing on a single performance metric. Furthermore, the findings suggest that TOU-based operation is more suitable for cost-oriented applications, whereas PV+BESS without TOU provides a more balanced solution for energy independence. The obtained results are consistent with previous studies (Han et al., 2021; Schmidt et al., 2017), confirming the validity and reliability of the proposed modeling framework.

Conclusion

This study presented a comprehensive techno-economic assessment of a grid-tied hybrid PV–battery system under Vietnam's climatic and tariff conditions. The results demonstrate that integrating battery storage significantly enhances system performance by improving both self-consumption and self-sufficiency ratios.

The PV+BESS configuration provides a balanced solution by reducing grid dependency while maintaining reasonable economic performance. In contrast, the PV+BESS+TOU configuration enables tariff-driven energy shifting and enhances operational flexibility; however, it does not necessarily improve economic performance in terms of LCOE and payback period due to increased grid import.

Overall, the findings highlight the importance of considering trade-offs between technical performance and economic optimization when designing hybrid PV–battery systems. The proposed framework can serve as a useful tool for evaluating and optimizing renewable energy systems under different operational and tariff conditions.

Limitations

This study is subject to several limitations. First, the analysis is based on simulation data and does not account for real-world operational uncertainties. Second, battery degradation effects are not explicitly modeled, which may affect long-term economic performance. Third, the results depend on specific load profiles and tariff structures in Vietnam, which may limit the generalizability of the findings to other regions.

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Data Availability: All data are included in the content of the paper.

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