Techno-Economic Optimization of a Grid-Tied Hybrid PV–Battery System under Vietnam Climatic Conditions

Vu Trong Tuan
Duy Tan University, Da Nang, Vietnam
Cao Hoang Kha
Nguyen Van Minh
Vinh Long University of Technology Education (VLUTE), Vietnam

Abstract

The rapid growth of electricity demand in Vietnam has increased pressure on the national power grid and highlighted the need for efficient renewable energy utilization. This study investigates the techno-economic performance of grid-connected photovoltaic–battery (PV–BESS) systems 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 further enhances operational flexibility by enabling peak shaving and tariff-aware energy shifting. As a result, grid import is substantially reduced while maintaining battery operation within safe SOC limits. The results demonstrate that hybrid PV–battery systems with tariff-aware energy management provide a technically viable and economically attractive solution for improving renewable energy utilization in Vietnam and similar tropical regions.

Keywords: Hybrid PV–Battery system; Techno-economic optimization; Grid-tied system; Energy management; Vietnam

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 photovoltaic (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). Battery energy storage systems (BESS) provide 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 (TOU) 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.

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.

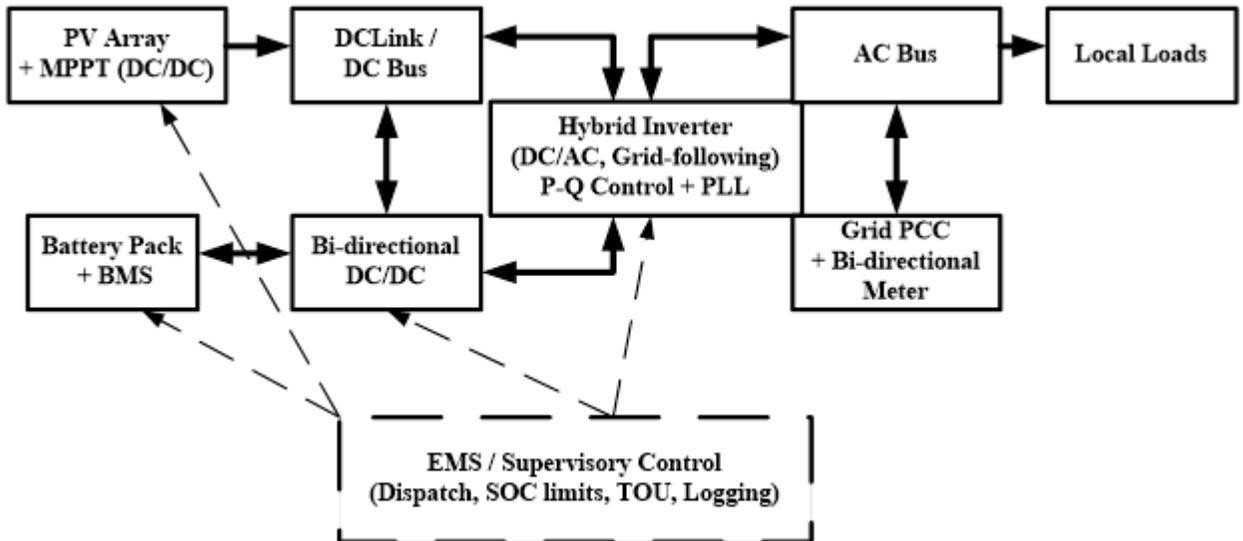The overall architecture of the proposed system is illustrated in Fig. 1.

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:

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

(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:

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

(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:

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

(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 ($P_{bat,dc}(t)<0$):

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

(4)

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

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

(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:

$$SOC_{min} \leq SOC(t) \leq SOC_{max}$$

(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:

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

(7)

Accordingly, the inverter efficiency can be expressed as:

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

(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.

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:

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

(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:

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

(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:

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

(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:

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

(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
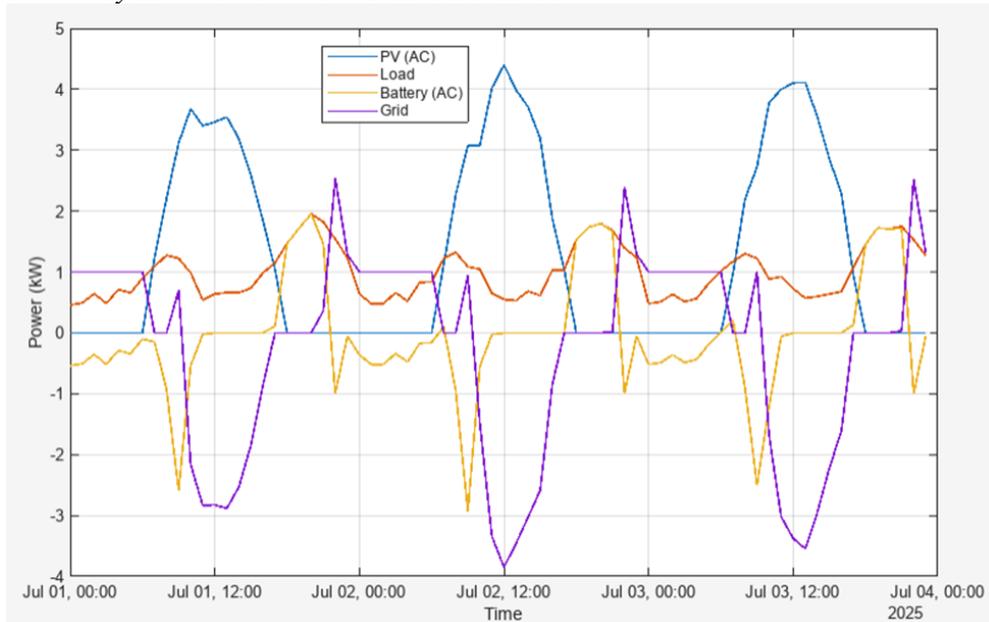
4.1.   System Power Flow Characteristics

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.

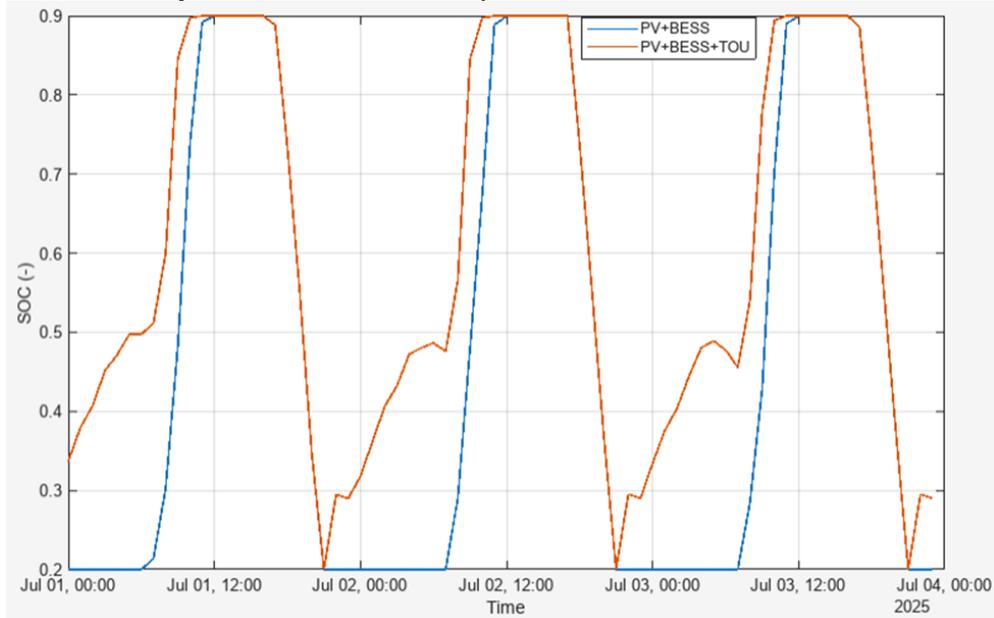## 4.2. *Battery SOC Evolution and Operational Behavior*

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	E_PV	E_Export	E_Import	E_Load
			pct	kWh	kWh	kWh	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 the highest values, with SCR and SSR reaching 0.63 and 0.69. This improvement results from the combined effect of PV energy storage and tariff-based energy shifting.

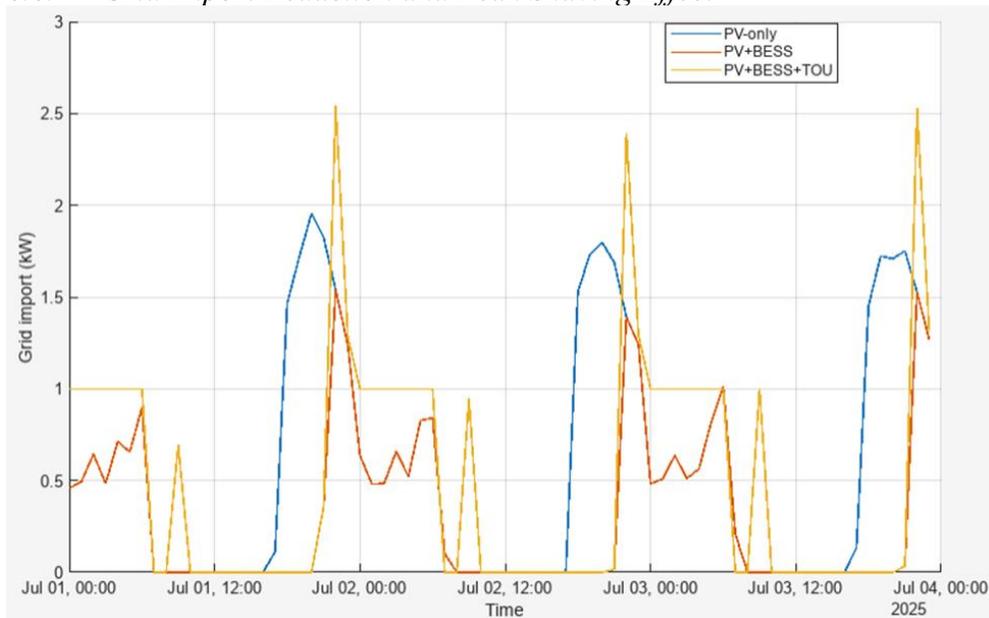*4.4.   Grid Import Reduction and Peak Shaving Effect*

Figure 4: Hourly grid import 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 further enhances operational flexibility through tariff-aware energy management. Although the initial investment is higher, the system benefits from improved PV utilization and optimized energy scheduling under time-of-use pricing.

4.6. Discussion and Practical Implications

The comparative analysis reveals several important insights. First, battery storage is essential for improving both SCR and SSR in grid-tied PV systems, especially in regions with high solar potential such as Vietnam. Second, EMS strategies that incorporate tariff information can further enhance economic performance by enabling peak shaving and energy arbitrage.

From a practical perspective, the results suggest that hybrid PV–Battery systems are particularly suitable for small commercial and residential applications with significant evening load demand. Moreover, the proposed modeling and optimization framework can be readily adapted to different tariff schemes and load profiles, making it applicable to a wide range of deployment scenarios.

Conclusion

This study presented a techno-economic assessment of a grid-tied hybrid photovoltaic–battery system under Vietnam's climatic conditions. A comprehensive system model was developed incorporating PV generation, battery storage, inverter efficiency, and grid interaction, together with an energy management strategy.

Simulation results demonstrate that integrating battery storage significantly improves system performance compared with a PV-only configuration. The PV+BESS scenario notably enhances both the self-consumption and self-sufficiency ratios by storing surplus PV energy and supplying local loads during periods of low solar generation.

Furthermore, the PV+BESS+TOU configuration achieves the most favorable operational performance by enabling peak shaving and strategic energy shifting under time-of-use tariffs.

Overall, the findings confirm that grid-connected PV–battery systems represent a technically viable and economically attractive solution for improving renewable energy utilization in Vietnam.

References:
1. Parra, D., et al. (2017). Techno-economic analysis of PV systems under different tariff schemes. *Applied Energy*.
2. Branker, K., Pathak, M. J. M., & Pearce, J. M. (2011). A review of solar photovoltaic levelized cost of electricity. *Renewable and Sustainable Energy Reviews*.
3. Cucchiella, F., D'Adamo, I., & Gastaldi, M. (2015). Economic analysis of residential photovoltaic systems. *Energy*.
4. Weniger, J., Tjaden, T., & Quaschning, V. (2014). Sizing of residential PV battery systems. *Renewable Energy*.
5. Every, J., Li, L., & Dorrell, D. G. (2017). Optimal selection of small-scale hybrid PV–battery systems. *Applied Energy*.
6. Han, X., Garrison, J., & Hug, G. (2021). Techno-economic analysis of PV–battery systems. *Energy Policy*.
7. Allwyn, R. G., et al. (2022). Optimization and techno-economic analysis of PV/battery grid-tied systems. *Energy Procedia*.

8. Makhubele, W. J., et al. (2025). Techno-economic optimization of grid-tied PV–battery systems under subtropical climate. *Sustainability*.
9. Schmidt, O., et al. (2017). Future cost and performance of lithium-ion batteries. *Energy & Environmental Science*.
10. Lai, C. S., et al. (2017). Levelized cost of electricity for hybrid renewable systems. *Renewable and Sustainable Energy Reviews*.
11. Mulder, G., et al. (2013). Operational strategies for battery storage in grid-connected PV systems. *Energy*.
12. Babacan, O., et al. (2017). Optimizing energy management of grid-connected PV–battery systems with TOU tariffs. *Applied Energy*.
13. Perez, K. X., et al. (2016). Peak shaving and load shifting using battery storage under TOU tariffs. *IEEE Transactions on Smart Grid*.
14. Khan, A. A., et al. (2025). Techno-economic-environmental analysis of grid-tied hybrid renewable systems. *Discover Sustainability*.
15. Le, P. T., et al. (2025). Economic and technical analysis of hybrid PV systems in Vietnam. *Journal of Technical Education*.