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Research article

Techno-Economic Assessment of Solar Rooftop Photovoltaic with Battery Energy Storage System towards Net-Zero Energy Building: A Case Study of the Faculty of Nursing, Thaksin University, Thailand

Chana Chancham[1], Sonphol Chiwamongkhonkarn[2], Sakrapee Khunphet[3], Fida Ali[2], Yves Gagnon[4], and Jompob Waewsak[2*]

[1] International College, Thaksin University, Songkhla Campus, Songkhla, 90000, Thailand
[2] Faculty of Engineering, Thaksin University, Phatthalung Campus, Phatthalung, 93210, Thailand
[3] Faculty of Industrial Technology, Nakhon Si Thammarat Rajabhat University, Nakhon Si Thammarat, 80280, Thailand
[4] Université de Moncton, Edmundston, New Brunswick, Canada
* Correspondence: jompob@tsu.ac.th

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Abstract: The transition toward low-carbon and energy-resilient infrastructure has intensified interest in Net-Zero Energy Buildings (NZEBs) across Thailand. This study assesses the technical and economic feasibility of achieving NZEB operation at the Faculty of Nursing, Thaksin University (Phatthalung Campus) through the integration of rooftop and carport solar photovoltaic (PV) systems with a battery energy storage system (BESS). A total of 941.2 kWp of PV capacity and a 3.072 MWh BESS were modeled in PVsyst using hourly simulations based on local meteorological conditions and measured building load data. The simulations quantified energy production, performance ratio, loss mechanisms, grid exchange, and battery dispatch. The hybrid system produced approximately 969 MWh annually, fully offsetting the building's annual electricity consumption and reducing grid imports to nearly zero in most months. A discounted cash-flow analysis was performed using a 70:30 debt–equity structure, Thai time-of-use (TOU) tariffs, and cost assumptions aligned with current national benchmarks for PV and BESS deployment. The results indicate strong economic feasibility, with a benefit–cost ratio greater than one, positive net present value (NPV), an internal rate of return (IRR) exceeding the 7% discount rate, and a competitive levelized cost of electricity (LCOE) relative to commercial tariffs. The BESS improved load matching, reduced on-peak grid demand, and enhanced system reliability. Overall, the findings demonstrate that the proposed PV–BESS configuration enables both technical self-sufficiency and financial viability, offering a replicable pathway for NZEB implementation in university campuses and other institutional buildings in tropical regions.

Keywords: Solar rooftop PV; battery energy storage system; net-zero energy building; techno-economic assessment

1. Introduction

The building sector remains one of the largest energy-consuming and carbon-emitting domains globally, accounting for roughly 30–40% of total final energy use and nearly one-quarter of anthropogenic CO_2 emissions [1]. In the accelerating efforts to mitigate climate change and meet carbon-neutrality

commitments, Net-Zero Energy Buildings (NZEBs) have become a vital component of sustainable development strategies. An NZEB is designed to balance its energy demand with on-site renewable energy generation, achieving a net-zero or near-zero operational energy balance while significantly reducing greenhouse gas (GHG) emissions [2].

Globally, NZEBs have transitioned from conceptual frameworks to practical implementations, driven by national policies such as the Energy Performance of Buildings Directive (EPBD) in the European Union, and by declining photovoltaic (PV) and battery costs coupled with advances in building-energy management systems [3,4]. However, the realisation of net-zero operation is not solely a technical challenge—it is equally a question of economic feasibility and long-term financial sustainability. While renewable technologies such as solar PV and battery energy storage systems (BESS) can technically achieve energy self-sufficiency, their practical adoption in NZEBs depends on achieving favourable lifecycle economics. Recent studies emphasise that NZEB design must integrate energy, environmental, and financial performance metrics, including uniform annual cost, payback period, and levelized cost of electricity (LCOE) to ensure both technical effectiveness and economic viability [5,6].

Despite substantial progress, economic realism remains underrepresented in NZEB research. Most existing studies emphasise energy design optimisation or deterministic simulations, while fewer integrate detailed techno-economic evaluation combining technical performance with financial viability [7]. For instance, [6] conducted a comprehensive energy–economic–environmental (E^3) assessment of a building-integrated photovoltaic–thermoelectric system with battery storage. Their study incorporated indicators such as uniform annual cost, payback period, and cost of electric power saving, providing a balanced view of energy and financial performance but without long-term financial metrics such as net present value (NPV) or internal rate of return (IRR). Similarly, Furukakoi et al. [8] developed a combined planning–operation model for university campuses integrating PV and BESS, achieving reductions in both electricity cost and CO_2 emissions; however, long-term investment risk and tariff sensitivity were only partly addressed. At the smaller scale, Chaichana et al. [9] implemented a hybrid PV–hydropower–battery system for a rural Thai school, reducing diesel usage by over 95% and achieving near-net-zero energy performance, but without a quantitative assessment of economic feasibility.

These studies collectively highlight a recurring limitation: the economic aspect of NZEB design, especially for hybrid PV-BESS systems in institutional or campus buildings, remains insufficiently investigated. This gap is significant because achieving a net-zero energy balance does not necessarily guarantee cost-effectiveness. Capital expenditure (CAPEX), operational expenditure (OPEX), maintenance costs, tariff structures, and discount rates all influence whether an NZEB is financially viable beyond initial pilot or demonstration projects [9,10]. Without integrated techno-economic frameworks that combine detailed energy simulation with real tariff and cost data, NZEB deployment may stay confined to experimental or policy-driven examples rather than scalable solutions.

Furthermore, such an integrated assessment is particularly critical for institutional and campus-scale buildings, which fundamentally differ from conventional residential or commercial structures. University campuses typically exhibit complex, mixed-use load profiles driven by teaching, research, and auxiliary facilities, with pronounced daytime electricity demand that aligns favorably with photovoltaic (PV) generation [11, 12]. Despite this technical synergy, campuses face significant constraints related to land availability, regulatory requirements, and capital budgets, necessitating careful trade-offs between energy self-sufficiency and economic performance [13]. Recent studies further demonstrate that optimising PV-BESS systems at the campus scale introduces additional technical–economic trade-offs, including system sizing, storage capacity, and cost–benefit balance, which are not captured in single-building analyses [14]. Consequently, a detailed, site-specific assessment that jointly evaluates technical performance and financial feasibility is essential for developing robust, investment-ready NZEB models for university campuses.

Thailand offers an ideal setting for such an investigation. The country's average solar irradiation exceeds 4.5 kWh m^{-2} day^{-1}, and its national plans, particularly the Alternative Energy Development Plan (AEDP 2018–2037) and the Power Development Plan (PDP 2023–2037), explicitly support distributed solar generation and energy-storage integration [15]. Nevertheless, most institutional buildings in Thailand are still

reliant on the grid, with renewable self-consumption rates below 40%, due to limited battery deployment and tariff-driven restrictions. Universities, with their predictable daytime loads and ample roof and carport space, present a promising opportunity to demonstrate the technical and financial feasibility of NZEB operation within real-world market conditions.

In parallel, several recent techno-economic assessments of rooftop PV in Thailand have relied on PVsyst as a standard tool for simulating long-term energy yield, performance ratio, and loss mechanisms using high-quality meteorological data. Khamharnphol et al. [16] modelled a 100 kWp bifacial rooftop PV system for five hospitals in central southern Thailand in PVsyst (with Meteonorm 7.3 inputs) and then evaluated benefit–cost ratio (BCR), net present value (NPV), internal rate of return (IRR), payback period (PBP) and levelized cost of electricity (LCOE) under self-consumption, FiT and PPA schemes. At the campus scale, Leeabai et al. [17] simulated a 207 kWp rooftop PV system for an educational facility in Bangkok using PVsyst 7.1 and combined the simulated energy yield with a discounted-cash-flow analysis to estimate NPV, IRR, payback time and carbon emission reductions. Similar simulation-driven approaches have been applied to hybrid generation systems; for instance, Khamharnphol et al. [18] optimised a 10 MW PV–wind–diesel–BESS microgrid for Koh Samui, southern Thailand, using HOMER Pro, selecting scenarios based on net present cost, LCOE and renewable fraction. Building upon this body of work, the present study uses PVsyst to evaluate the technical performance of a rooftop-carport PV system with a BESS, paired with a comprehensive discounted cash-flow model to determine whether NZEB operation is feasible under realistic university tariff and financing conditions.

Against this context, the present study conducts a comprehensive techno-economic assessment of a hybrid solar energy system comprising conventional rooftop-mounted PV arrays and carport-mounted PV arrays integrated with a battery energy storage system (BESS) at the Faculty of Nursing, Thaksin University (Phatthalung Campus), Thailand. The system aims to meet annual energy needs while reducing grid imports and lifecycle costs. Hourly energy simulations based on real weather and load data review PV generation, losses, and storage dispatch, while financial modelling incorporates local costs, tariff schemes, and system lifespans to calculate NPV, IRR, LCOE, and payback period. By bringing financial realism into NZEB evaluation, this study seeks to close the gap between technical possibility and economic practicality, contributing to both academic knowledge and policy development. The results offer insights that are adaptable for institutional facilities and policymakers aiming for cost-effective decarbonisation pathways in the education and public sectors. Ultimately, this work aspires to push NZEB research toward more investment-ready frameworks that achieve not only net-zero operational energy but also sustainable financial outcomes.

The rest of this paper is organised as follows: Section 2 details the system design, data sources, and methodology; Section 3 presents the simulation results and economic analysis; and Section 4 concludes with key findings, policy implications, and recommendations for future NZEB initiatives.

2. Materials and Methods

2.1 Study Site Description

The study was conducted at the building of the Faculty of Nursing, Thaksin University (Phatthalung Campus), Thailand. The building is a multi-story educational facility characterised by high daytime occupancy due to academic activities, administrative operations, and laboratory use. These operational characteristics make the building highly compatible with solar energy generation, which also peaks during daytime.

A perspective view of the building is shown in Figure 1, highlighting the roof area used for solar PV installation and the adjacent open spaces suitable for constructing solar carports. The geometry, height, and structural layout of the building informed the design constraints for module placement, tilt angle, and roof accessibility.



Figure 1. Perspective of the building of the Faculty of Nursing of Thaksin University (Phatthalung Campus), Thailand.

2.2 Load Profile Characterisation

A detailed understanding of the building's electricity consumption was essential for accurately sizing the rooftop PV system and battery energy storage system (BESS). Therefore, the load profile of the Faculty of Nursing building was analysed using hourly electricity consumption data over an entire year, allowing the identification of daily operational patterns, seasonal variations, and peak-demand requirements that directly inform system design.

The short-term load behaviour is illustrated in Figure 2, which presents a detailed 7-day power-demand profile from 7–13 March 2025. The green shaded area represents the total building demand, while MDB1 and MDB2 curves highlight the distribution of load across the two main distribution boards. The building exhibits a clear daytime-dominant consumption pattern, with demand frequently rising to 80–120 kW during working hours (08:00–17:00) due to increased use of air-conditioning, lighting, and academic activities. During nighttime (after 18:00), demand drops significantly to 10–30 kW, reflecting minimal occupancy. Cyclic variations and sharp peaks indicate cooling system operation and intermittent equipment usage, characteristic of educational facilities with fluctuating daytime occupancy.

The corresponding annual consumption pattern is shown in Figure 3, which depicts monthly energy use across MDB1, MDB2, and the total (MDB1+MDB2) building consumption. Total monthly electricity usage ranges from approximately 22,000 to 53,700 kWh, driven by seasonal temperature variations, academic schedules, and building utilisation. Higher consumption during the hotter months (May–Sept) results from increased cooling loads, while lower usage from October to April reflects reduced air-conditioning demand. MDB1 consistently accounts for a larger share—typically 55–65% of the total—indicating that major operational areas such as classrooms, laboratories, and administrative spaces are primarily fed through this distribution board. This long-term load profile provides the baseline for determining the PV system capacity and BESS sizing necessary to achieve net-zero annual energy balance.

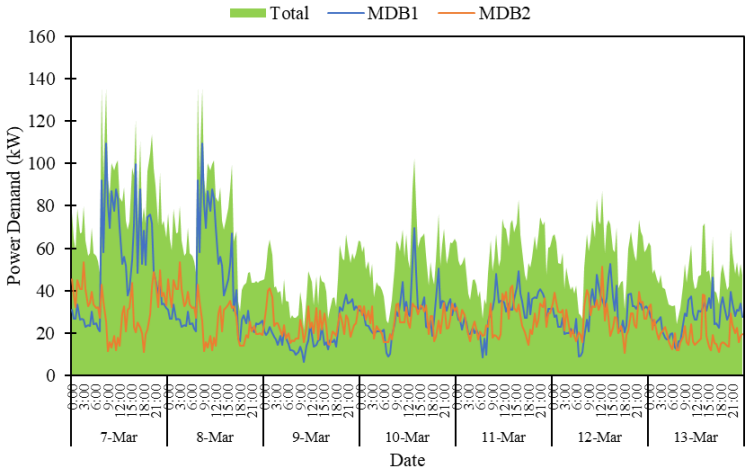


Figure 2. Daily variation and peak demand of a Faculty of Nursing building.

2.3 PV and BESS System Specifications

Table 1 summarises the complete technical specifications of the rooftop and carport solar PV systems integrated with a BESS designed for the Faculty of Nursing building at Thaksin University (Phatthalung Campus). The rooftop PV installation consists of 28 strings of 18 modules connected in series (totaling 504 modules), mounted on the south-facing roof at a fixed tilt angle of 7°, resulting in an installed capacity of 287.28 kWp and interfaced with two 125-kW inverters. Solar Carport 1 comprises 45 strings of 17 modules (765 modules), also oriented south at a 7° tilt, providing a capacity of 436.05 kWp and connected through three 125-kW inverters. Solar Carport 2 includes 12 strings of 15 modules (180 modules) mounted on a north-facing carport structure at a 7° tilt, delivering 102.6 kWp through two 40-kW inverters. Together, the rooftop and carport systems integrate 1,449 PV modules, contributing a total PV capacity of 941.2 kWp.

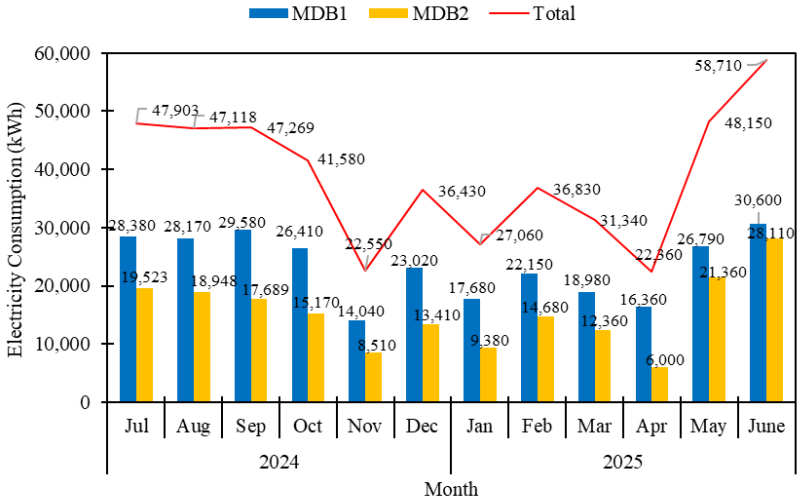


Figure 3. The electricity consumption of a Faculty of Nursing building for one year.

To enhance energy autonomy and support peak-load management, the system incorporates a 3.072 MWh BESS configured as 2 cells in series and 150 units in parallel. This configuration enables sufficient storage to capture excess solar energy during daytime and discharge during evening and peak-tariff periods, thereby reducing grid imports and improving system reliability. The combined PV–BESS configuration ensures stable operation of the hybrid renewable energy system and forms the backbone of the proposed net-zero energy strategy for the building.

The BESS capacity was selected based on the temporal energy balance between the simulated PV generation and the measured hourly electricity demand of the building rather than by adopting a predetermined PV-to-storage ratio. The sizing criterion was to provide sufficient storage for absorbing daytime PV surplus and shifting the stored energy to evening, low-generation, and peak-tariff periods, thereby reducing grid dependence and supporting the annual net-zero energy objective. Sensitivity simulations with different storage capacities indicated a progressive reduction in grid-imported energy as BESS capacity increased, with grid imports approaching zero in most months at approximately 2–3 MWh of storage. Based on these results, a nominal BESS capacity of 3.072 MWh was adopted together with 941.2 kWp of PV, corresponding to a storage-to-PV ratio of approximately 3.26 kWh/kWp. The selected capacity should therefore be interpreted as a case-specific design configuration that provides a high degree of energy autonomy for the investigated building rather than as a universally optimal PV: BESS ratio.

2.4 Energy Simulation Model

The technical performance of the rooftop and carport PV systems with BESS was simulated using the PVsyst software package, which is widely employed for the design and assessment of grid-connected PV plants and has been used extensively in Thai rooftop PV studies. The model was configured as a grid-connected system with DC-coupled battery storage, using hourly meteorological data representative of Phatthalung province and the detailed PV and inverter configurations in Table 1. PVsyst computes the energy balance from global horizontal irradiance through transposition to the tilted plane, optical and thermal losses, array and inverter efficiencies, and BESS charge–discharge behaviour, providing monthly and annual indicators such as normalized energy yield, performance ratio and loss diagram. These outputs form the basis of the results on the seasonal energy production, performance ratio, energy flows between PV, battery and grid, and cumulative loss structure of the proposed NZEB system, presented in Section 3. By relying on an industry-standard PV simulation environment, the study ensures that the energy-yield estimates are consistent with best practices for rooftop and carport PV-BESS design in tropical climates.

The reliability of the PVsyst simulation was assessed through input-data verification and physical-consistency checks of the simulated outputs. The electricity-demand profile used in the model was derived from measured hourly consumption data for the Faculty of Nursing building, thereby ensuring that the simulated PV–BESS operation reflected the actual temporal characteristics of the building load. The measured load profile was examined for completeness, temporal consistency, and agreement with the corresponding monthly electricity consumption.

Meteorological data used in PVsyst were also examined for consistency with the climatic characteristics of Phatthalung Province. The resulting PV simulation outputs were evaluated using key performance indicators, including annual energy production, specific energy yield, performance ratio (PR), and the PVsyst loss diagram. Particular attention was given to the consistency of the simulated energy balance among PV generation, direct self-consumption, battery charging/discharging, grid import, and grid export.

Since the proposed rooftop–carport PV–BESS system has not yet been fully commissioned, measured PV generation and battery-operation data were not available for direct statistical validation of the simulated outputs. Therefore, the present validation should be regarded as a model-consistency and input-data verification approach rather than a direct measurement-based validation. Future work will validate the model using measured irradiance, PV power output, battery state of charge, and grid-exchange data after system commissioning.

2.5 Spatial Layout and Structural Design of the PV and BESS Systems

The spatial distribution of the rooftop PV arrays, solar carport systems, and the battery energy storage system (BESS) is illustrated in Figure 4. The rooftop installation consists of 504 south-facing modules positioned on the central building, while two dedicated carport systems containing a combined 945 modules are located in the adjacent open parking area. The containerised BESS, with a total storage capacity of 3.072 MWh, is positioned between the rooftop and carport arrays to minimise cable lengths and facilitate efficient integration with the AC distribution network. This layout ensures optimal land use, reduces shading losses, and provides straightforward access for operation and maintenance activities.

Table 1. Description of solar PV rooftop and solar carport systems for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

System	No. of Strings/Units	Orientation	Tilt Angle	No. of Module	kWp	Inverter
Solar PV Rooftop	28 x 18 in series	S	7°	504	287.28	125 kW x 2
Solar Carport 1	45 x 17 in series	S	7°	765	436.05	125 kW x 3
Solar Carport 2	12 x 15 in series	N	7°	180	102.6	40 kW x 2
Battery Energy Storage System (BESS)	2 in series 150 in parallel	-	-	-	3.072 MWh	-
Total				1,449		941.2

The internal structure of the BESS is a hierarchical assembly from individual cells to blocks, battery modules, rack-level systems, and the final containerised pack. This modular configuration provides high energy density and enables efficient thermal management, safety protection, and simplified electrical interconnection. The container integrates monitoring, communication, fire-suppression, and environmental control systems necessary for reliable long-term storage operation.

Figure 5 expands on the mechanical design of the solar carport system, showing the top-view layout, structural framing, and PV module mounting configuration. The engineering drawings detail column spacing, beam alignment, module rows, and fastener specifications, while the 3D representations demonstrate the final structural form of the carport. This design supports both vehicular shading and efficient PV deployment, ensuring adequate airflow beneath the modules, structural integrity under local wind conditions, and optimal tilt and azimuth for solar energy capture.

Together, the spatial layout and structural design shown in Figures 4 and 5 demonstrate how the PV arrays and BESS are physically integrated on the site to support efficient power generation, storage, and reliable operation of the proposed net-zero energy system.

2.6 Electrical Architecture and System Integration

The overall electrical configuration of the hybrid solar PV and BESS is illustrated in Figure 6, which presents the complete single-line diagram used for system integration, protection design, and operational modelling. The rooftop PV systems, Solar Carport 1 and Solar Carport 2, are each connected to dedicated DC combiner boxes, where individual strings are aggregated before feeding their respective unidirectional DC/DC solar charge controllers. These charge controllers regulate PV generation and ensure safe operation of the DC bus under varying irradiance and load conditions. The BESS unit is interfaced through a bidirectional DC/DC converter that manages both charging from PV surplus and discharging during periods of insufficient generation or peak-load demand. All PV subsystems and the BESS share a common 1,000 V DC bus, which then connects to three unit substations equipped with Huawei inverters: two 125-kW inverters for the rooftop PV, three 125-kW inverters for Solar Carport 1, and two 40-kW inverters for Solar Carport 2. These inverters convert DC power into 400 V AC, which is fed into the building's electrical network via Distribution Board Solar No. 1 and Distribution Board Solar No. 2.

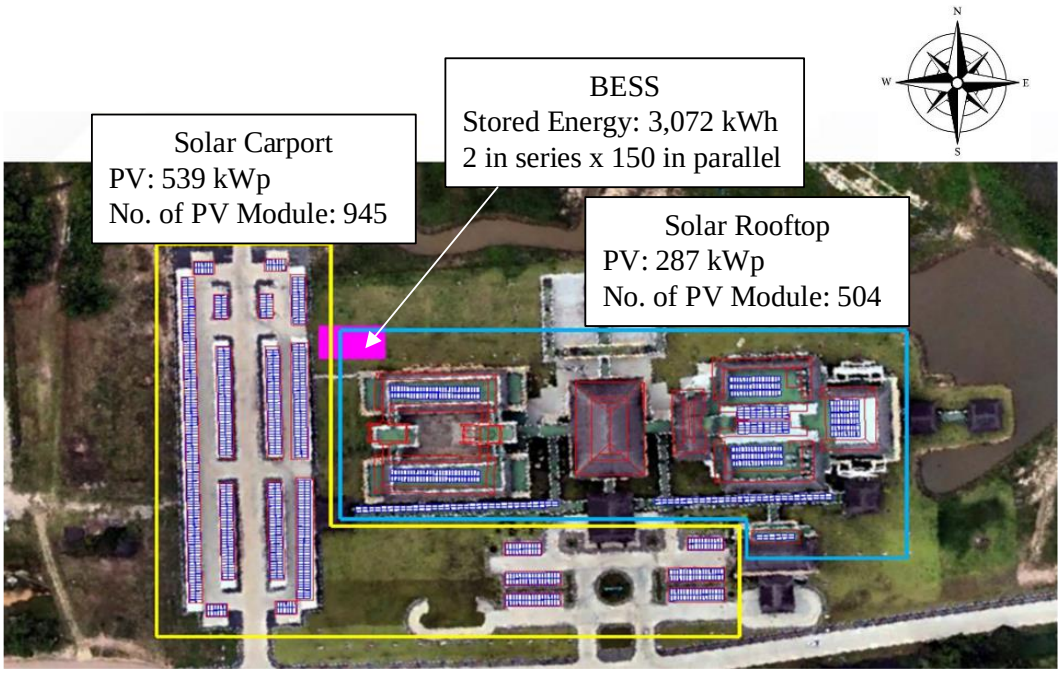


Figure 4. Top view of solar PV rooftop and solar carport systems with a BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

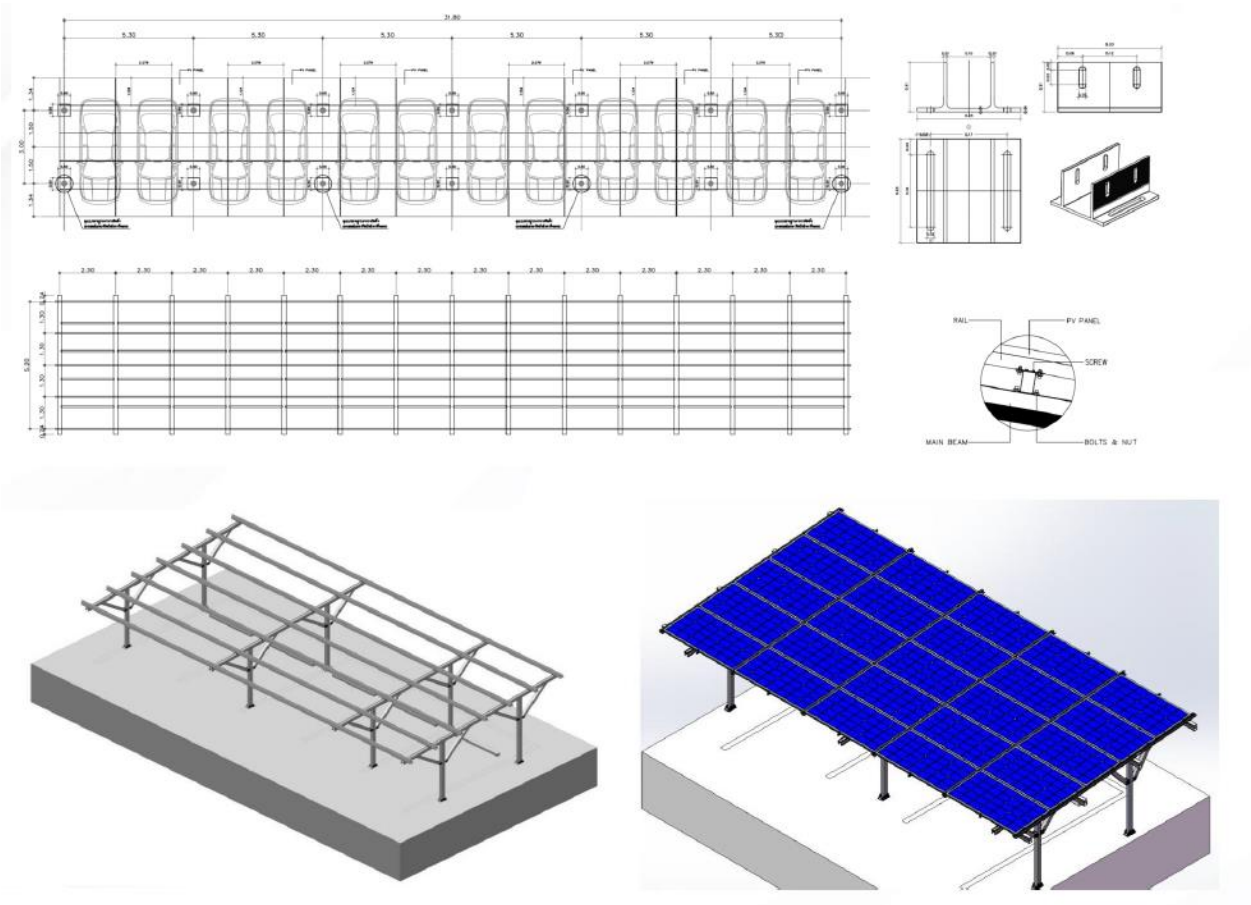


Figure 5. Top view of a solar PV carport with a BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

Protection devices such as circuit breakers, fuses, surge protectors, and current transformers are installed at key nodes to safeguard the system against overcurrent, voltage fluctuations, and external disturbances. The system also incorporates an Internet of Things (IoT)-based monitoring and smart-logger platform that enables real-time supervision of PV generation, BESS operation, inverter performance, and power exchange with the grid. Communication is supported by a LAN/WiFi router integrated with the monitoring unit, facilitating data collection for both simulation validation and operational diagnostics. This configuration ensures that the PV–BESS hybrid system operates safely, efficiently, and reliably, while enabling seamless interaction between the generation system and the building's main distribution boards (MDB1 and MDB2). The single-line architecture in Figure 6 served as the primary reference for electrical sizing, system simulation, and performance analysis conducted in subsequent sections of the study.

2.7 Economic Analysis

The economic viability of the proposed PV–BESS NZEB system was evaluated using a discounted cash-flow framework, consistent with recent techno-economic studies of utility-scale wind, 100 kWp rooftop PV, and 1 MW university PV systems in Thailand. The analysis combines detailed capital and operating cost assumptions (Figure 7 and Table 2) with simulated annual energy production from PVsyst and current time-of-Use (TOU) electricity tariffs for the Provincial Electricity Authority (PEA).

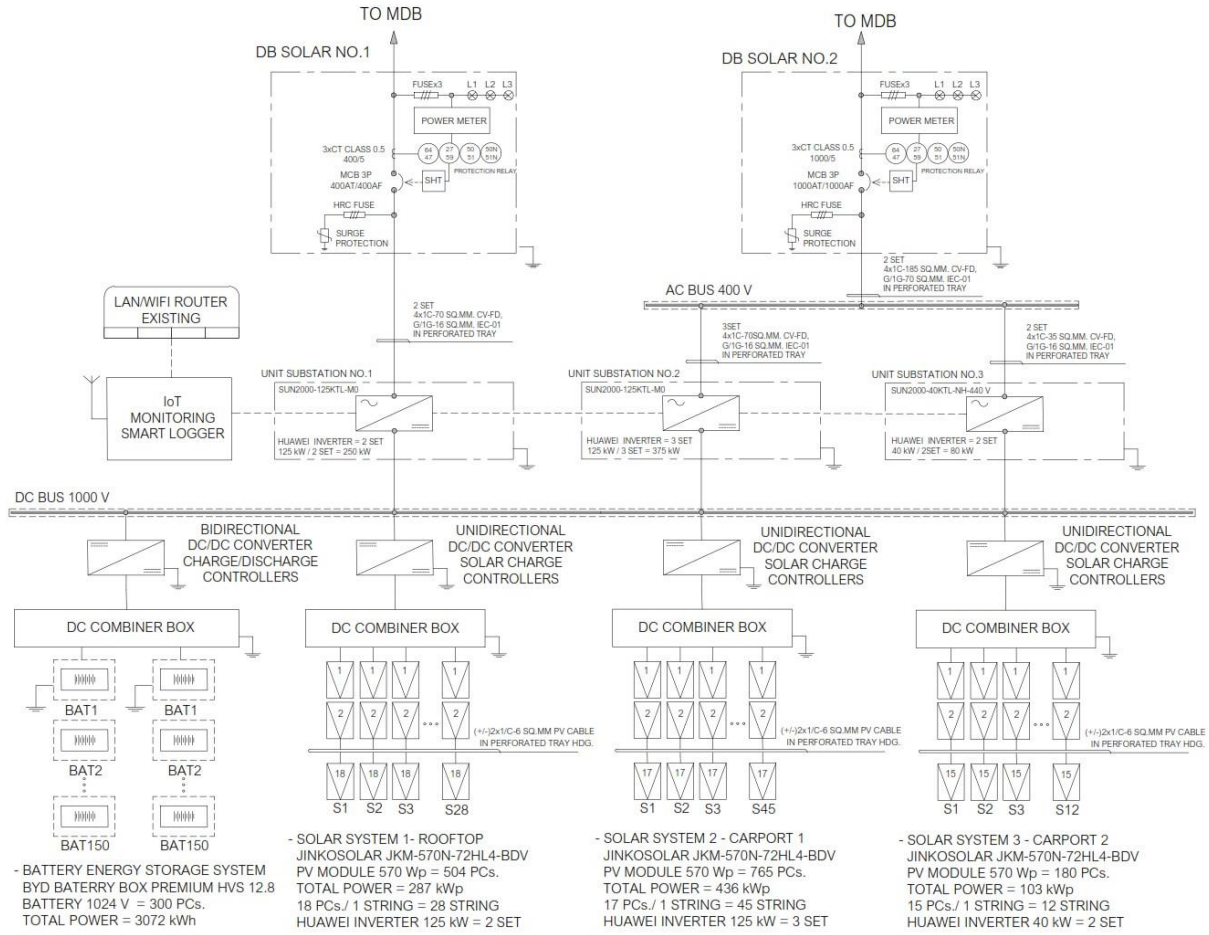


Figure 6. Single-line diagram of a solar PV rooftop and carport with a BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

2.7.1 Cost Structure and Financial Assumptions

The total capital expenditure (CAPEX) includes PV modules, inverters, mounting structures, balance-of-system components (cabling, combiner boxes, protection devices and monitoring equipment), civil works, engineering and permitting, as well as the BESS. As summarised in Figure 7, the BESS represents roughly 55%

of total investment, while the rooftop and carport PV subsystems contribute the remaining 45%, reflecting the high cost share of large-scale lithium-ion storage in hybrid PV–BESS projects.

Table 2 consolidates the key economic and financial parameters used in the analysis. The installed cost of the PV system was set at 19 MTHB/MWp, and the BESS cost at 7 MTHB/MWh, values consistent with recent Thai benchmarks for grid-connected PV and storage projects. The combined installed capacity of the system is 941 kW, with an annual energy production of 969,248 kWh obtained from PVsyst simulations. A 70:30 debt-to-equity ratio was assumed, with a 6.5% bank interest rate (minimum lending rate, MLR) and a 7% real discount rate representing the required return on capital. Time-of-Use tariffs were incorporated using on-peak and off-peak prices of 0.1562 USD/kWh and 0.0795 USD/kWh, respectively, with an on/off-peak consumption ratio of 63.34:36.66. Annual operation and maintenance (O&M) costs of 42,119 USD year^{-1} were estimated using a PV O&M cost model. All monetary values were expressed in USD, using an exchange rate of 32.7352 THB/USD, and the economic lifetime of the project was taken as 25 years, consistent with recent PV and wind techno-economic assessments in Thailand.

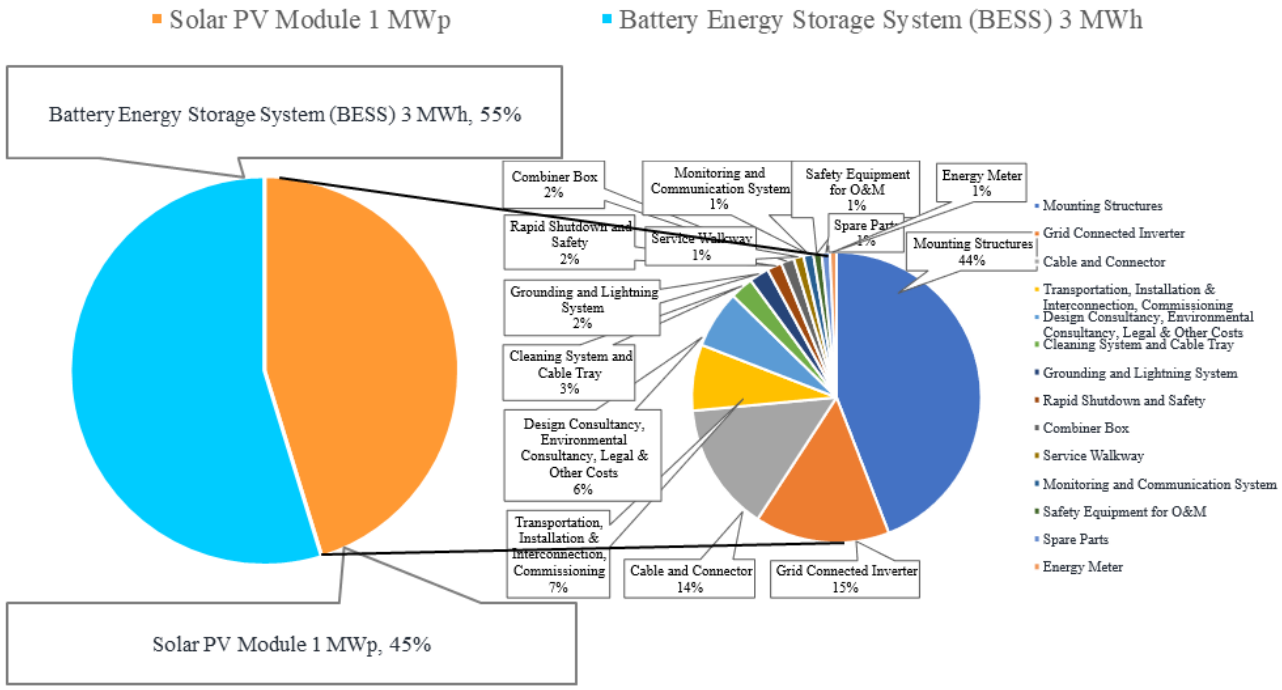


Figure 7. Breakdown cost of a solar PV rooftop and carport with a BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

2.7.2 Cost-Benefit Analysis

The economic evaluation was carried out using a single financing configuration in which Thaksin University invests in the PV–BESS system through a 70:30 debt–equity structure, consistent with the financial assumptions in Table 2. The economic benefit of the system was calculated as the difference between the electricity bill without the PV–BESS installation and the reduced bill with the system operating under the PEA Time-of-Use (TOU) tariff. This captures the financial value of self-consumed solar energy and any surplus electricity exported to the grid at TOU rates. The annual project costs include loan repayments for the financed portion, annual O&M expenses, and scheduled replacements of major components such as inverters and battery modules over the 25-year lifetime. This cost–saving structure forms the basis for computing the key financial indicators, including NPV, IRR, BCR, PBP, and LCOE.

Table 2. Assumptions used in the economic analysis of solar PV rooftop and solar carport systems for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

Categories	Value	Unit	Source/Data basis
Total Installed Cost	580,415	USD/MWp	Project Quotation
Installed Capacity	941	kW	System Design/PVSyst Input
Debt Ratio	70:30	-	Financing Assumption
Interest Rate (MLR)	6.5	%	Kasikorn Bank [18]
Annual Energy Production (AEP)	969,248	kWh	PVSyst Simulation
Battery Energy Storage System (BESS)	213,837	USD/MWh	Project Quotation
Discount Rate	7	%	Assumption
On-Peak Tariff	0.156207996	USD/kWh	PEA TOU Tariff
Off-Peak Tariff	0.079538234	USD/kWh	PEA TOU Tariff
On-Off Peak Ratio	63.34:36.66	%	Calculated based on the 2025 Calendar
O&M (PV-OM-Cost Model)	42,119	USD/year	NREL [19]
Project Lifetime	25	year	Manufacturing Assumption

Note: All monetary values are expressed in USD. Costs originally available in Thai Baht (THB) were converted using an exchange rate of 32.7352 THB/USD [20].

2.7.3 Benefit–Cost Ratio (BCR)

The benefit–cost ratio measures the ratio of the present value (PV) of benefits to the PV of costs [21]:

$$\text{BCR}= \frac{\sum_{t=0}^{T}\frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T}\frac{C_t}{(1+r)^t}} \quad (1)$$

where B_t and C_t are the annual benefits and costs in year t, i is the discount rate, and n is the project lifetime. A value greater than 1 indicates that the project yields more economic benefits than costs.

2.7.4 Net Present Value (NPV)

The net present value aggregates discounted net cash flows over the project lifetime, and is calculated by [22]:

$$\text{NPV}= \sum_{1}^{t}\frac{B_t+C_t}{(1-i)^t} \quad (2)$$

Where B_t and C_t are the revenue or positive cash flow, and the cost or negative cash flow in year t, and i is the interest rate. An NPV greater than zero indicates that the project is financially attractive at the chosen discount rate.

2.7.5 Internal Rate of Return (IRR)

A project's internal rate of return (IRR) is the interest rate that makes the NPV equal to zero. Usually, it evaluates the desirability of projects, where a high IRR makes a project more desirable to undertake and is given by [23]:

$$0=\sum_{t=0}^{T}\frac{C_t}{(1+r)^t} \quad (3)$$

where c_t denotes the cash flow in period t and r represents the internal rate of return.

2.7.6 Payback Period (PBP)

The simple payback period estimates the time required for cumulative net benefits to recover the initial investment and is calculated using :

$$\text{PBP} = \text{Investment}/\text{ Net cash flow} \quad (4)$$

where C_0 is the total initial CAPEX, and the denominator is the average yearly net benefit. Shorter payback periods indicate faster capital recovery and lower investment risk.

2.7.7 Levelized Cost of Electricity (LCOE)

The levelized cost of electricity represents the discounted unit cost of energy over the project lifetime [24]:

$$\text{LCOE}=\frac{\sum_{t=1}^{n}\frac{I_{t+M_t+I_t}}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \quad (5)$$

where I_t, M_t, F_t and E_t are the investment costs in year t, the maintenance costs in year t, the fuel expenditures in year t and the electric power production in year t, respectively. Here, r denotes the discount rate and n shows the lifespan, in years, of the PV system.

All economic indicators (BCR, NPV, IRR, PBP, and LCOE) were computed for the proposed PV–BESS system under the specified economic and financial assumptions.

3. Results and Discussion

3.1 Monthly Normalized Energy Production

Figure 8 illustrates the monthly normalized energy output per installed kWp for the rooftop and carport PV systems with integrated BESS. The combined profile of produced useful energy (YF), collection losses (Lc), and system losses (Ls) demonstrates a strong seasonal dependence driven by incident solar radiation and climatic conditions. Normalized output peaks between February and April, reaching values close to 6 kWh/kWp/day, coinciding with high irradiance and favorable solar angles during Thailand's dry season. By contrast, the lowest normalized yields are observed in October and November, where values fall to approximately 4.3–4.4 kWh/kWp/day, reflecting the transitional monsoon period marked by increased cloud cover, humidity, and diffuse irradiance that reduce conversion efficiency. Collection losses remain the dominant loss mechanism across all months, averaging around 1.38 kWh/kWp/day, while system losses associated with inverter and balance-of-system components stay comparatively minimal at about 0.06 kWh/kWp/day. The produced useful energy component remains relatively stable around 3.5 kWh/kWp/day, indicating that seasonal irradiance variability rather than inverter limitations is the main driver of output fluctuations. These seasonal patterns align with performance characteristics reported in tropical PV installations, where high ambient temperatures and intermittent cloud cover impact array efficiency more significantly than system-side losses.

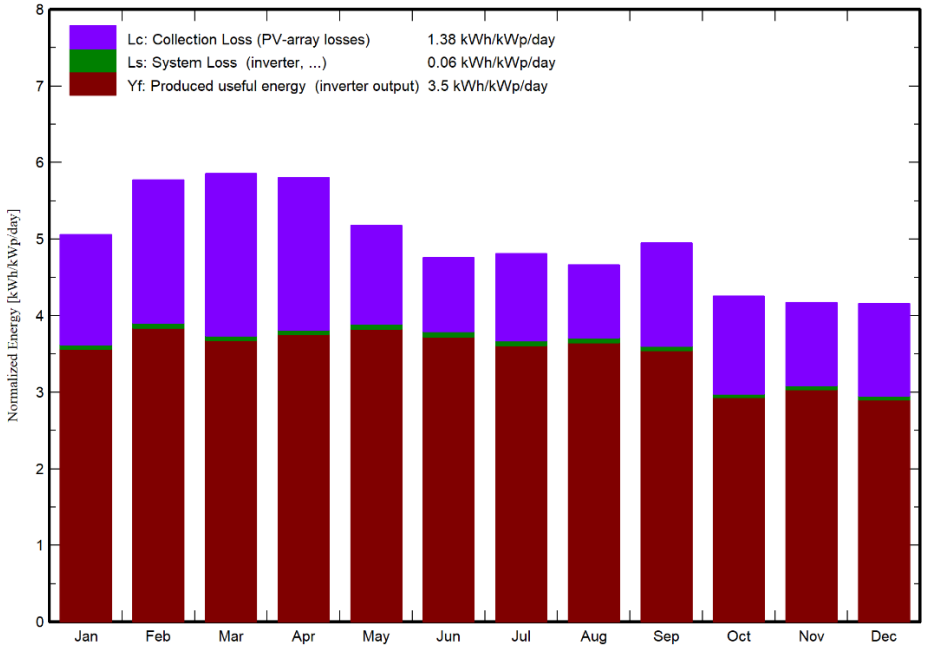


Figure 8. Normalized energy production per installed kWp of solar PV rooftop and solar carport systems with a BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

3.2 Performance Ratio Dynamics

The annual average PR obtained in the present study was approximately 0.65, with monthly values ranging from approximately 0.58 to 0.72 as presented in Figure 9. This value is lower than the PR values exceeding 0.85 reported by Khamharnphol et al. [16] for 100-kWp rooftop PV systems at five hospitals in southern Thailand. The difference can be attributed partly to differences in system configuration and operating boundaries. Unlike conventional grid-connected rooftop PV systems, the present configuration integrates rooftop and carport PV arrays with a large-scale BESS, introducing additional battery charging/discharging and conversion losses. Differences in array orientation, inverter loading, climatic conditions, and system sizing may also contribute to the observed variation in PR.

According to the PVsyst loss analysis, several system-level factors contribute to the overall performance reduction. Temperature-related losses account for approximately 8.47%, while inverter/MPP and nominal-power-related losses represent approximately 17.16%. Additional losses arise from array mismatch, wiring, irradiance-level effects, battery charging/discharging, and associated power-conversion processes. The relatively large inverter-related loss suggests that the PV–inverter sizing and DC/AC configuration warrant further optimization.

The annual PR obtained in the present study was approximately 0.65, which is lower than values reported for some conventional grid-connected PV installations in previous studies [25, 26]. This difference may be attributed not only to the warm tropical operating environment but also to differences in PV–inverter sizing, system configuration, conversion losses, and the integration of battery storage. In particular, the PVsyst loss analysis indicates that inverter/MPP-related and temperature-related losses are important contributors to the overall system performance. Therefore, the moderate PR observed in the present study suggests that further optimization of the PV–inverter configuration may improve system performance.

The obtained PR is lower than values commonly reported for conventional grid-connected rooftop PV systems, including previous studies of institutional PV installations in Thailand. This difference should be interpreted cautiously because the present configuration integrates rooftop-mounted and carport-mounted PV arrays with a 3.072 MWh BESS, resulting in a more complex energy-conversion and storage pathway than a conventional PV-only system. PVsyst defines PR as a system-level indicator incorporating optical, array, conversion, and relevant storage-related losses; therefore, additional conversion stages and energy-management constraints can affect the resulting system performance. The PR of 0.65 consequently reflects the combined influence of tropical operating temperatures and system-design factors rather than climate alone. These findings indicate opportunities for further optimization of the inverter loading ratio, PV array configuration, storage sizing, and battery dispatch strategy. Notably, the inverter/MPP-related loss of approximately 17.16% is considerably larger than the other electrical loss components, suggesting that further optimization of inverter sizing and the DC/AC ratio could improve the overall system PR.

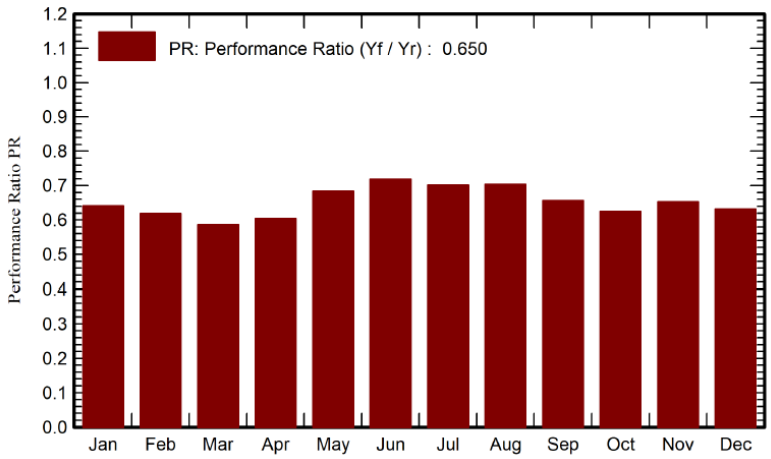


Figure 9. The performance ratio of solar PV rooftop and solar carport systems with a BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

3.3 Energy Flows: Solar Production, Grid Supply, and Consumption

Figure 10 provides insight into the monthly distribution of solar energy generation (E_Solar), energy injection into the grid (E_Grid), and global irradiance (GlobInc). The highest solar production occurs between June and July, with E_Solar reaching above 50,000 kWh per month. Grid injection exceeds 60,000 kWh in March. These months coincide with the period of maximum irradiance, as reflected by the elevated GlobInc curve. Production drops during October and November due to reduced sunlight hours and increased monsoon-related cloudiness. The energy injected from the grid (EFGrid) under varying battery capacities indicates that grid dependence decreases substantially when larger battery capacities are employed. When BESS capacities reach 2.0–3.0 MWh, grid imports remain close to zero in most months, demonstrating the effectiveness of the storage system in enhancing energy autonomy. The seasonal alignment between solar generation and irradiance trends confirms the sensitivity of the system's energy balance to climatic conditions, with the BESS playing a crucial role in smoothing variability and supporting operational continuity.

Figure 10 demonstrates how increasing BESS capacity affects the simulated grid-energy interaction. The results should not be interpreted as direct verification of monthly NZEB energy balance because measured monthly building electricity-demand data were unavailable.

The reduction in grid dependence with increasing BESS capacity is consistent with previous campus-scale PV–battery studies. Furukakoi et al. [8], for example, demonstrated that coordinated PV and battery capacity planning can substantially reduce electricity costs and emissions at university facilities. However, the present study adopts a substantially larger storage-to-PV ratio because the design objective extends beyond electricity-cost reduction toward achieving a high degree of energy autonomy and annual net-zero energy operation. This comparison demonstrates that appropriate BESS sizing is strongly dependent on the optimization objective, load characteristics, tariff structure, and required level of grid independence.

From the NZEB perspective, the contribution of BESS should be distinguished from that of PV generation. While the PV system provides the renewable electricity required to move the building toward an annual net-zero energy balance, the BESS primarily improves temporal energy matching by storing surplus daytime PV generation and supplying it during periods of insufficient solar production. Previous studies [25, 26] have similarly demonstrated that energy storage can enhance renewable-energy utilization and reduce grid dependence in building-scale energy systems. Nevertheless, the magnitude of these benefits depends strongly on the building load profile, PV capacity, storage size, tariff structure, and battery-control strategy. In the present study, increasing BESS capacity progressively reduced simulated grid imports, demonstrating the technical value of storage for improving energy autonomy.

The contribution of the BESS to NZEB performance should be interpreted primarily in terms of temporal energy management rather than additional renewable-energy production. The BESS stores surplus electricity generated by the PV system during periods of high solar availability and supplies the stored energy during periods of insufficient PV generation. Consequently, battery storage can reduce grid dependence and improve the utilization of locally generated renewable electricity. However, because measured monthly and annual electricity-consumption data for the case-study building were not available, the present study does not claim formal verification of an annual net-zero energy balance. Rather, the simulation results demonstrate the technical potential of the proposed PV–BESS configuration to facilitate the transition toward NZEB operation. A complete NZEB verification would require measured building electricity consumption together with monitored PV generation, grid import/export, and BESS operation over an appropriate assessment period.

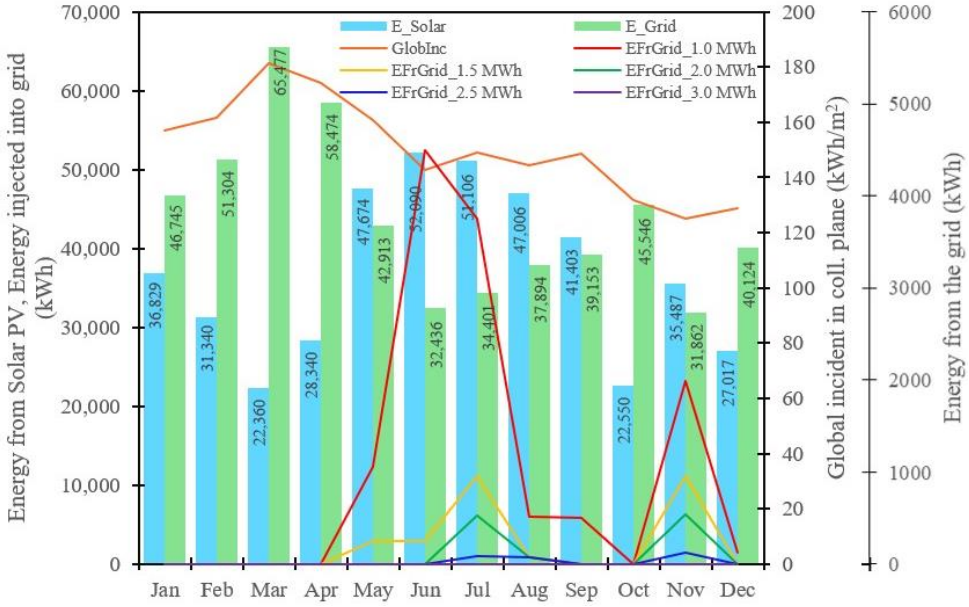


Figure 10. Monthly simulated PV energy production and grid-energy interaction under different BESS capacities for the proposed PV–BESS system.

3.4 Loss Distribution and System Efficiency

Figure 11 summarises the loss diagram of the PV–BESS system, tracing the energy flow from global horizontal irradiance to final useful energy. The PV conversion efficiency was 22% at the standard test conditions (STC). From the annual irradiance of 1798 kWh/m², only 1761 kWh/m² reaches the collectors after accounting for IAM losses and angular incidence effects. The effective irradiation on collectors (1,454,604 kWh) is reduced through temperature losses (−8.47%), irradiance-level mismatch (−0.64%), module quality effects, wiring losses (−1.02%), and array mismatch (−1.34%). The most significant inverter-related loss occurs at the MPP and during nominal inverter power operations (−17.16%), which is characteristic of high-power midday periods in tropical climates where inverter clipping becomes more prominent. Overall, the available energy at the inverter output totals 1,056,575 kWh. Battery charging, conversion, and discharging incur additional losses of approximately 1.60%, 0.11%, and 1.31%, respectively. Ultimately, 521,083 kWh is injected into the grid, and 448,298 kWh is consumed directly on-site, with 31.6% of solar electricity passing through the battery. The minimal unused energy fraction indicates effective system sizing and energy management, ensuring that most generated energy is either consumed or exported.

3.5 Financial Performance of System Configurations

Figure 12 presents financial indicators—NPV, IRR, PBP, BCR, and LCOE—for different deployment models, including PV-only and PV+BESS under self-consumption, ESCO, and bankable financing scenarios. For self-consumption, PV-only shows moderate viability, with a BCR of 1.16, a short PBP of around 14 years, and a slightly positive NPV. Introducing BESS reduces the economic performance under the same model due to additional capital costs, resulting in a negative NPV and an IRR of –0.11%. The ESCO model (Energy Service Company) is a framework where an energy service company implements energy efficiency projects for a client, covering design, financing, and implementation, and gets paid from the guaranteed energy cost savings, often without the client needing upfront capital, effectively turning energy inefficiencies into future cash flows for investment and profit sharing. In this analysis, the discount rate for every unit of electricity consumed by the university is 20%. Under the ESCO model, the PV-only configuration becomes less attractive, with NPVs turning slightly negative and PBP exceeding practical investment thresholds. The PV+BESS ESCO scenario performs even poorer due to the higher upfront costs relative to energy savings. The bankable model shows consistent improvement: both PV and PV+BESS achieve marginally positive NPV, low but positive IRR, and acceptable payback periods, suggesting that access to favorable financing conditions significantly enhances

economic feasibility. LCOE values remain stable at around 4.96–4.98 cents/kWh across all configurations, reflecting the dominant influence of capital cost and irradiance availability on long-term energy cost. Overall, the financial analysis indicates that while the PV system alone offers reasonable economic benefits, the addition of BESS becomes financially compelling primarily when paired with supportive financing structures or mechanisms that value energy autonomy and reliability.

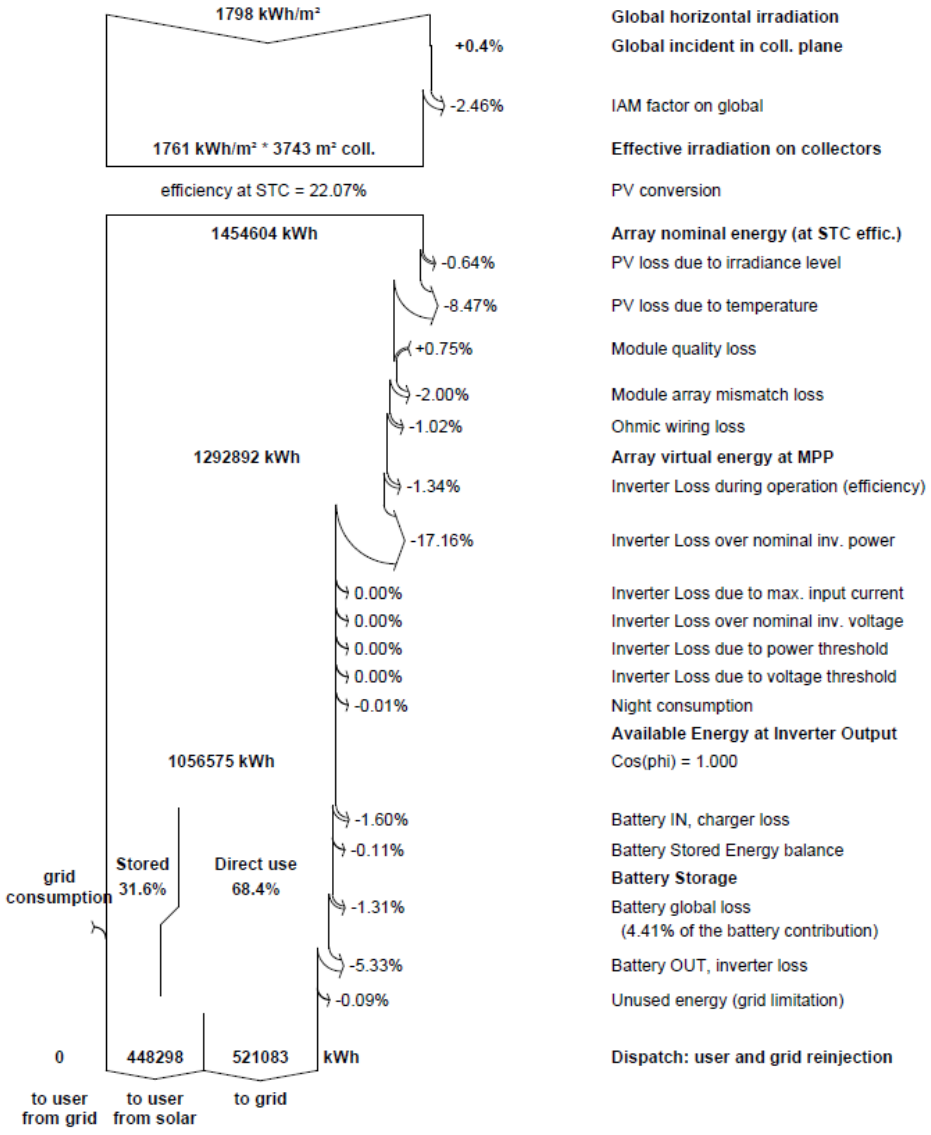


Figure 11. Loss diagram of the solar PV rooftop and solar carport systems with BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

The estimated LCOE of approximately USD 0.050/kWh in the present study is competitive with previously reported institutional PV projects in Thailand. For example, Khamharnphol et al. [16] reported a minimum LCOE of approximately USD 0.07/kWh for a 100-kWp rooftop PV system at a hospital in southern Thailand. Nevertheless, direct comparison should be interpreted cautiously because the present study considers a substantially larger hybrid rooftop–carport PV system integrated with BESS, whereas the previous study examined conventional rooftop PV under self-consumption, feed-in tariff, and power-purchase-agreement schemes. Differences in installed cost, system scale, financing structure, electricity tariff, battery cost, and analysis period can substantially influence the resulting LCOE. The main findings of this study and the related previous works were compared and provided in Table 3.

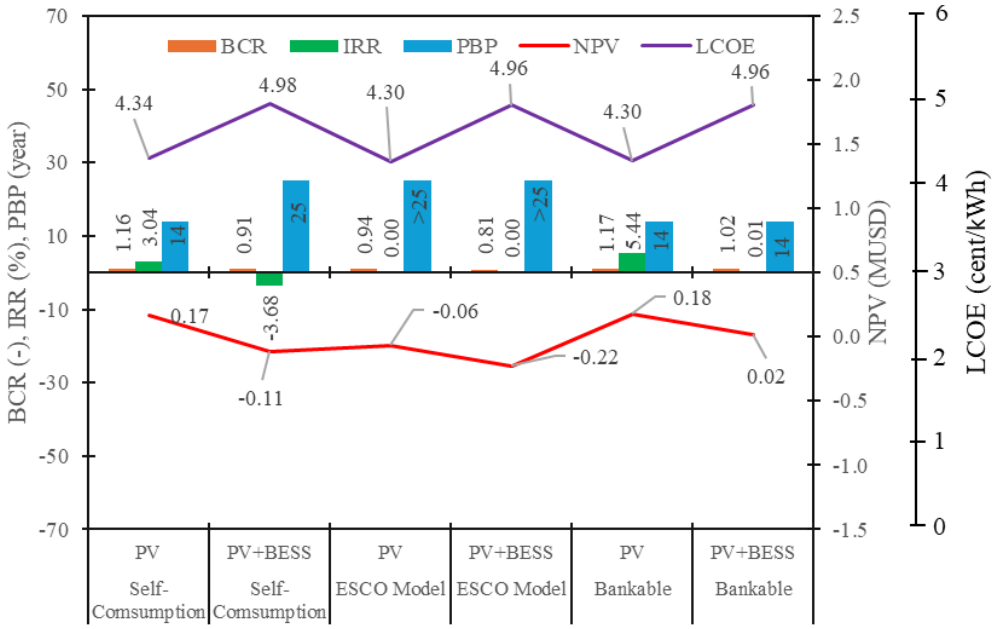


Figure 12. Financial indices of solar PV rooftop and solar carport systems with BESS for a net-zero building of the Faculty of Nursing at Thaksin University (Phatthalung Campus).

The economic results also reinforce findings from previous PV–BESS studies that the financial attractiveness of battery storage is highly sensitive to capital cost, financing conditions, electricity tariffs, and the value assigned to energy autonomy [27, 28]. In the present study, the PV-only self-consumption scenario showed moderate economic viability, whereas incorporating the 3.072 MWh BESS under conventional financing assumptions resulted in less favorable financial indicators. This indicates that, although BESS provides technical benefits through reduced grid dependence and improved temporal utilization of PV electricity, these benefits do not necessarily translate into superior financial performance under current battery-cost assumptions. More favorable financing conditions, declining battery costs, or additional revenue streams may therefore be required to improve the economic case for BESS deployment.

Table 3. Comparison of the present study with related PV and PV–BESS studies.

Study	Application	PV (kWp)	BESS (kWh)	Method	Main technical/economic findings
Khamharnphol et al. [16]	Hospitals, Southern Thailand	100/site	-	PVsyst + CBA	PR >85%; lowest LCOE ≈ USD 0.07/kWh
Leeabai et al. [17]	Educational facility, Thailand	207	-	PVsyst + financial/carbon assessment	Technical, economic and carbon benefits
Furukakoi et al. [8]	University campus	640	428	Planning + operational optimization	Reduced electricity cost and CO_2 emissions
Present study	University institutional building, Thailand	941.2	3.072	PVsyst + discounted cash flow	969 MWh/year; PR ≈ 0.65; near-zero grid imports in most months at high BESS capacity; LCOE ≈ USD 0.050/kWh

3.6 Implications of Financing Scenarios for Project Implementation

The comparison among financing scenarios provides important implications for the practical implementation of the proposed system. From a financial perspective, the PV-only self-consumption configuration appears to be the most attractive option under the current assumptions, with a BCR of

approximately 1.16, a payback period of approximately 14 years, and a slightly positive NPV. In contrast, adding the 3.072 MWh BESS under conventional financing conditions substantially increases the initial investment and results in a negative NPV and IRR of approximately −0.11%, indicating that the economic value generated by the battery is currently insufficient to offset its additional capital cost. The ESCO scenario also exhibits less favorable financial performance under the assumptions adopted in this study.

Accordingly, a staged investment strategy is recommended for the case-study building. The PV system may be implemented first to capture the immediate economic benefits of on-site solar generation and electricity-bill reduction. Subsequent deployment of BESS may then be considered when more favorable financing conditions, capital subsidies, lower battery prices, or additional revenue streams become available. If simultaneous deployment of PV and BESS is required to support energy autonomy and the transition toward NZEB operation, the bankable financing scenario represents the more suitable option among the financing structures investigated because it improves project feasibility relative to conventional investment and ESCO-based arrangements. Thus, the selection of financing strategy should reflect the primary project objective: maximizing financial return favors PV-only self-consumption, whereas achieving higher energy autonomy and supporting NZEB transition may justify PV–BESS deployment under supportive financing conditions.

4. Conclusions

This study evaluated the technical performance and economic feasibility of achieving net-zero energy operation for an institutional building through the integration of rooftop and carport solar photovoltaic systems with a battery energy storage system. Using the Faculty of Nursing building at Thaksin University (Phatthalung Campus, Thailand) as a case study, the research addressed the central question of whether a hybrid PV–BESS configuration can realistically deliver annual energy self-sufficiency while remaining financially viable under local climatic conditions, load characteristics, and tariff structures.

The results demonstrate that the proposed system is technically capable of achieving a net-zero annual energy balance. An installed PV capacity of 941.2 kWp combined with a 3.072 MWh battery produces approximately 969 MWh of electricity annually, fully offsetting the building's yearly demand. Hourly simulations show a strong temporal match between daytime electricity consumption and solar generation, characteristic of university buildings, while the battery system efficiently manages excess generation and supplies energy to load during evening and peak-tariff periods. The simulated annual average PR of approximately 0.65 demonstrates technically feasible operation but also indicates scope for further optimization, particularly in PV–inverter sizing, array configuration, and PV–BESS energy management.

From an economic perspective, the analysis reveals that the PV system alone offers strong financial performance under a self-consumption framework, with a competitive levelized cost of electricity and acceptable investment metrics. The integration of battery storage significantly enhances energy independence, reduces grid reliance, and improves alignment with time-of-use tariffs; however, the capital costs involved considerably influence overall financial outcomes. The PV–BESS setup becomes economically viable mainly when supported by favourable financing conditions or bankable investment arrangements, highlighting the importance of financing mechanisms in large-scale net-zero energy building projects. These findings stress that while battery storage is technically advantageous, its economic justification depends on market conditions, cost trends, and the value assigned to reliability and peak-demand reduction.

The main contribution of this work is its integrated techno-economic assessment approach, combining detailed energy simulations with comprehensive financial analysis at the campus-building scale. By explicitly linking technical performance with investment viability, this study advances beyond purely energy-focused evaluations and offers an investment-oriented perspective on net-zero energy buildings. The results show that universities and similar institutional buildings in tropical regions, with predictable daytime load profiles and available rooftop or carport space, are strong candidates for scalable net-zero energy implementation.

Several limitations should be acknowledged. The economic assessment is based on current cost assumptions, tariffs, and financing parameters, which may change over time as battery costs decrease or tariffs evolve. Additionally, the study concentrates on operational energy and economics without explicitly evaluating life-cycle environmental impacts or long-term degradation effects. Future research should include

sensitivity analyses on storage cost reductions, tariff increases, and alternative battery sizing strategies, as well as life-cycle sustainability assessments and demand-side management measures.

Overall, the findings demonstrate that a well-designed rooftop and carport PV system, complemented by appropriately sized battery storage, can technically and economically support net-zero energy operation for university buildings in Thailand. The proposed framework provides a replicable and practical pathway for institutional decarbonization and offers valuable guidance for planners, university administrators, and policymakers seeking cost-effective solutions to transition towards low-carbon, energy-resilient buildings.

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