

Tariff-Based Strategy of Energy Storage System Allocation at University Technical Malaysia Melaka with Solar Photovoltaic Systems

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Abstract

The increasing demand for reliable and sustainable energy solutions has prompted a surge in the rapid deployment of renewable energy and Energy Storage Systems (ESS). This study presents a tariff-based strategy of ESS allocation at commercial buildings with solar PV in Malaysia. This involves determining the optimal dispatch power and size of ESS for a Universiti Teknikal Malaysia Melaka (UTeM), considering various PV penetration levels and electricity tariffs. An effective ESS dispatch strategy is proposed to minimize electricity cost through maximum demand reduction, charging excess PV generation and maximizing the daily shifted energy from peak period to off-peak period. The strategy incorporates an iterative algorithm to determine daily charge and discharge thresholds, leading to a flattened demand profile. A Cost and Benefit Analysis—based optimization approach is utilized to identify the optimal capacity of ESS for maximizing the total Net Present Value (NPV) of ESS investment considering the strategic ESS scheduling. Numerical results express that the proposed strategy able to effectively dispatch and size ESS for maximizing the total profits of ESS investment. Maximum NPV is obtained when ESS of 6MW/37MWh is integrated in UTeM building with 0% PV penetration level under Time-of-Use (TOU) Tariff. While optimal ESS capacity increases with PV penetration under the general tariff, the required optimal ESS capacity under the TOU tariff decreases with higher levels of PV integration. Despite the reduction in system size at higher PV levels, the TOU tariff continues to yield substantially greater economic returns compared to the general tariff, achieving an NPV between MYR 28 million and MYR 35 million. Furthermore, the combination of TOU tariffs with the proposed optimal ESS capacity creates a more promising economic environment for ESS investments in commercial buildings with high PV penetration.

Keywords

Energy Storage System, Commercial Building, Electricity Cost, Electricity Tariff, Cost-Benefit Analysis

1. Introduction

Renewable energy (RE) sources, particularly solar photovoltaic (PV) and wind, are increasingly being incorporated into power systems as part of global efforts to mitigate climate change and achieve targets such as net-zero CO₂ emissions by 2050. Under Malaysia's New Capacity Target scenario, the country aims to expand its RE capacity, aligning with enhanced decarbonization goals for the electricity sector by the 2035 milestone. It represents the official commitment by the Government to achieve 31% (12.916 GW) and 40% (17.996 GW) RE target by 2025 and 2035 respectively. Malaysia has launched various schemes to promote renewable energy, leading to a substantial increase in solar PV capacity. The schemes include 2 GW fifth round of the nation's Large-Scale Solar (LSS5) tender, Government Rooftop Tendering Program, Corporate Power Purchase Agreement (PPA) via Third-Party Access (TPA) Framework, Green Tariff and Renewable Energy Certificate (REC) Trading [1].

Despite government initiatives to promote renewable energy, Malaysia's total electricity consumption in 2020 reached 152,250 GWh, with the commercial sector contributing 26.6% of the total [2]. A study conducted by Sustainable Energy Development Authority (SEDA) revealed that the rooftops of 520,000 commercial buildings across Peninsular Malaysia offer a potential of 5.2 GW for rooftop solar PV [1]. Realizing the potential of solar PV in reducing a building's electricity cost and climate change issues, many commercial building owners are interested in investing in rooftop solar PV systems. However, the high penetration of PV and the growing adoption of electric vehicles (EVs) pose challenges such as voltage fluctuations, reverse power flow, and increased load demand [3]. Implementing behind-the-meter (BTM) Energy Storage Systems (ESS), typically up to 5 kW/13.5 kWh for residential customers and 5 MW/10 MWh for commercial and industrial units can mitigate these issues [4]-[6]. With ESS in the network, flexible energy flow can be obtained, allowing more benefit both to the consumer and utility. Specifically, it provides on-site services for end-users, such as electricity cost management, increase RE self-consumption, improve power supply resilience and mitigate power quality issues [7]-[9].

The high installed cost of ESS, mainly the battery system, is the main obstacle to its implementation. Integrating PV with a Battery Energy Storage System (BESS) result in lower profits compared to a standalone PV system [10]. As a result, extensive studies and pilot projects have been carried out to develop strategies in determining the optimal ESS size and operational characteristics which can maximize the profitability of ESS investments.

A comprehensive approach for peak shaving in a Malaysia's commercial building using a grid connected PV generator with BESS integration is proposed in [11]. The optimal dynamic demand limit and rule-based peak-shaving control algorithms are developed for commercial buildings under general tariff to limit the utility grid power, reducing peak demand and electricity cost. The study considers four different cases of different load demand and PV power profiles based on seasonal conditions. The research in [12] confirms that depending on BESS application, a simplified ranking and sizing methodology can be developed. The authors proposed a ranking system of BESS installation based on the load profile of CCNY campus buildings and its return on investment (ROI).

Considering the diversity of utility tariffs for commercial loads, an optimization of building's net load through Battery Energy Storage System (BESS) and RE resources is modeled and explored for minimizing billing cost in [13]. Results exhibit that for the same building load and RE generation, the tariff type can have an overwhelming impact on costs and savings. Tariffs without Time of Use (TOU) charges or peak demand charge components offer lower savings opportunity from BESS optimization. Similarly, a study presented in [14] exhibits that adding BESS is more profitable for commercial buildings with lower load factors and Critical Peak Pricing (CPP) rate structures in comparison to buildings with general energy rates. A techno-economic model to assess the viability of commercial building-integrated BESS is proposed in [15]. The model introduces a Benefit-Cost Ratio (BCR) versus an energy-to-power factor, β relationship to describe the tariff structure and BESS parameters independently of the building load profile. The proposed model is used to determine the optimal size of the BESS, considering cost reductions across various future scenarios. The abovementioned studies have proposed the optimal ESS capacity for commercial buildings under different scenarios.

Existing studies highlight the importance of exploring optimal ESS scheduling and sizing to enhance investment profitability in specific research contexts. However, some research gaps remain as follows:

- 1) ESS allocation strategy for commercial buildings considering different PV penetration levels is still lacking. This study is vital as it represents the future scenario of commercial buildings with high PV integration, aligning with the nation's sustainability target. The integration of PV systems has a significant impact on ESS sizing and profitability, especially in Malaysia, where the typical operating hours of these buildings are coincided with the time of PV generation.
- 2) Some studies only focused on general tariff, overlooking other tariff options available for commercial buildings. However, the strategic dispatch profile and sizing of ESS are highly influenced by the choice of tariff. By evaluating the optimal ESS size and profitability in relation to the selected tariff, general guidelines can be developed to assist in tariff selection based on a commercial building's specific load profile and PV generation.

Therefore, this study delves into the investigation of behind-the-meter ESS sizing and operation for commercial-scale applications such as large apartment

buildings, hotels, universities, or shopping mall with PV integration. The key contributions of this article are as follows:

- 1) Proposed a tariff-based strategy (*i.e.* general or TOU tariffs) to dispatch ESS for a commercial building with different PV penetration level.
- 2) Developed a methodology for determining the optimal capacity of ESS for maximizing NPV of ESS investment for commercial buildings with different PV penetration level considering the current installed ESS costs, technical specification of ESS and electricity tariff.
- 3) Identified the relationship between ESS capacity and the profitability of ESS deployment for commercial buildings under different PV penetration levels with the MD reduction and electricity tariff.

Following the introduction, the rest of the paper is structured as follows: The system modelling and detailed methodology of the proposed tariff-based ESS dispatch scheduling and optimal sizing are presented in Section 2. Section 3 outlines the description of the case study and discussion of the results. Section 4 highlights the conclusions and contributions of the work.

2. Methodology

2.1. Overview

This section outlines a methodology proposed for the optimal deployment of ESS in commercial buildings, aimed at maximizing electricity cost reduction and evaluating its economic impact. **Figure 1** illustrates the general framework of the proposed ESS allocation strategy. ESS allocation is defined in this work as the ESS dispatch power and optimal size. The inputs of the ESS allocation strategy include a year of half-hourly historical or forecasted load power and solar PV generation of the building, technical specification and costs associated with ESS installation, electricity tariff applied and current discounted rate. Optimization approach specifically Genetic Algorithm (GA) is used to solve the ESS allocation problem formulation. GA is selected due to its good global search performance and low algorithm complexity. Note that the contribution of the study is more on developing ESS operational characteristics and sizing formulation. Enhancement and selection of optimization technique are not under the scope of this study. The decision variable of the allocation problem is the utilized capacity of ESS unit in kWh, E_{ES} , which is a continuous variable. Utilized capacity of ESS unit in kWh, is defined as the net capacity of ESS unit that can be used daily for discharge and charge before considering the technical characteristics of ESS technology such as its round-trip efficiency, degradation rate, allowable SOC and Depth of Discharge (DOD).

As shown in **Figure 1**, the daily half-hourly active power dispatched by ESS unit (*i.e.*, P_{ES}) are determined using iterative and analytical methods considering the specified electricity tariff and SOC limits and initial E_{ES} . ESS is dispatched with specific objectives depending on the electricity tariff considering the characteristics of the charges associated with the tariffs. Under a general tariff, ESS is scheduled to dispatch power for minimizing maximum demand (MD). For commercial

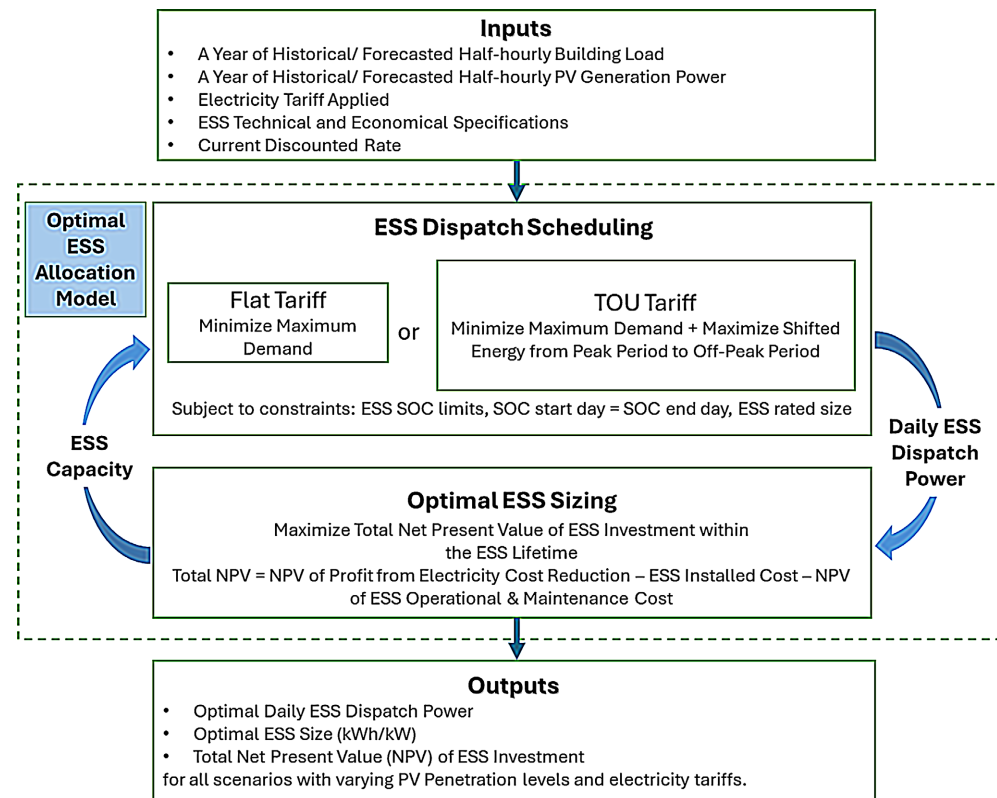


Figure 1. General framework of ESS allocation for commercial building with solar PV in Malaysia.

buildings under TOU tariff, an additional dispatch strategy is employed to maximize the shifting of energy from peak to off-peak periods. Rated power and energy capacity of ESS (*i.e.*, P_{ESR} and E_{ESR} , respectively) are calculated based on the computed values P_{ES} , the technical characteristics of adopted ESS technology and E_{ES} . Next, the optimal ESS size is identified based on the cost-benefit analysis of ESS investment. Considering the rated size of ESS obtained, current ESS installed cost and discounted rate, the total NPV of ESS investment is evaluated until the desired stopping criteria of the optimization problem is met. Using the proposed ESS deployment strategy, the optimal ESS scheduling and size, and total NPV of ESS investment for commercial buildings in Malaysia with different PV penetration levels and electricity tariffs can be identified. The detailed steps and their related mathematical formulations are elaborated in the next subsections.

2.2. Load and PV Model

Load is represented as PQ constant load model. It is assumed to follow a half-hourly commercial building specifically UTeM building load curve, which can be collected either from the historical or forecasted data. As electricity cost in Malaysia is charge based on half-hourly building load power, ESS allocation strategy is developed using the same sampling time as computed by the utility. Rooftop PV generation can be represented by half-hourly historical or forecasted PV generation power at the commercial building. Normalized PV generations based on the

historical data is used in this work to represent much higher size of solar PV that can be integrated to the commercial building.

A month of PV generation data is used in the analysis as the input data to represent PV generation of all months in a year. As Malaysia experiences a tropical climate every day in a year with almost no seasonal changes, this approach is adequate for planning purposes. In this study, detailed assessment is conducted to evaluate the effect of PV penetration level on the net demand of the commercial building and optimal size of ESS required for electricity cost reduction. The PV penetration level varies with an increment of 20% from 0% to 100% penetration level. The percentage of PV penetration level in this paper is defined as follows,

$$PV_{pen} = \left(\frac{E_{pv}}{E_{load}} \right) * 100\% \quad (1)$$

where E_{pv} is the annual energy generated by solar PV in kWh and E_{load} is the annual energy consumption of the building in kWh. Given any PV capacity installed at the commercial building, net demand power of the building $P_{D,t}$ at every half-hourly time segments, t is expressed as

$$P_{D,t} = P_{L,t} - P_{PV,t} \quad (2)$$

in which $P_{L,t}$ and $P_{PV,t}$ respectively are the power of load and PV generation at every half-hour time segments.

2.3. ESS Operational Characteristics

For reducing electricity cost of commercial building, P_{ES} is computed with an objective of minimizing electricity cost as much as possible based on the utilized capacity of ESS, E_{ES} . Dispatch strategy of ESS is dependent on the deployed electricity tariff. For commercial building in Malaysia, 2 types of electricity tariff can be selected, *i.e.* general and TOU tariff. The rate applied for these tariffs is listed in **Table 1**. This section presents an effective ESS dispatch schedule/algorithm that can be applied to obtain maximum profit from ESS deployment in commercial building with solar PV system under general and TOU tariff.

Table 1. Electricity charge rate for non-domestic medium voltage building: General and TOU tariff in Malaysia [16].

Tariff	General	TOU
Peak Energy MYR/kWh	NA	0.3132
Off-peak Energy MYR/kWh	NA	0.2723
Energy MYR/kWh	0.2983	NA
Capacity Charge MYR/kW	29.43	30.19
Network Charge MYR/kW	59.84	66.87

Under the framework of this study, the network is assumed to operate under the Self-Consumption (SELCO) mechanism [17]. Under this policy, any excess

solar PV generation is not allowed to be exported to the grid and is not remunerated, meaning that surplus PV holds a financial value of zero.

Because exported or curtailed energy yields no economic return, the proposed ESS dispatch strategy is specifically designed to maximize the charging of this excess daytime generation. By prioritizing the capture of surplus PV, the system effectively shifts this zero-cost energy to be discharged during the higher-demand evening periods, thereby maximizing the economic benefit and cost savings of the ESS investment.

2.3.1. ESS Dispatch Strategy for Commercial Building with General Tariff

Under general tariff, building owner is charged for energy consumption and maximum demand (MD) only, in which MD is billed based on the highest half-hourly power consumption in kW recorded across all days and hours of the month. Considering these charges, “Load Following” control method is developed in MATLAB to charge ESS during low demand period despite the time of its occurrence and discharge at high demand during peak period as shown in **Figure 2**. This approach is focused on reducing maximum demand only as energy consumption is not changed with ESS deployment. ESS in this application will conduct energy shifting, to flatten the demand profile. Using this approach, the energy remaining in the ESS at the beginning of the day is equal to that at the end of the day [18]. Specifically, the control mechanism will charge the battery if the total demand power is below the charge threshold, P_{cha} and discharge the battery if the total demand power is above the discharge threshold, P_{dis} . These daily thresholds are determined using an iterative algorithm described as follows [18].

Step 1: Set the initial values of P_{dis} and P_{cha} as the maximum and minimum demand power, P_D of the day, respectively.

$$P_{dis} = \max(P_{D,t}), \quad t = 17, 18, \dots, 44 \quad (3)$$

$$P_{cha} = \min(P_{D,t}), \quad t = 1, 2, \dots, 48 \quad (4)$$

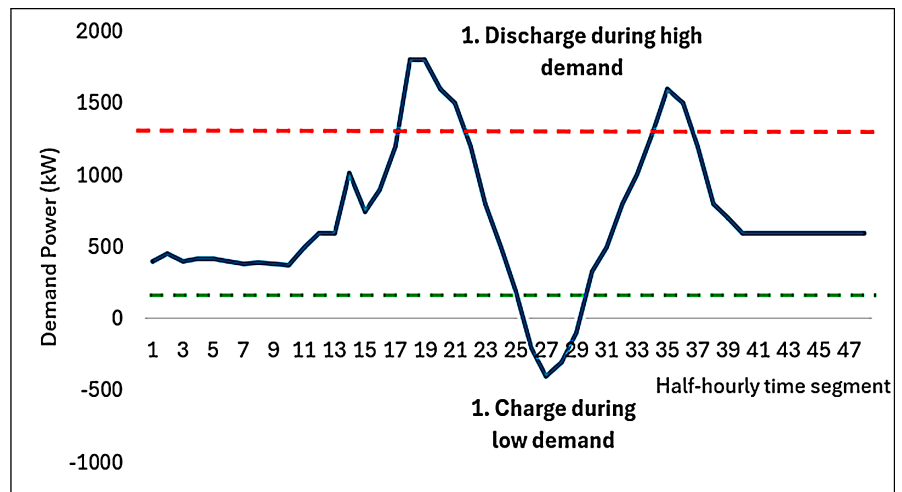


Figure 2. ESS dispatch strategy for commercial building with PV under general tariffs.

Step 2: Compute the total diurnal charged and discharged energy, E_{dis} and E_{cha} respectively.

$$E_{dis} = \sum_{t=1}^{44} (P_{D,t} - P_{dis}) \quad \in P_{D,t} > P_{dis} \quad (5)$$

$$E_{cha} = \sum_{t=1}^{48} (P_{cha} - P_{D,t}) \quad \in P_{D,t} < P_{cha} \quad (6)$$

Step 3: Increase P_{cha} by 0.01 if the difference between the diurnal charged energy and the total capacity of E_{ES} is more than 0.1. Otherwise, decrease P_{dis} by 0.01 if the difference between the diurnal discharged energy and the total capacity of E_{ES} is more than 0.1.

$$P_{cha} = \begin{cases} P_{cha} + 0.01, & \text{if } |E_{ES} - E_{cha}| > 0.1 \\ P_{cha}, & \text{otherwise.} \end{cases} \quad (7)$$

$$P_{dis} = \begin{cases} P_{dis} - 0.01, & \text{if } |E_{ES} - E_{cha}| > 0.1 \\ P_{dis}, & \text{otherwise.} \end{cases} \quad (8)$$

Step 4: Repeat Steps 2 and 3 until the difference between the amount of the diurnal charged and discharged energy and the total capacity of E_{ES} is less than 0.1.

Using the values of P_{dis} and P_{cha} obtained from the iterative method, total active power dispatched by ESS at every half-hourly time segment in a day, $P_{ES,t}$ can be computed as follows:

$$P_{ES,t} = \begin{cases} (P_{D,t} - P_{dis}) & \in P_{D,t} \geq P_{dis} \\ (P_{D,t} - P_{cha}) & \in P_{D,t} \leq P_{cha} \\ 0 & \in P_{cha} < P_{D,t} < P_{dis} \end{cases} \quad (9)$$

where $P_{D,t}$ is the demand power at half-hourly time segment, t . Positive $P_{ES,t}$ represents the power charged while its negative value corresponds to the power discharged by the ESS. The energy variation, $M_{ES,t}$ and state of charge (SOC) of a ESS unit located at the commercial building over the time segment, t can be formulated respectively, as follows:

$$M_{ES,t} = M_{ES,t-1} - P_{ES,t} \Delta t \quad (10)$$

$$SOC_t = SOC_{t-1} - \frac{P_{ES,t} \Delta t}{E_{ES}} \quad (11)$$

It is worth stating that in the proposed strategy, ESS unit operates at unity power factor. This means that ESS only dispatch real power as the main application addresses in this study is minimizing the electricity cost of the building. Dispatching reactive power may not significantly affect the electricity cost incurred by the building owner. Furthermore, it will increase ESS's inverter size, thus increase the capital cost of ESS installation.

2.3.2. ESS Dispatch Strategy for Commercial Building with Time of Use (TOU) Tariff

Under TOU tariff, electricity charge is divided into three components, *i.e.* energy

consumption charge during peak hour, energy consumption charge during off-peak hour and maximum demand charge as listed in **Table 1**. MD under this tariff is billed based solely on the highest half-hourly power consumption in kW recorded during peak period, which is on weekdays from 2 pm to 10 pm. Based on these charges, ESS can provide two potential saving that are through maximum demand reduction and by shifting energy consumption from peak period to off-peak period. This is because the charge of energy consumption during the off-peak period is much lower than peak period. Therefore, ESS is dispatched strategically to minimize MD and maximize the shifted energy from peak to off-peak period. To achieve that, ESS needs to discharge during peak hour (2 pm - 10 pm) and charge during off-peak hour (10 pm - 2 pm) only if there is no excess generation from PV system during midday. Excess generation from PV occurs when the half-hourly PV generation power is more than the building load power. Without ESS deployment, this excess generation will flow back to the grid, which reduces the utilization of PV generation. Therefore, for commercial buildings with high PV penetration levels, ESS is scheduled to charge the excess PV energy first before conducting energy shifting subject to the rated capacity of ESS as shown in **Figure 3**. ESS charge power to store the excess PV generation at specific day can be computed as follow:

$$P_{cr,t} = \begin{cases} |P_{D,t}| & \in P_{D,t} < 0 \\ 0 & \in P_{D,t} \geq 0 \end{cases} \quad (12)$$

$$E_{tot_cr} = \sum_{t=1}^{48} (P_{cr,t}) \quad (13)$$

$$E_{cr,t} = E_{cr,t-1} - P_{cr,t} \Delta t \quad (14)$$

$$P_{EScr,t} = \begin{cases} (P_{cr,t}) & \in E_{cr,t} < E_{ES} \\ (E_{ES} - E_{cr,t-1}) & \in E_{cr,t} > E_{ES} \text{ and } E_{cr,t-1} < E_{ES} \\ 0 & \in E_{cr,t} > E_{ES} \text{ and } E_{cr,t-1} > E_{ES} \end{cases} \quad (15)$$

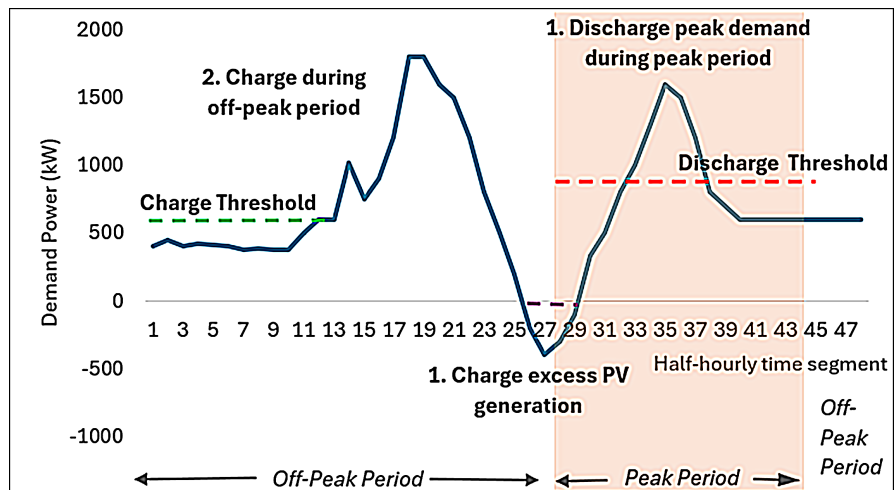


Figure 3. ESS dispatching strategy for commercial building with PV under TOU tariff.

Next, the diurnal ESS's charging energy from the excess PV generation, E_{tot_c1} and ESS's energy reservoir left for charging, E_{cha1} are respectively calculated using (16) and (17).

$$E_{tot_c1} = \sum_{t=1}^{48} (P_{EScr,t}) \quad (16)$$

$$E_{cha1} = E_{ES} - E_{tot_c1} \quad (17)$$

Next, the daily charge threshold, P_{cha} is computed by considering demand power during off-peak period while the discharge threshold, P_{dis} is computed based on the demand power during peak period. These values are determined as follows:

Step 1: Set the initial values of P_{dis} and P_{cha} as the maximum demand power during peak-period and minimum demand power during off-peak period, respectively.

$$P_{dis} = \max(P_{D,t}), \quad t = 28, 29, \dots, 44 \quad (18)$$

$$P_{cha} = \min(P_{D,t}), \quad t = 1, 2, \dots, 27 \text{ \& } t = 45, \dots, 48 \quad (19)$$

Step 2: Compute the total diurnal charged and discharged energy, E_{dis} and E_{cha} respectively.

$$E_{dis} = \sum_{t=28}^{44} (P_{D,t} - P_{dis}) \quad \in P_{D,t} > P_{dis} \quad (20)$$

$$E_{cha} = \sum_{t=1}^{27} (P_{cha} - P_{D,t}) + \sum_{t=45}^{48} (P_{cha} - P_{D,t}) \quad \in P_{D,t} < P_{cha} \quad (21)$$

Step 3: Increase P_{cha} by 0.01 if the difference between ESS's energy reservoir left for charging, E_{cha1} and the total capacity of E_{ES} is more than 0.1. Otherwise, decrease P_{dis} by 0.01 if the difference between the diurnal discharged energy and the total capacity of E_{ES} is more than 0.1.

$$P_{cha} = \begin{cases} P_{cha} + 0.01, & \text{if } |E_{cha1} - E_{cha}| > 0.1 \\ P_{cha}, & \text{otherwise.} \end{cases} \quad (22)$$

$$P_{dis} = \begin{cases} P_{dis} - 0.01, & \text{if } |E_{ES} - E_{dis}| > 0.1 \\ P_{dis}, & \text{otherwise.} \end{cases} \quad (23)$$

Step 4: Repeat *Steps 2* and *3* until the difference between the amount of the diurnal E_{cha1} and discharged energy and the total capacity of E_{ES} is less than 0.1. Using the values of P_{dis} and P_{cha} obtained from the iterative method, total active power dispatched by ESS at every half-hourly time segment in a day, $P_{ES,t}$ for commercial building with TOU tariff can be computed as follows:

$$P_{ESmd,t} = \begin{cases} (P_{D,t} - P_{dis}) & \in P_{D,t} \geq P_{dis}, t = 28, 29, \dots, 44 \\ (P_{D,t} - P_{cha}) & \in P_{D,t} \leq P_{cha}, t = 1, 2, \dots, 27 \text{ \& } t = 45, \dots, 48 \\ 0 & \in P_{cha} < P_{D,t} < P_{dis} \end{cases} \quad (24)$$

$$P_{ES,t} = P_{EScr,t} + P_{ESmd,t}, \quad t = 1, 2, \dots, 48 \quad (25)$$

The energy variation, $M_{ES,t}$ and state of charge (SOC) of a ESS unit located at a commercial building over the time segment, t can be formulated as in (10) and

(11) respectively.

There are three important elements in designing BESS which are location sizing, and dispatch strategy. This section presents the methodology to identify the strategic location, dispatch strategy and size of BESS.

2.4. Problem Formulation

This ESS planning problem is formulated as an optimization problem that has an objective function of maximizing the total NPV obtained from ESS deployment as follows:

$$F_{obj} = SE - C_{ES} - OM \quad (26)$$

In which, SE is the NPV value from the saved electricity cost of the commercial building with ESS. The total investment cost of ESS includes the capital cost, C_{ES} and the NPV value of the operation and maintenance costs, OM . All the formulation of the benefit and costs are detailed in this section. The objective function in (26) is maximized subjected to several constraints, which are the rated capacity of ESS unit and allowable SOC limits

2.4.1. Saved Electricity Cost

ESS integration in commercial building can reduce the peak demand thus provide electricity cost saving to the building owner. It is found that, for typical commercial building in Malaysia, most of electricity cost are coming from the maximum demand charges. Under the new RP4 electricity tariff, maximum demand charge is consisting of capacity charges and network charges. By discharging energy during peak demand, maximum demand charges can be lowered. Hence, monthly electricity cost of the building, EC and NPV of electricity cost saving after ESS is installed, SE for General Tariff and TOU Tariff can be formulated as follows:

$$EC_{Flat} = (C_{MD} \times MD) + (E_{B,month} \times C_{EC}) \quad (27)$$

$$EC_{TOU} = (C_{MD} \times MD) + (E_{Bp,month} \times C_{ECp}) + (E_{Bop,month} \times C_{ECop}) \quad (28)$$

$$SE = \sum_{n=1}^{Nyr} \frac{\sum_{m=1}^{12} (EC_m - ECs_m)}{(1 + IR')^n} \quad (29)$$

In which, C_{MD} is maximum demand charge rate which is the summation of network and capacity charge rate per kW, E_b is the total energy consumption, E_{Bp} is the total energy consumption during peak period and E_{Bop} is the total energy consumption during off-peak period of the respective month, m . C_{EC} is the general energy consumption charge, C_{ECp} is the energy consumption charge during peak hour, C_{ECop} is the energy consumption charge during off-peak hour, ECs is the monthly electricity cost of the building with ESS installed, IR' is the effective interest rate and Nyr in the planning horizon.

2.4.2. Capital and O&M Costs

The ESS capital cost is a function of two main parts. The first part is related to the storable energy which includes the replacement cost of ESS. Another part depends

on the maximum dispatch power provided by ESS based on the proposed dispatch strategy. In addition, specific technical characteristics of ESS technology, which are round-trip efficiency η , the maximum depth of discharge γ and self-discharge rate κ , are taken into consideration to determine the rated energy and power size of ESS. The replacement cost of ESS is not included in this study as the planning horizon considered in this study is the same as the lifetime of ESS. This means that, ESS unit will not replace throughout the assessed planning horizon as it is still capable to provide the specified applications. The NPV values for the capital and O&M cost of ESS over a N_{yr} planning horizon are formulated as in (30)-(31), respectively:

$$C_{ee} = (C_p / (E_{esr} / S_{esr})) + C_e ;$$

$$C_{es} = C_{ee} \times E_{esr} ;$$

$$C_{ES} = (C_E \times E_{ESR}) + (C_P \times P_{ESR}) \quad (30)$$

$$OM = \sum_{n=1}^{N_{yr}} \frac{C_M \times P_{ESR}}{(1 + IR')^n} \quad (31)$$

$$E_{ESR} = (1 + \kappa) \times \left(\frac{M_{ES}}{\eta} + (1 - \gamma) \times M_{ES} \right) \quad (32)$$

$$P_{ESR} = \frac{\max(|P_{ES,m,t}|)}{\eta} \quad (33)$$

C_P and C_E are respectively the capital power conversion system (PCS) and energy of ESS; C_M is the annual operation and maintenance costs of ESS.

3. Numerical Result

3.1. Case Study

The proposed methodology was verified on a Universiti Teknikal Malaysia Melaka (UTeM) building. UTeM is categorized as a commercial building that is connected to 33 kV substation. The load data were collected in April, representing peak academic activity (active lectures, laboratory sessions, and full student presence) and the building's highest energy consumption. Repeating this peak month across the year creates a conservative, 'worst-case' estimation. While this approach overestimates the cumulative annual load, it is highly beneficial from a system planning perspective. It ensures that any proposed BESS sizing or energy management strategy is robust enough to reliably meet the building's maximum demand without falling short during critical active academic periods. **Figure 4** shows the load duration curve of UTeM building for a month. During this month, UTeM recorded a maximum demand of 5.901 MW, energy consumption value of 1.47 GWh and an average daily load factor of 0.35. The figure also indicates that in that month, UTeM consumed power exceeding 2 MW during only 30% of the hours.

Historical data of PV generation for 28 kWp PV modules located at Solar PV System and Smart Grid Laboratory, Faculty of Electrical Technology and Engi-

neering, UTeM is utilized in this study. The generation data is normalized to be used for higher capacity of PV. **Figure 5** presents a box plot of UTeM's normalized PV output power distribution for a month, categorized by different hours of the day. **Figure 6** shows the demand profile of UTeM building in a day subjected to different PV penetration levels computed using (2). It is shown that the net demand of the building recorded reverse a power flow (net demand less than zero) when PV penetration level is more than 60% of the building's energy consumption. Lithium-ion batteries are chosen as the preferred technology for ESS allocation in commercial buildings due to their maturity for BTM applications, high efficiency, and cost-effectiveness.

Table 2 lists all the costs associated with ESS and economic parameters used in the analysis. The planning horizon is set to be 15 years. All GA parameters are in default values except for the time limit, stall time limit and *tolfun*, which are set to be *inf*, *inf* and 100 respectively. As GA is a heuristic algorithm that may not guarantee the same solution even after running the same problem several times, each case was run ten times with different initial populations. The best solution

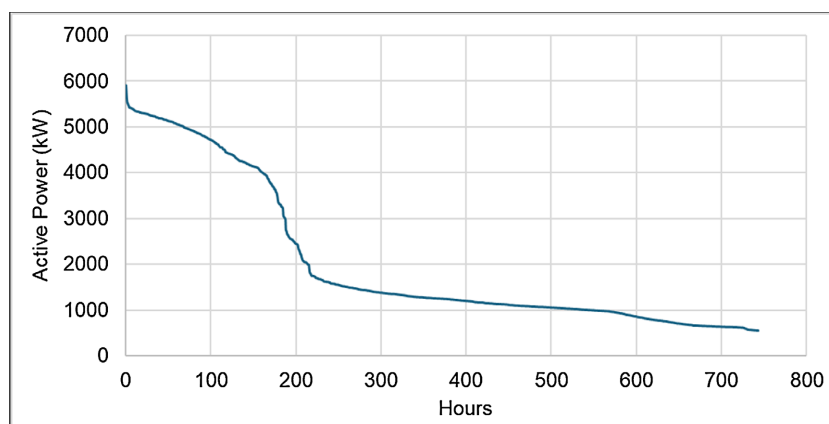


Figure 4. Typical UTeM building load duration curve in a month.

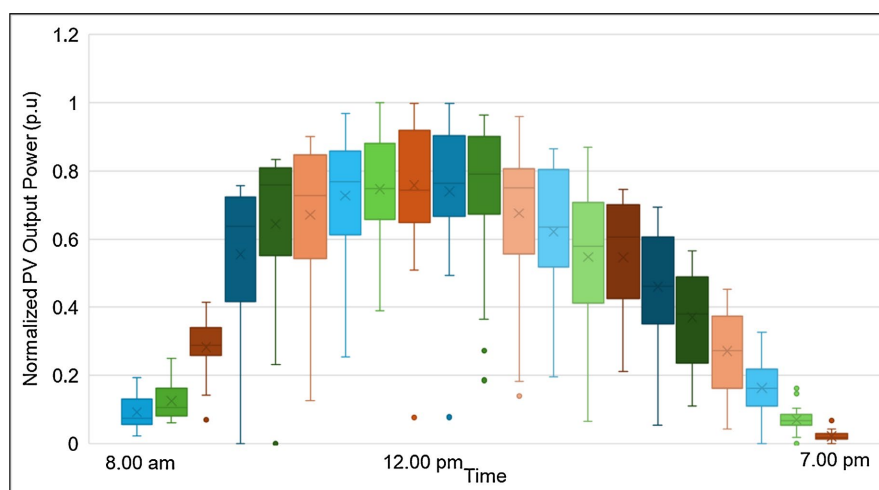


Figure 5. Box plot of UTeM normalized PV output power distribution for a month at specific hours.

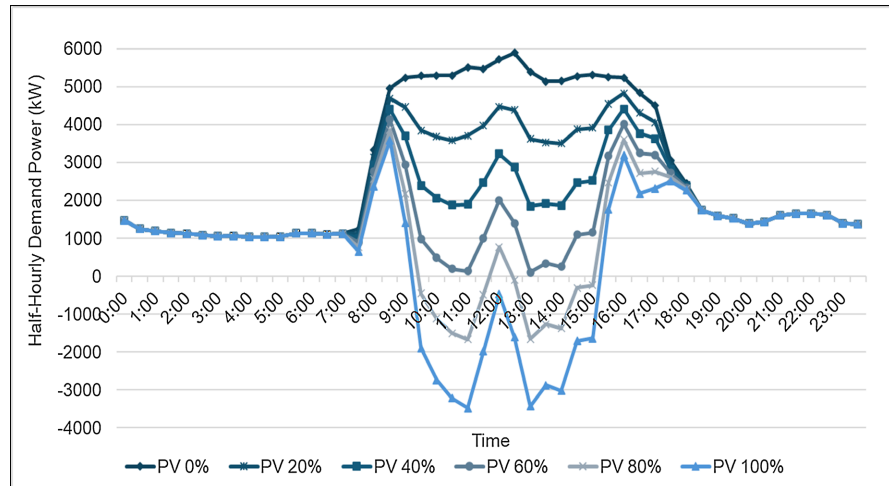


Figure 6. UTeM building demand profile on a day subjected to different PV penetration.

Table 2. Considered values of economics parameters and ESS specification.

Economics/ESS Parameters	Value
Annual O&M costs of ESS, CM (\$/kW)	5 [19]
Effective interest rate, IR (%)	6
Planning horizon, Nyr (year)	15
Replacement period, r (year)	15 [19]
ESS State of Charge Limits	0.2 - 1.0
Degradation loss of ESS, κ	0.1 [20]
Round Trip efficiency ESS, η	0.9 [19]
Maximum Depth of Discharge, γ	0.9 [19]
Standard coal consumption rate of the generation plants for peak shaving, Cps (kg/kWh)	0.48 [20]
Standard coal consumption rate of the generation plants for routine period, Cch (kg/kWh)	0.27 [20]
Li-ion Energy Component Cost (\$/kWh [MYR/kWh])	250 (1187.5) [19]
Li-ion Power Component Cost (\$/kW (MYR/kW))	230 (1092.5) [19]

(solution that results in maximum objective function) was then reported in the result section.

3.2. ESS Dispatch Power for Commercial Building with PV Generation

This section presents the result of ESS dispatch strategy for UTeM building under optimal ESS sizing, different PV penetration levels and electricity tariffs to achieve maximum NPV of ESS deployment. The results from **Figures 7-10** validate the paper's primary contribution by demonstrating how the proposed tariff-based ESS dispatch strategy adapts to varying solar PV penetration levels to minimize

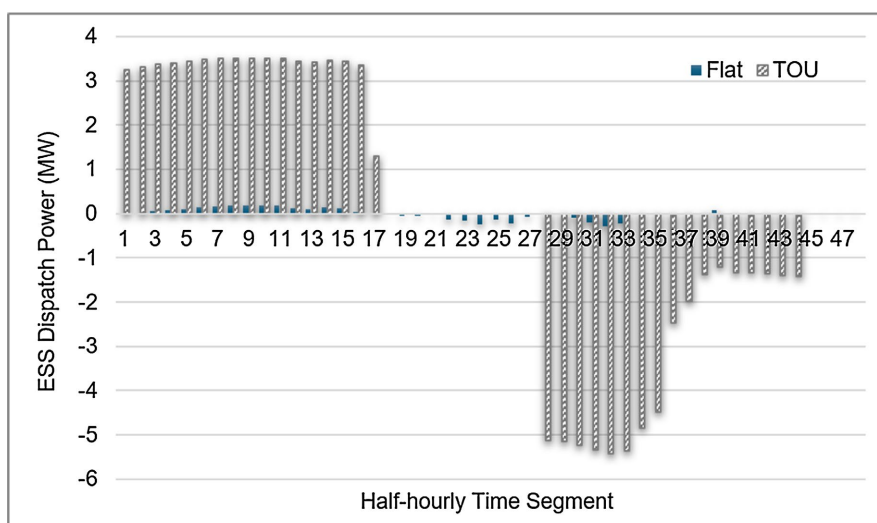


Figure 7. ESS dispatch power for UTeM building with 0% PV penetration under general and TOU tariff.

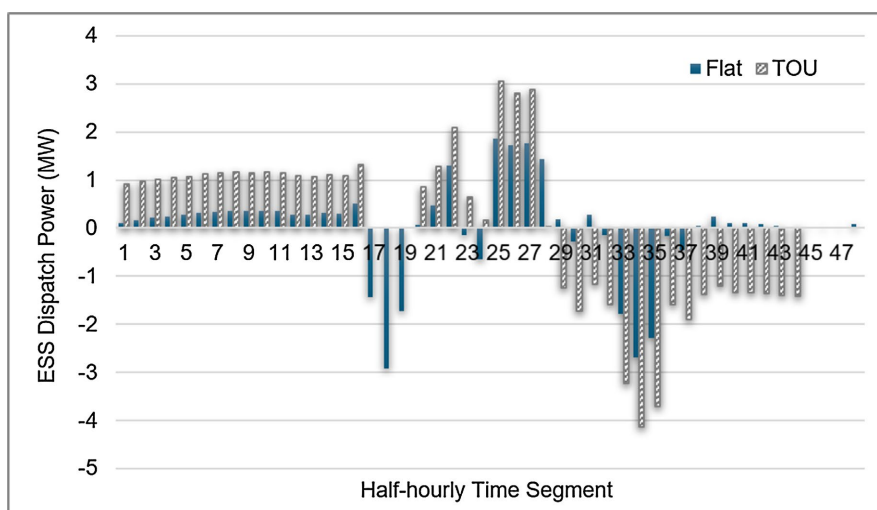


Figure 8. ESS dispatch power for UTeM building with 60% PV penetration under general and TOU tariff.

electricity costs. For a building with 0% PV penetration, there is a significant difference in the amount of ESS dispatch power between the general and TOU tariffs. This huge disparity is directly due to the optimal sizing obtained from the proposed methodology. The optimal ESS capacity computed for the general tariff is much lower than the capacity required for the TOU tariff.

Under a general tariff, the dispatch strategy dictates charging the ESS strictly during low-demand periods, such as at half-hourly time segment $t = 39$ for a building with 0% PV, or $t = 23, 24, 26$, and 29 for a building with 60% PV, while discharging occurs during high demand. Conversely, under a TOU tariff, the algorithm optimizes the ESS to charge during off-peak hours ($t = 1$ to 27) and during periods with excess PV generation (e.g., $t = 28$), ensuring the battery is filled when energy is cheapest or free. During the actual peak billing window

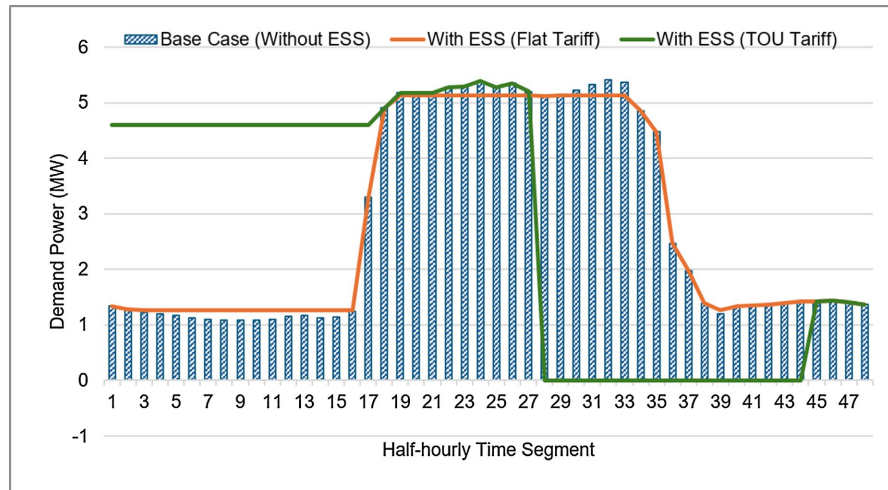


Figure 9. Demand power of UTeM building with 0% PV penetration and ESS under general and TOU tariff.

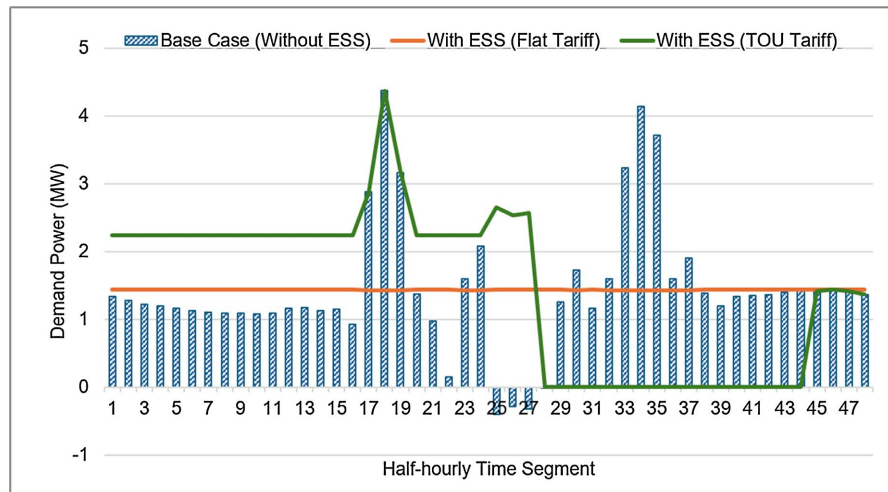


Figure 10. Demand power of UTeM building with 60% PV penetration and ESS under general and TOU tariff.

(segments 28 to 44), the ESS discharges to serve the building's load, dropping the grid demand to almost zero. This reduction directly substantiates the stated 96% reduction in billed MD. While the building's overall power draw does reach approximately 5.4 MW, this occurs during the off-peak period when the ESS is actively charging from the grid. Because the utility does not penalize off-peak demand under the TOU MD charge, this off-peak spike does not affect the billed maximum demand.

The resultant diurnal demand profiles illustrate that operating the ESS under a TOU tariff yields significantly lower energy consumption during peak hours compared to the general tariff. Ultimately, the figures confirm that the iterative algorithm effectively tailors charging and discharging thresholds to the specific electricity pricing structure, consistently reducing maximum demand while maximizing the energy-shifting benefits unique to TOU pricing and high PV penetration

scenarios.

3.3. Optimal ESS Sizing

Optimal capacity of ESS with respect to its energy and power components is identified for UTeM building with various PV penetration levels using the proposed sizing strategy. **Figure 11** and **Figure 12** depict the optimal size of ESS and NPV of ESS investment for 15 years of planning horizon under general and TOU tariff respectively. The optimal size of ESS for UTeM building without PV under General tariff is 0.7 MW/1.3 MWh with the resultant NPV is MYR 4.21 million. Meanwhile, the optimal size of ESS and NPV for UTeM building without PV under TOU tariff are higher than that for general tariff, that are 6 MW/37MWh and MYR 35 million respectively. This is due to the larger optimal ESS size computed for the case with the TOU tariff compared to the general tariff, contributing

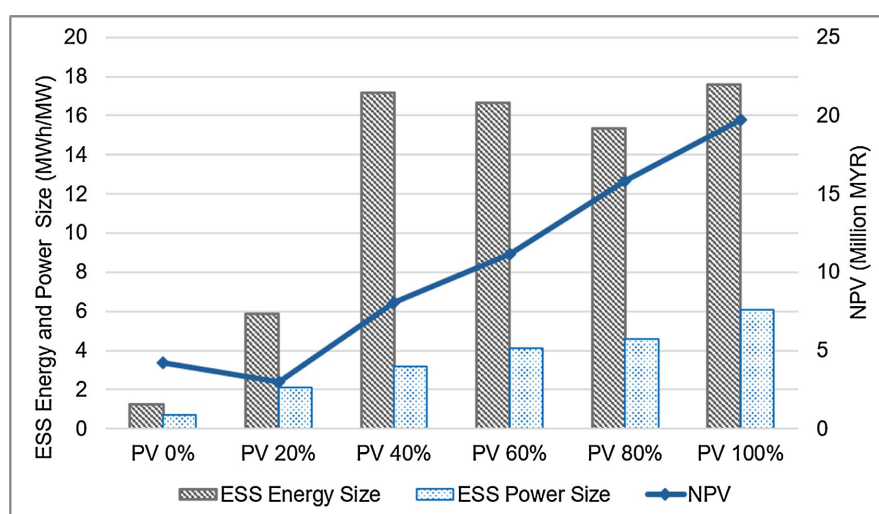


Figure 11. Optimal ESS energy and power size with NPV at different levels of PV penetration under general tariff.

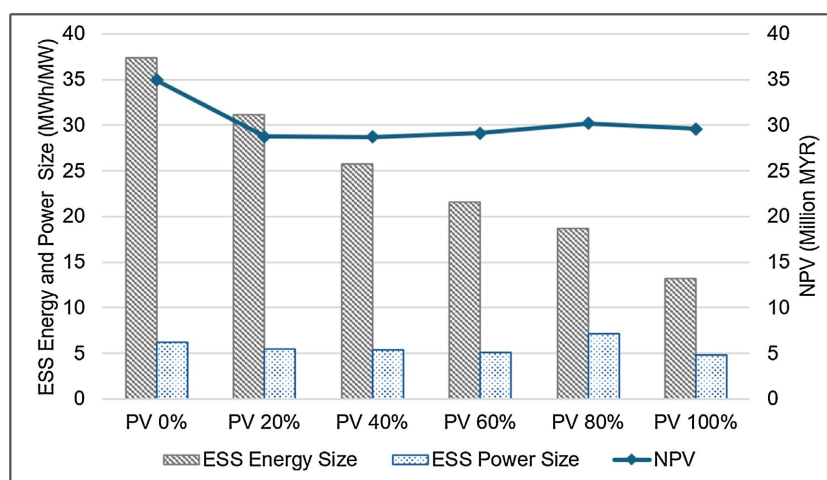


Figure 12. Optimal ESS energy and power size with NPV at different levels of PV penetration under TOU tariff.

to more energy shifted from peak period to off-peak period. Consequently, the maximum NPV is achieved when a 6 MW/37 MWh ESS, the largest optimal capacity proposed, is integrated into the UTeM building with 0% PV penetration under TOU tariff. Because this 6 MW power rating is equivalent to 100% of UTeM's MD, it drives a remarkable 96% reduction in MD. Furthermore, the massive 37 MWh energy reservoir allows the system to shift nearly all peak energy consumption to off-peak periods. This enables the building to operate almost entirely on cheaper stored energy during peak hours, successfully bypassing the expensive TOU peak energy rates entirely.

Furthermore, the significant outcomes from **Figure 11** and **Figure 12**, alongside **Table 3**, underscore the economic relationship between solar PV penetration, optimal ESS sizing, and tariff structures. As illustrated in **Figures 11**, while optimal ESS energy and power sizes remain relatively small at lower PV penetrations (0% to 20%), they rise sharply as PV penetration increases from 40% to 100%. This increase in required capacity directly correlates with a higher NPV, making high PV penetration scenarios considerably more economically viable over the long term under the general tariff. Conversely, the required optimal ESS capacity under the TOU tariff decreases with higher levels of PV integration. Despite this reduction in system size, the TOU tariff continues to yield substantially greater economic returns compared to the general tariff, achieving an NPV between MYR 28 million and MYR 35 million. This economic advantage is further confirmed by **Table 3**, which reveals that under a general tariff, adding an ESS results in linear electricity cost reductions, reaching its highest reduction of 100% PV integration. In contrast, under the TOU tariff, the introduction of the optimal ESS based on the proposed strategy, drives substantially larger cost decreases for all levels of PV penetration, highlighting its economic viability and efficiency.

Table 3. Monthly electricity cost of UTeM building with different levels of PV penetration and electricity tariff with the optimal ESS deployment.

Scenario	General Tariff			TOU Tariff		
	Monthly Electricity Cost (Million MYR)	Monthly Electricity Cost with ESS (Million MYR)	Electricity Cost Reduction (%)	Monthly Electricity Cost (Million MYR)	Monthly Electricity Cost with ESS (Million MYR)	Electricity Cost Reduction (%)
PV 0%	0.97	0.91	5.89	0.97	0.43	55.85
PV 20%	0.82	0.71	13.30	0.83	0.38	54.24
PV 40%	0.75	0.47	37.25	0.74	0.32	56.56
PV 60%	0.70	0.39	44.48	0.66	0.26	60.49
PV 80%	0.67	0.33	51.13	0.59	0.18	69.53
PV 100%	0.66	0.24	63.44	0.52	0.16	69.23

4. Conclusion

This study successfully developed and validated a tariff-based Energy Storage Sys-

tem (ESS) dispatch and sizing strategy for commercial buildings integrated with varying levels of solar photovoltaic (PV) generation. By employing an iterative algorithm tailored to specific electricity pricing structures, the proposed approach effectively minimizes electricity costs through maximum demand (MD) reduction and strategic energy shifting from peak to off-peak periods. The comparative analysis utilizing the UTeM building load profile demonstrates that higher PV penetration levels necessitate larger ESS capacities, which correspondingly yield greater long-term profitability, or Net Present Value (NPV). Furthermore, the findings reveal that operating under a Time-of-Use (TOU) tariff consistently outperforms the general tariff, driving larger optimal ESS sizes and significantly higher financial returns. Ultimately, the highest NPV was realized under a TOU tariff with 0% PV integration, where deploying a 6 MW/37 MWh ESS successfully curtailed maximum demand by 96% and reduced overall electricity costs by nearly 56%. Ultimately, this research provides crucial guidelines for building owners and investors, proving that the combination of TOU tariffs and high PV integration creates a highly viable and profitable economic landscape for ESS deployment in commercial facilities.

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Author Contributions

Junainah Sardi: Methodology, Formal analysis, Investigation, Data curation, Writing—original draft preparation, Writing—review & editing. Mohamad Fani Sulaima: Validation, Supervision, Writing—review & editing. Surina Mat Suboh: Conceptualization, Validation, Writing—review & editing. All authors contributed to the interpretation of the results, critically reviewed the manuscript, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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