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Data-Driven Optimization of Hybrid Solar Photovoltaic (PV) and Battery Energy Storage Systems (BESS) for Electric Vehicle Charging Using a Hybrid Data Approach

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Abstract: This study addresses the challenge of designing hybrid solar photovoltaic (PV) and battery energy storage systems (BESS) for electric vehicle (EV) charging under the constraint of fully integrated real-world data sets that capture PV generation, storage and EV charging. The objective is to assess the technical, economic and environmental impacts of a hybrid PV-BESS system integrated with an EV using a data-driven approach.

Performance of the system was analysed using high resolution time-series data from real PV generation, load and battery operation data, and a realistic modelling of the EV charging demand based on the system characteristics. The resulting system performance was evaluated through energy balance analysis, cost modelling using time of use pricing, and emission estimation.

Results reveal a substantial imbalance between PV generation (197,834.8 kWh) and total demand (564,431 kWh), with high grid dependency. EV charging accounts for 29.95% of demand and raises the peak load from 16.002 kW to 19.222 kW. Battery storage integration reduced the total energy cost by 20.64%, grid import by 23.87%, and carbon emissions by 23.87%, and enhanced grid stability through peak shaving and load variability reduction.

The research shows that integrating multi-source real-world data with a constrained EV charging demand model offers an effective and scalable method to assess hybrid energy systems. It provides useful insights for system optimisation, better use of renewable energy, and enabling sustainable EV integration.

Keywords: *Hybrid Energy System, Photovoltaic (PV), Battery Energy Storage System (BESS), Electric Vehicle (EV) Charging, Time-of-Use Pricing, Energy Optimization, Grid Stability, Carbon Emissions.*

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I. INTRODUCTION

There has been a rapid transition to sustainable energy systems in recent years to reduce greenhouse gas emissions, improve energy security and resilience. Renewable energy technologies, including solar photovoltaic (PV) systems, have contributed to this transition, due to its scalability, affordability and sustainability (Aslam et al., 2022; Wang et al., 2024). However, solar energy is intermittent and this limits its ability to provide reliable energy supply (Fezzani et al., 2023; Islam et al., 2024).

To overcome these challenges, hybrid PV-battery energy systems have become a focus. Energy storage systems are essential to provide flexibility, shift energy, and balance supply and demand in modern energy systems (Aghmadi & Mohammed, 2024; Almihat & Munda, 2026). Battery storage systems enhance reliability, and reduce traditional grid electricity consumption by storing surplus energy during high generation and supplying it during high demand or low generation periods (Amin et al., 2023; Lin et al., 2024).

However, designing and operating PV-battery hybrid systems is challenging. These challenges include sizing the battery system, dispatching energy effectively, and optimising the overall system cost across different demand and price scenarios (Bamisile et al., 2024; Jakus et al., 2025). Specifically, time-of-use (ToU) tariffs for electricity provide further opportunities for cost reduction through strategic charging and discharging, but also complicate system operation (Díaz-Bello et al., 2024; Zhang et al., 2025).

Furthermore, data-driven techniques for prediction and optimization play a crucial role in energy systems. Load prediction is crucial for energy management to schedule storage systems and minimise energy uncertainty (Habbak et al., 2023; Maleki et al., 2024). The application of machine learning and time-series analysis has led to more accurate load prediction, enabling more efficient and smart system operation (Chandrasekaran & Paramasivan, 2025; Wang et al., 2024).

Environmentally, PV-battery hybrid systems help to reduce carbon emissions by reducing fossil-fuel-based grid electricity consumption. But this depends on system design, renewable energy integration, and system operation (Chong et al., 2025; Wang et al., 2024). As a result, a holistic assessment that accounts for technical, economic, and environmental factors is needed to determine system performance.

While some studies have addressed hybrid renewable energy systems, many of these studies either focus on theoretical optimization or individual system components, with little consideration given to integrating real-time load profiles, energy costs and data-driven analysis (Khan et al., 2025; Giedraityte et al., 2025). Additionally, there is a lack of detailed empirical studies that integrate load profiling, battery storage evaluation and cost analysis into a comprehensive framework.

To address these limitations, this research offers a detailed study of a hybrid PV–battery energy system, examining system performance, cost-efficiency and environmental benefits under real-world conditions. It integrates visual, statistical and time series techniques to represent dynamics.

The study seeks to:

- Evaluate the influence of PV generation on load demand;
- Assess the effect of electric vehicle (EV) charging on load demand and peak load;
- Evaluate the influence of energy storage on cost, peak shaving and grid stability;
- Identify the optimal battery size for cost reduction under time of use tariff;
- Assess the environmental benefits on carbon emissions;
- Evaluate the temporal load demand and variability using time series data.

In this research, these components are integrated to add to the existing knowledge on hybrid renewable energy systems and to provide insights on system design, operation and sustainability.

II. LITERATURE REVIEW

Overview of Hybrid Renewable Energy Systems

Hybrid renewable energy systems (HRES) that combine different energy sources (for example, solar photovoltaic (PV), storage and grid connection) are becoming more prevalent for enhancing the energy security and sustainability. These systems are designed to address the challenges faced by single source renewable energy systems by incorporating different components that improve system adaptability and robustness (Khan et al., 2025; Dosa et al., 2025). Recent research shows that hybrid systems enhance energy efficiency and system stability by matching supply and demand at different timescales (León Gómez et al., 2023; Cheng et al., 2025). For instance, energy storage technologies allow the efficient utilisation of intermittent renewable energy and minimises reliance on conventional energy supply (Alhousni et al., 2025; Nasser & Liu, 2024). Moreover, hybrid systems are the key to implementing distributed energy systems and smart grids, where local energy supply and consumption needs sophisticated coordination strategies (Kiasari et al., 2024; Shen et al., 2021). However, such systems are difficult to design and operate, especially in terms of sizing and control.

Solar Photovoltaic Systems and Generation Variability

Solar photovoltaic (PV) systems are one of the most deployed renewable energy technologies due to their eco-friendly nature and low cost of deployment. however, PV systems are inherently dependent on sunlight, making PV energy generation intermittent and weather-dependent (Aslam et al., 2022; Fezzani et al., 2023).

Experimental studies demonstrate that PV generation is highly temporally variable, with high generation during the day and low generation during the night or on overcast days (do Nascimento et al., 2020). This may lead to a supply-demand mismatch, particularly in grid systems with steady or fluctuating demand curves.

PV generation also varies due to environmental and climatic factors such as temperature, shadow and geographical location (Aslam et al., 2022). These factors introduce uncertainties in energy planning and make it necessary to include other technologies, such as batteries, to ensure supply continuity.

Role of Battery Energy Storage Systems

Battery energy storage systems (BESS) are an important component of hybrid energy systems, providing energy storage and shifting capabilities. They are typically applied for peak shaving, load leveling, arbitrage and grid stability (Aghmadi & Mohammed, 2024; Islam et al., 2024). The integration of batteries and PV systems has been shown to increase the flexibility of the system and reduce the electricity imported from the grid, particularly during peak

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periods (Amin et al., 2023; Lin et al., 2024). Batteries enable time-shifting of loads by providing a temporary storage for excess generation during low demand periods and supplying energy during periods of high demand and/or cost.

However, the performance of battery systems depends on sizing and dispatch strategies. If the size is not selected correctly, there can be underutilisation or higher upfront costs, and if the dispatch is not optimal, it can affect efficiency (Costa et al., 2023; Jakus et al., 2025). Therefore, battery-sizing and dispatch strategies are crucial for improving economical and technical efficiency.

➢ *Optimization of Hybrid Energy Systems*

Cost optimisation is essential for hybrid energy systems to achieve cost-effective designs while consuming less energy. Techniques such as mathematical programming, metaheuristic optimisation and simulation have been applied to determine the optimal system design (Bamisile et al., 2024; Nassef et al., 2023). It has been demonstrated that the optimal system design is achieved by jointly optimising PV array size, battery capacity and system operating parameters (Zhang et al., 2023; Saurabh et al., 2025). In particular, the law of diminishing returns is often observed when excess system capacities do not add value. Time-of-use (ToU) pricing adds costs and complexities. Recent research suggested that ToU prices should be taken into account in the optimization process to reduce costs by taking advantage of energy arbitrage (Díaz-Bello et al., 2024; Lin et al., 2024). This demonstrates that the economy needs to be considered in control.

➢ *Energy Management and Demand Response Strategies*

Improving hybrid system efficiency requires energy management. Smart control strategies, which include demand response and smart energy management, enable the dynamic balance of generation, storage and demand (Rajendran et al., 2025; Rahman, 2025). Demand response strategies allow consumers to adapt their demand in response to prices or system conditions, thereby shifting demand and improving system efficiency (Díaz-Bello et al., 2024). Similarly, smart energy management systems use real-time data analysis and optimisation methods for enhanced decision-making and responsiveness.

These approaches are critical in high-renewable energy systems, which operate under uncertainty and variability, and require responsive and adaptive control strategies (Vieira et al., 2022). However, for these strategies to be effective, data analytics is essential.

➢ *Environmental Impact and Carbon Emission Reduction*

Hybrid renewable energy systems are very important in environmental sustainability by cutting down greenhouse gas emissions. Integrating PV with battery storage enables more utilization of renewable energy and reduced dependence on carbon-intensive grid electricity (Chong et al., 2025; Wang et al., 2024). Life-cycle and operational analysis indicate that significant emissions will be achieved by the appropriate matching of renewable generation and demand (Abdoos et al., 2025). The magnitude of these impacts is however affected by system design, storage efficiency and grid emissions. Moreover, decarbonization is not just associated with increased renewable production but also with effective energy control and optimization (Herc et al., 2022; Pastore, 2026). This puts the emphasis on the holistic system design to ensure environmental sustainability.

➢ *Research Gap*

Although much research has been conducted on hybrid renewable energy systems, research gaps exist. The research is primarily founded on the theoretical modelling or the components of a system, and less attention is paid to the practical patterns of demand, cost structures and the effect of electric vehicle (EV) charging on the hybrid energy systems (Khan et al., 2025; Giedraityte et al., 2025).

In particular, not many studies take into account:

- The variability of PV power and its effects on loads
- battery performance and sizing
- optimal cost under time of use tariffs
- carbon emission implications
- and load forecasting in an integrated approach.

Additionally, previous research often fails to consider the interplay of these factors and their impact on system performance, resulting in disjointed analysis.

➢ *Contribution of the Study*

This research offers a holistic assessment of a hybrid PV-battery by using a combination of graphical, statistical, optimization and predictive modeling. The study provides a holistic evaluation of system performance in terms of technical, economic and environmental aspects. Through the integration of actual demand, cost, and time-series analysis, this research helps in building efficient, reliable, and sustainable energy systems.

III. METHODOLOGY

➢ *System Modeling Framework*

This research presents a data-driven system model for a grid-interconnected hybrid energy system with photovoltaic (PV) generation, battery energy storage systems (BESS), electric vehicle (EV) charging demand and grid interactions. The aim is to assess the system's performance, cost-effectiveness and environmental sustainability under real and simulated demand scenarios.

The system functions as an energy management system with PV as the renewable energy source, battery for intra-day energy storage shifting and grid as the balancing source and export sink. The EV charging load is included as a dynamic demand to account for electrification. The system's control logic involves dynamic balancing of generation, storage and demand. If PV generation is greater than total demand, the surplus energy will be stored by the battery or fed into the grid. When PV generation is lower than demand, the system will discharge battery before importing from the grid.

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Fig 1 Shows the System Architecture, and Fig 2 Shows the Data Integration and Processing.

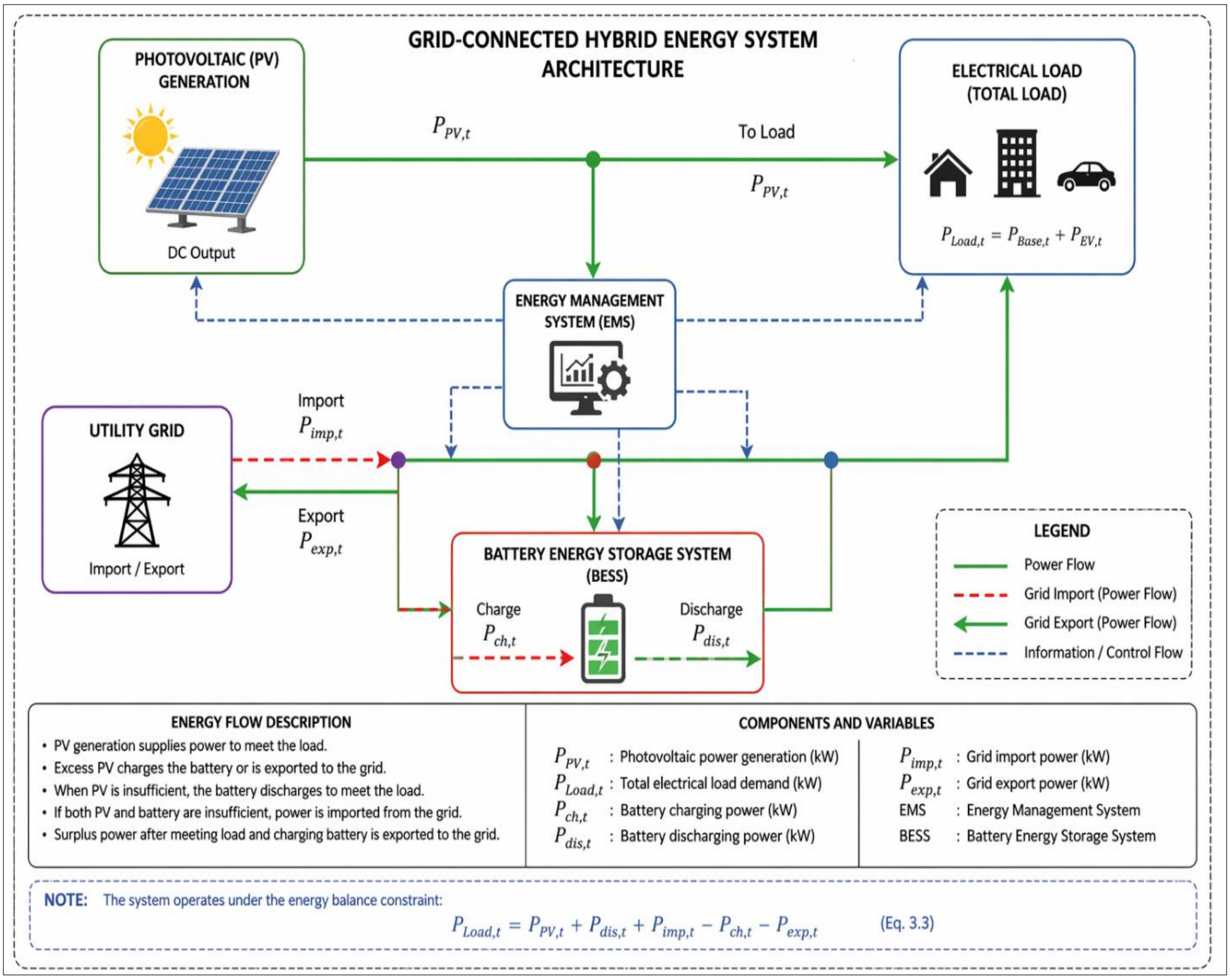

Fig 1 Schematic Architecture of the Grid-Connected Hybrid Energy System

➢ *Data Sources*

This research uses multiple databases from established research repositories and published studies to ensure the robustness and realism of system modelling. These datasets come from various geographical backgrounds and are summarized below:

- *PV–Battery Telemetry Dataset:*

High-resolution operational data (5-minute interval, one-year duration) obtained from a real-world photovoltaic and battery energy storage system located in Southeast Asia. This data includes detail information on power generation, consumption, battery charging/discharging and interaction with the grid.

- *Multi-User Energy System Dataset:*

A complete energy community dataset containing both 15-minute resolution load demand data and PV generation, battery storage, and electric vehicle data for 250 residential users. The dataset includes an urban energy community in Europe, including open-source data for EV charging infrastructure in Porto and Vila Nova de Gaia.

- *Solar Irradiance and Weather Dataset:*

Meteorological data from a standard solar measurement dataset, which corresponds to average climatic conditions for PV performance modelling.

- *Electric Vehicle Charging Dataset (Modelled):*

EV charging demand was simulated using realistic EVs usage behavioural patterns, such as arrival/departure, charging duration, and charging energy consumption, owing to the lack of full integration of real-world charging dataset aligned with PV–BESS system.

Standard electricity pricing and emission factors were used throughout all datasets to ensure consistency in pricing and emission factors in the context of the target application. A multi-regional real-world data integration and EV charging model constraint is used to create a flexible framework for hybrid PV–BESS–EV system evaluation.

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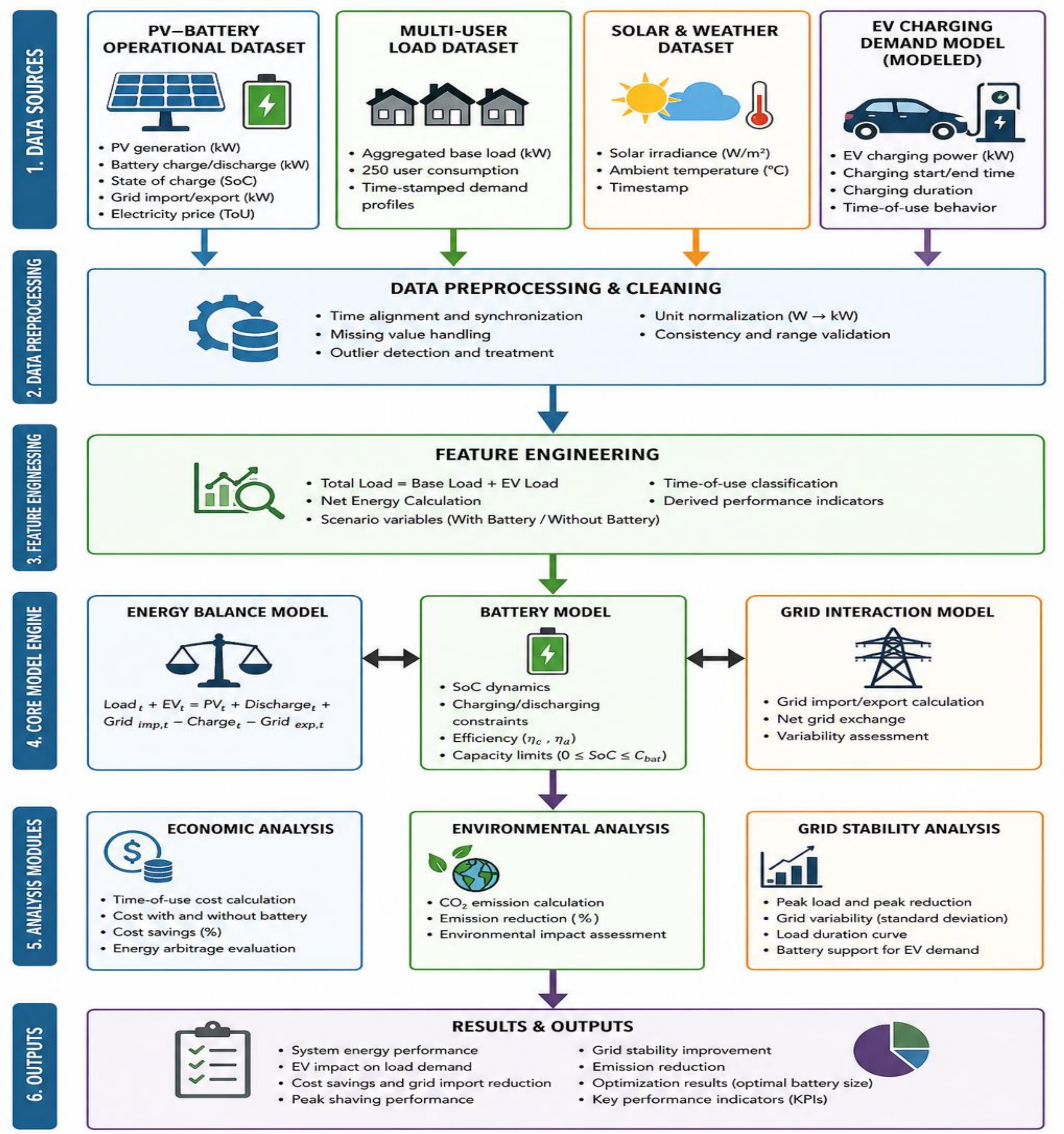

Figure 2: Data Integration and Computational Workflow for Hybrid PV–Battery–EV Energy System

Fig 2 Data Integration and Computational Workflow for Hybrid PV–BESS–EV System

- *Dataset Description and Temporal Resolution*

This study employs a multi-source dataset that has different temporal resolutions to develop realistic energy system behaviour. The primary data is a multi-user energy dataset that consists of 250 residential users, 15-minute resolution (96 time steps a day) of load demand, PV generation, EV charging, and battery specifications.

Real-world telemetry data of PV-battery systems, resolution 5 minutes, and 1 year duration were also used in the study to ensure realistic system dynamics. To model PV variability, meteorological data (solar irradiance and temperature) was incorporated.

The EV charging data was partly created based on the user characteristics (arrival and departure time, charge time and consumption) to consider the future electrification. To ensure consistency, the datasets were resampled to a steady resolution (hourly) to analyze the system.

➢ *Data Structure and Preprocessing*

The dataset is represented as a time-series structure:

$$D = \{t, PV_t, Load_t, EV_t, Grid_{imp,t}, Grid_{exp,t}, Charge_t, Discharge_t, SoC_t, Cost_t\}$$

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Where:

- t: Time index
- PV_t: PV generation (kW)
- $Load_t$: Base load demand (kW)
- EV_t: EV charging demand (kW)
- $Grid_{imp,t}, Grid_{exp,t}$: Grid import/export (kW)
- $Charge_t, Discharge_t$: Battery operation (kW)
- SoC_t: State of charge (%)
- $Cost_t$: Electricity cost

Total system demand is defined as:

$$Total\_Load_t = Load_t + EV_t$$

Data preprocessing includes:

- Times in normal datetime format.
- Missing values (where suitable) imputed to zero.
- Unit uniformity (e.g. W to kW)
- Temporal feature analysis (e.g. hourly aggregation)

➢ *Energy Balance Model*

At every time step the energy is conserved:

$$Total\_Load_t = PV_t + Discharge_t + Grid_{imp,t} - Charge_t - Grid_{exp,t}$$

This equation summarizes the connection between generation, storage and grid import/export, enabling the system to balance the energy flow.

➢ *Battery Storage Model*

The state of charge equation is used to model the battery dynamics:

$$SoC_t = SoC_{t-1} + \eta_c \cdot Charge_t - \frac{Discharge_t}{\eta_d}$$

Subject to:

$$0 \le SoC_t \le C_{bat}$$

$$Charge_t \cdot Discharge_t = 0$$

This limitation does not allow the battery to be charged and discharged simultaneously.

Where:

- C_{bat}: Battery capacity (kWh)
- η_c, η_d: Efficiencies of charging and discharging

The efficiency of batteries is calculated as:

$$\eta_{bat} = \frac{\sum Discharge_t}{\sum Charge_t}$$

➢ *Grid Interaction Model*

Grid exchange is defined as:

$$Grid_{imp,t} = \max(0, Total\_Load_t - PV_t - Discharge_t)$$

$$Grid_{exp,t} = \max(0, PV_t + Discharge_t - Total\_Load_t)$$

The total grid energy equals:

$$E_{imp} = \sum Grid_{imp,t},$$

$$E_{exp} = \sum Grid_{exp,t}$$

Standard deviation is also used to calculate the grid variation with a view of determining the stability of the system.

➢ *Cost Modeling Under Time-of-Use Pricing*

To enhance numerical stability and visualisation, the values of the cost were scaled (divided by 1000) in the case of the optimization model. However, the economic outcomes provided in the tables are in real terms.

The time-of-use (ToU) tariffs are used to calculate electricity cost:

$$Cost = \sum Grid_{imp,t} \cdot P_t$$

Where:

$$P_t = \begin{cases} P_{off}, & \text{off-peak} \\ P_{mid}, & \text{mid-peak} \\ P_{peak}, & \text{peak} \end{cases}$$

The baseline (no battery storage) scenario is defined as:

$$Cost_{NoBat} = \sum Total\_Load_t \cdot P_t$$

Cost savings are computed as:

$$Savings(\%) = \frac{Cost_{NoBat} - Cost}{Cost_{NoBat}} \times 100$$

➢ *EV Load Integration and Impact Analysis*

The EV charging demand is modeled as a time-dependent load. The EV charging impact is assessed by:

- Comparison of peak load (with and without EV)
- Total EV energy consumption
- EV load contribution to total demand:

$$EV\ Contribution = \frac{\sum EV_t}{\sum Total\_Load_t} \times 100$$

This allows evaluation of EV integration on system performance, stress on the system, and energy management strategies.

➢ *Peak Load and Load Profile Analysis*

Peak demand is defined as:

$$Peak = \max(Total\_Load_t)$$

Peak reduction due to battery operation is:

$$Peak_{red} = Peak_{NoBat} - Peak_{Bat}$$

The load duration curve (LDC) is constructed by ordering load values in descending order:

$$LDC(r) = \text{sorted}(Total\_Load_t)$$

➢ *Energy Performance Indicators*

Key performance indicators include:

- *Self-Consumption:*

$$SC = \sum \min(PV_t, Total\_Load_t)$$

- *Self-Sufficiency:*

$$SS = \frac{\sum(PV_t + Discharge_t)}{\sum Total\_Load_t}$$

These indicators assess the level of renewable energy use and grid independence.

➢ *Environmental Impact Model*

Carbon emissions are calculated based on grid energy use:

$$CO_2 = \sum Grid_{imp,t} \cdot EF$$

Where:

- EF: Emission factor (kgCO_2/kWh)

Emission reduction is estimated using battery and non-battery scenarios.

➢ *Optimization Model*

The system optimization seeks to find the size of the battery that will reduce the energy cost:

$$\min_{C_{bat}} Cost$$

Subject to:

- Energy balance constraints
- Battery operational limits
- Grid interaction conditions
- The optimization behavior uses:

$$\frac{\partial Cost}{\partial C_{bat}} \to 0$$

Showing a point of diminishing returns for larger battery capacities.

➢ *Optimization Implementation and Scenario Analysis*

To determine the optimal size of the battery, the parametric approach was used. The battery capacity was varied between the initial and final capacity (e.g., 0-500 kWh) and the total system cost is calculated for each system configuration under time-of-use pricing.

This method can be used to determine the cost-effective battery size and the law of diminishing returns of storage capacity.

➢ *Statistical and Variability Analysis*

System variables were summarized using descriptive statistics:

$$\mu = \frac{1}{n}\sum x_i$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum(x_i - \mu)^2}$$

Variability of the grid is examined to assess system stability with integrated batteries.

➢ *Implementation and Reproducibility*

All analyses were carried out in Python using:

- Pandas for handling data
- NumPy for computing numerical values
- Matplotlib and Seaborn for visualization
- SciPy for optimization

The data integration workflow involves data preprocessing, time-series aggregation, system modelling, scenario analysis and visualisation, with complete reproducibility.

➢ *Data Integration Workflow*

The data integration workflow brings together different data sources for analysis. This involves data loading, cleaning, transformation, feature extraction, model building and generation of results. This process is shown in Figure 2: Data Integration and Processing Flowchart, which gives a clear picture of how data is processed for analysis.

IV. RESULT AND DISCUSSION

➢ *Energy Performance and Demand Characteristics*

The system performance analysis shows a significant mismatch between supply and demand, which is a typical feature of under sized hybrid renewable energy systems. As shown in Table 1, the overall system load (564,431 kWh) is substantially higher than the energy produced by the photovoltaic (PV) subsystem (197,834.8 kWh) suggesting

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that the PV subsystem is under-sized to supply system demand. As a result, the system imports significant energy (293,392.74 kWh) from the grid, accounting for a large share of the total energy supply.

However, the system still exports 55,711.43 kWh to the grid. This paradox is a result of a temporal mismatch between PV generation and load demand. In particular, PV overproduction occurs during low demand (typically midday) and high demand during low or zero PV production (evening and night). This is readily observed in Figure 1 (Hourly PV Generation vs Load Demand) where PV generation is highest when the sun is shining, but cannot provide sufficient energy to satisfy the load during periods of high demand. This time mismatch is commonly observed in grid-connected PV systems and stems from the variable nature of solar irradiance (Aslam et al., 2022; Fezzani et al., 2023).

Figure 2 provides more information on the demand in the Load Duration Curve. The curve shows that the maximum demand (approximately 16 kW) is not reached very often, and most of the demand lies within the middle range (4-10 kW). Besides, a relatively steady base load (approximately 2 kW) suggests a constant consumption. This pattern is relevant to system design: the peak demand determines the capacity of the system to be constructed, and the base load determines the total energy demand. Islam et al. (2024) point out that the one of the strategies that could be used to control such variability is energy storage technologies with the purpose to redistribute energy and increase the flexibility of the system.

The inclusion of EV charging increases the demand profile. The EV charging demand contributes 169,027 kWh (or 29.95 of the total energy demand) as shown in Table 1. Such a high proportion does not only increase the energy demand, but also inflates the imbalance between supply and demand. EV demand will generally be peaked during times of current peak consumption even in the absence of managed charging, thereby making grids more dependent.

These findings indicate that the sizing and integration of PV and storage systems should be appropriately sized in terms of system design. The current state of the system indicates that PV generation contributes a significant percentage of energy demand, yet is not enough to achieve energy self-sufficiency. The optimal system efficiency, as studies on Hybrid renewable energy systems point out, is a harmonious balance between the capacity of the generation, energy storage, and demand management (Khan et al., 2025; Giedraityte et al., 2025). Without such balance, the system will experience inefficiencies, including both import and export of energy at the same time, a low degree of renewable energy utilization, and increased expenses.

Table 1 System Energy and EV Load Summary

Metric	Value
Total PV Generation (kWh)	197834.8
Total Load Demand (kWh)	564431
Grid Import (kWh)	293392.7
Grid Export (kWh)	55711.43
Total EV Energy (kWh)	169027
EV Contribution (%)	29.95

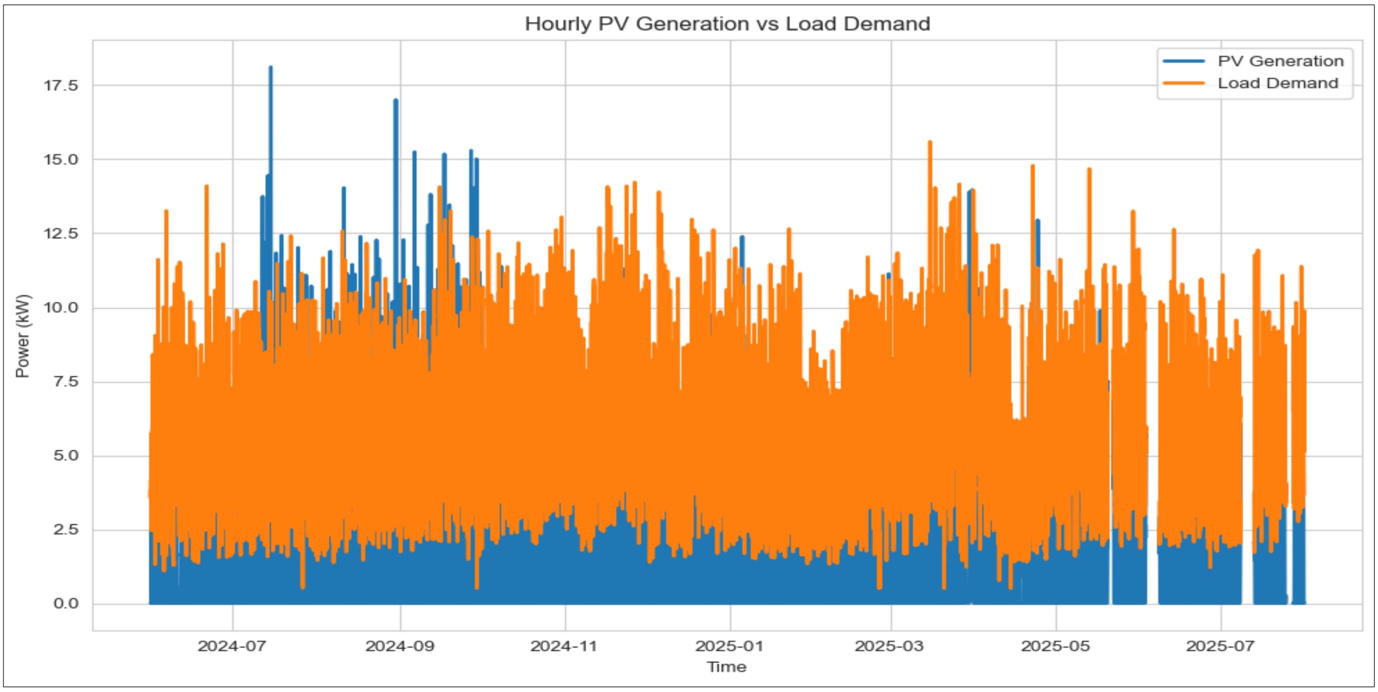

Fig 3 Hourly PV Generation vs Load Demand

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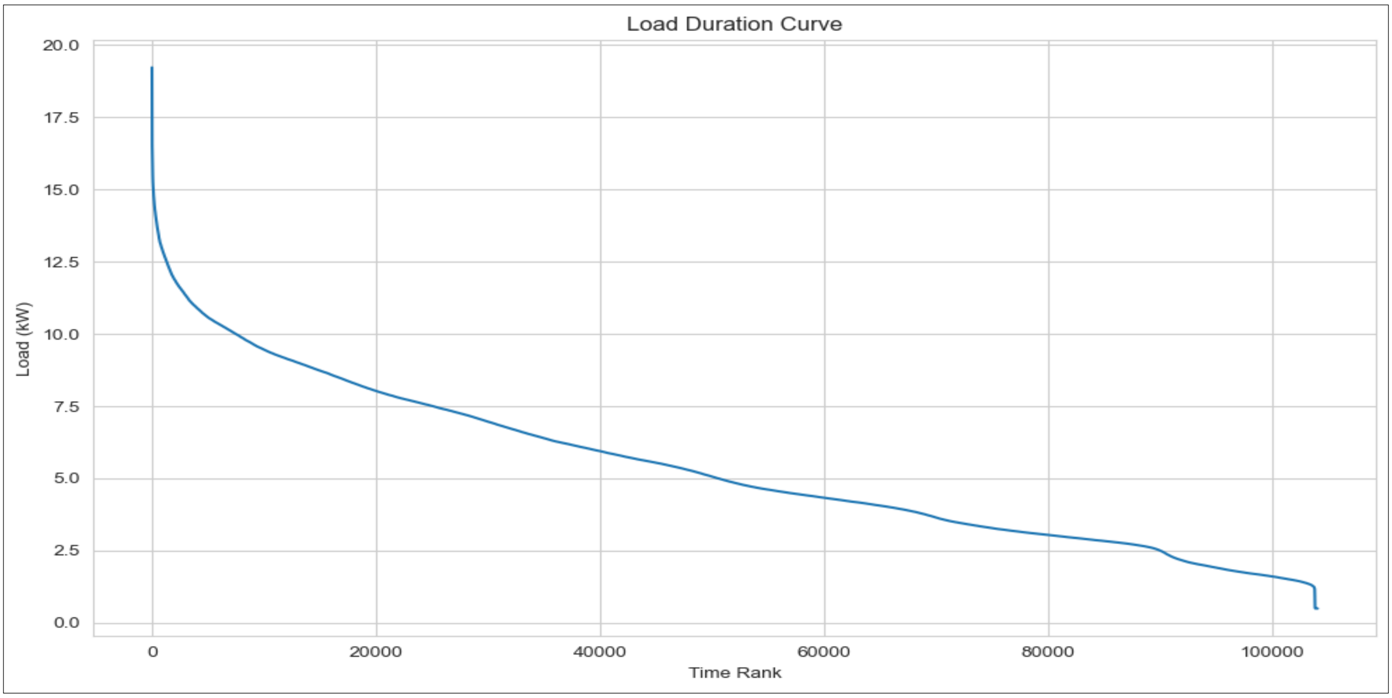

Fig 4 Load Duration Curve

➢ *Impact of EV Charging on System Load*

A key dynamic component in the system load profile is the addition of electric vehicle (EV) charging that impacts the extent and variability of load. As indicated in Table 2, EV charging addition increases the peak load by 16.002 kW to 19.222 kW which increases load in the system by a considerable margin. This is also added to the overall EV energy requirement of 169,027 kWh, and constitutes 29.95 percent of overall system energy requirement (Table 1).

Figure 3 (Impact of EV Charging on Load Demand) illustrates the impact of EV charging on load. The graph shows that the load with integration of EV is much higher and more variable than that of base load. The variability can be attributed to the uncertainty surrounding EV charging that is influenced by the preference of the user and the charging time and time-of-usage policies. EV charging demand is also less predictable and can cause high peaks of demand.

Additionally, the results indicate that EV charging demand is seasonal and at the peak of demand, which contributes to the increased load on the system and the rise in grid dependency. This aspect is even more intense in systems where the renewable generation capacity is low because it worsens the mismatch between supply and demand. According to Bilal et al. (2025), the uncontrolled charging of EVs may pose a significant load to the hybrid energy system, leading to the increase in operational costs and the decrease in the efficiency.

Fig 6 (Battery Support for EV Charging Demand) illustrates the advantages of battery storage on the effect of EV charging. This value is used to show that the rate of battery discharge is directly proportional to the EV load, which indicates that stored energy is being used to satisfy EV charging demand. This dynamism highlights the importance of storage in balancing demand and eliminating grid support dependency.

Regarding operation, the results suggest that EV charging cannot be regarded as a passive load but as a component of the energy system. EV charging can be an active resource to grid stability, through coordination of EV charging and energy management. As an example, EV charging can be scheduled to take place during the peak PV generation to maximize the use of renewable energy and reduce the amount of electricity used on the grid.

This solution aligns with the current studies on Electric vehicle grid integration, that emphasizes the role of intelligent charging schemes in enhancing energy systems (Wei et al., 2024; Neeraja et al., 2025). These approaches involve time-of-use pricing, demand response and vehicle-to-grid (V2G).

The results indicate that EV charging has profound implications on system performance, increasing the variability and demand. However, EVs can also play a major role as an enabler of system flexibility and renewable energy integration with appropriate integration and management.

Table 2 Peak Load and EV Impact

Metric	Value
Peak Load Without EV (kW)	16.002
Peak Load With EV (kW)	19.222
Peak Load With Battery (kW)	15.617

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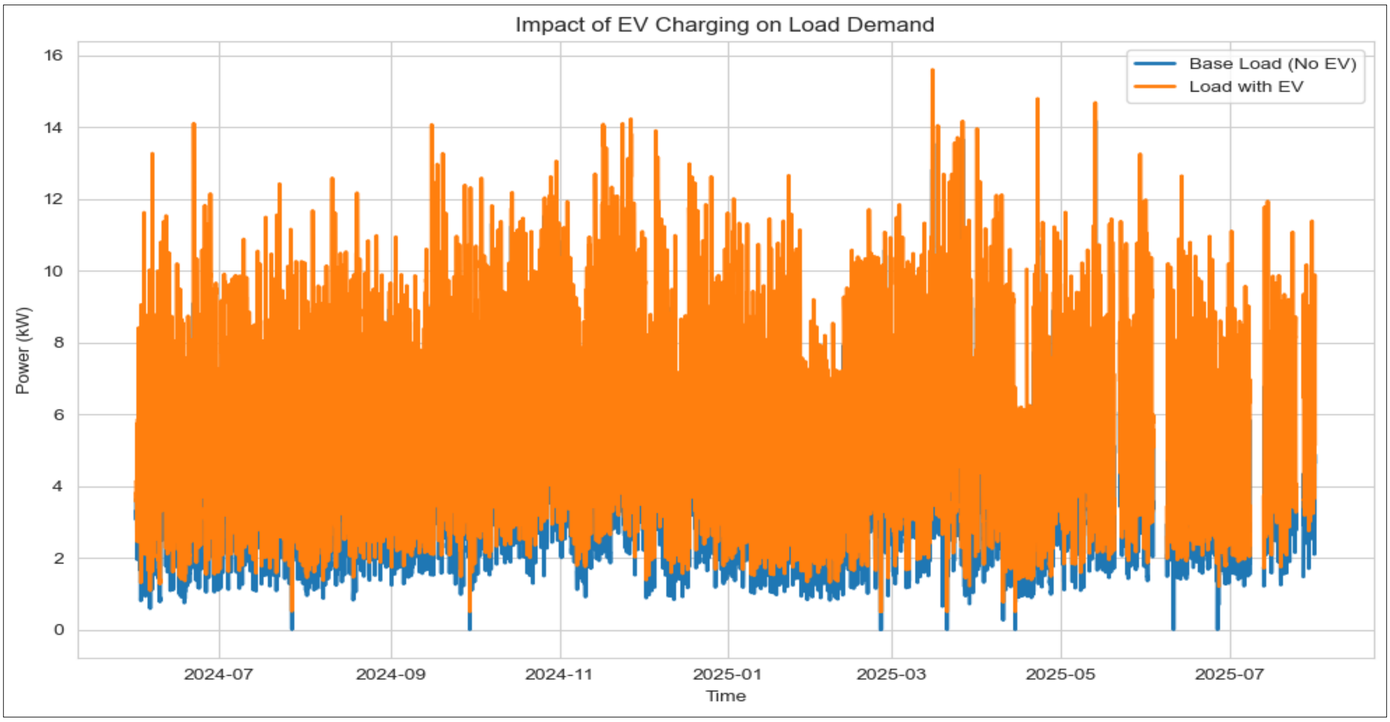

Fig 5 Impact of EV Charging on Load Demand

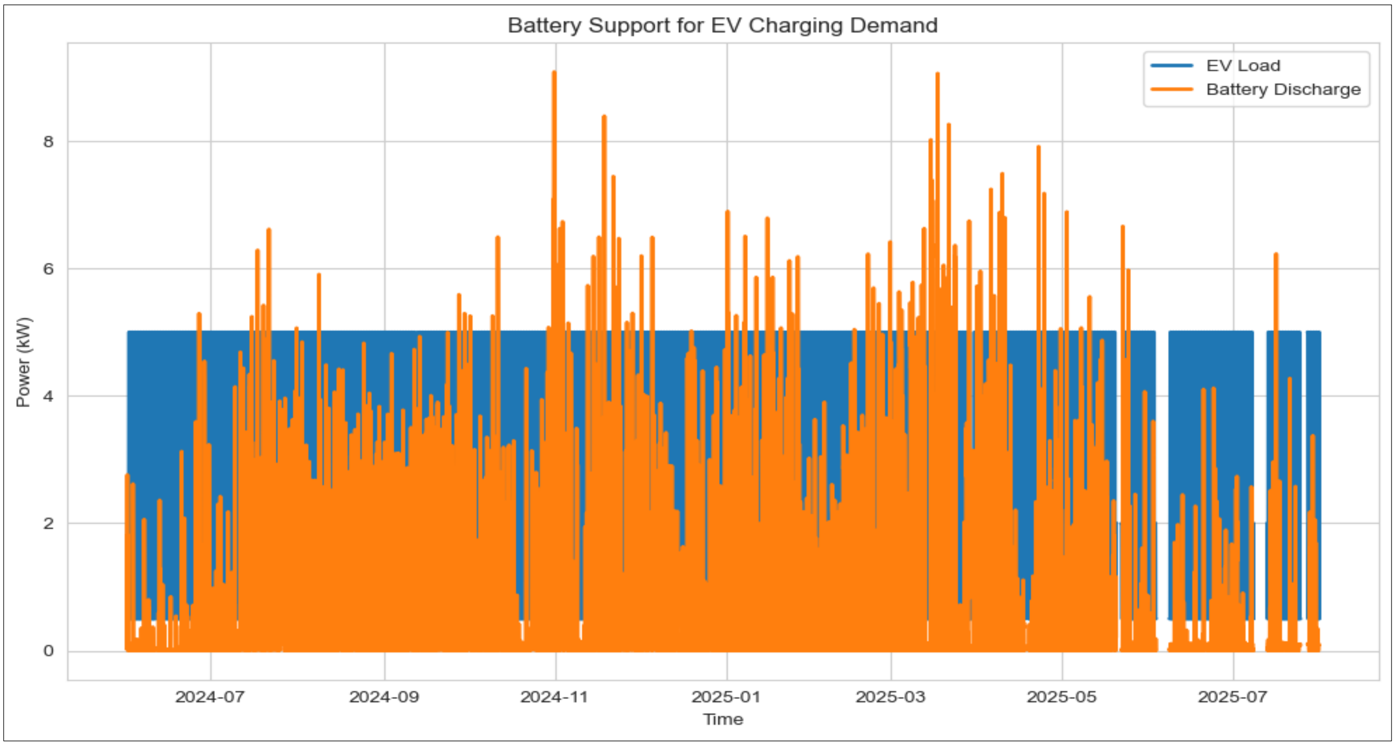

Fig 6 Battery Support for EV Charging Demand

➢ *Economic Performance and Energy Arbitrage*

The cost analysis shows the tremendous cost savings that comes with the hybrid PV systems with battery energy storage systems (BESS). The total cost of the system decreases to 54,539.32 (including battery) which is approximately 20.64 less than the cost without a battery, Table 3. In addition, grid import is reduced by 23.87, which indicates energy independence and reduced dependency on the grid.

This cost savings is primarily done with the notion of energy arbitrage where energy is stored cheaply and consumed expensively. This includes the storage of PV energy in the battery when the demand is low (and the price of electricity is low) and the usage of the stored energy when the demand is high (and the price of electricity is high). This is the best method to minimize the energy expenses and enhance the performance of the system.

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This approach is especially useful when time-of-use (ToU) tariffs are used, which have price variations that can be taken advantage of by use of storage. This price cut is consistent with the findings of Díaz-Bello et al. (2024) and Lin et al. (2024), who demonstrate that storage is a factor in the economic performance of PV systems with dynamic pricing.

The reduction in grid imports not just results in cost savings, but also in system resilience and sustainability. The decreased grid import decreases susceptibility to fluctuations in the price and enhances energy security, particularly in localities where the electricity supply is unpredictable. The results, however, also indicate that the system is not at an optimum since the grid continues to provide a lot of energy.

Battery capacity and cost have a non-linear correlation. Even though the system is currently able to provide high cost-saving, an increment in battery capacity might not have relative advantages. This is not a new phenomenon, as the literature on Energy system optimisation has emphasised the importance of optimal sizing as a means of driving cost savings and operational efficiency (Bamisile et al., 2024; Jakus et al., 2025).

Also, EV charging generates new economic aspects. EVs create an extra load on energy, which could escalate expenditures. However, EV charging can make systems more efficient in energy consumption and enhance the performance of the system in conjunction with battery storage and PV systems. This feature of EVs, which can be used as a cost and as a chance to increase efficiency, is the reason to consider holistic energy management solutions.

In a more general sense, the results confirm that battery storage is a vital component in the realization of economic efficiency in hybrid energy systems. However, its efficiency is a matter of the selection of system design, tariff and energy management policies. According to Saurabh et al. (2025), the key to sustainable and cost-effective energy systems is techno-economic optimisation.

Although battery storage has a dramatic effect on economic efficiency, the design of battery capacity is an important consideration. To address this, a comprehensive battery capacity optimization analysis is carried out in Section 4.7 to establish the optimal (cost-minimizing) size of storage and to evaluate diminishing returns.

Table 3 Economic Performance Comparison

Metric	With Battery	Without Battery
Total Cost	54539.32	68720.45
Grid Import (kWh)	293392.7	385360

Cost Savings: 20.64%
Grid Import Reduction: 23.87%

➢ *Grid Stability and Peak Load Management*

The use of battery energy storage systems (BESS) provides benefits for grid stability and peak shaving. Table 4 shows the grid variability reduced from 3.299 (without battery) to 3.169 (with battery), suggesting a stabilization of power variations. While the absolute decrease is small, it represents a significant stability mechanism, in which fast variations in net load are smoothed by the charging and discharging of the battery.

This is an important mechanism in systems with high renewable integration and random load variations, such as EV charging. Variability in the absence of battery storage is mainly caused by stochastic PV generation and random demand peaks. By using storage, excess energy can be stored when demand is low and used when demand is high, thereby reducing the variability (or spikes) in grid interaction. This finding is consistent with research in Energy storage systems which show that storage plays a vital role in enhancing system flexibility and variability (Islam et al., 2024; Aslam et al., 2025). The peak load analysis allows for further considerations of system stability. As mentioned in Table 3 above, the peak load is 19.222 kW with EV integration. But with the use of battery storage, the peak load is reduced to 15.617 kW, showing the ability of the system to smooth the load curve. This is important as peak demand affects the planning, capacity, and tariff of the system.

The Peak Shaving Effect (Figure 5) shows how the battery discharge is applied during peak demand periods, thereby reducing the demand peaks. This practice is an implicit form of demand response, substituting energy storage for grid supply. Rajendran et al. (2025) highlight that such coordinated control measures are crucial in modern smart grids, improving system efficiency and resilience.

However, while the improvements have been noted, the peak reduction indicates that the system is not completely dedicated to peak shaving. Rather, the battery storage system seems to favour economic dispatch (minimizing cost) over peak shaving. Such economic-technical trade-offs are well reported in hybrid energy systems (Bamisile et al., 2024; Dosa et al., 2025), and require multi-objective approaches to achieve cost, reliability and performance.

In a higher context, the findings affirm that battery storage helps in grid stability by not only shaving peak demand but also by flattening power profiles and increasing predictability. Such enhancements are crucial for the integration of distributed energy resources and reliable grid operation, especially in the context of growing EV adoption and variable renewables.

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Table 4 Grid Stability Performance

Metric	Value
Grid Variability (With Battery)	3.169
Grid Variability (Without Battery)	3.299

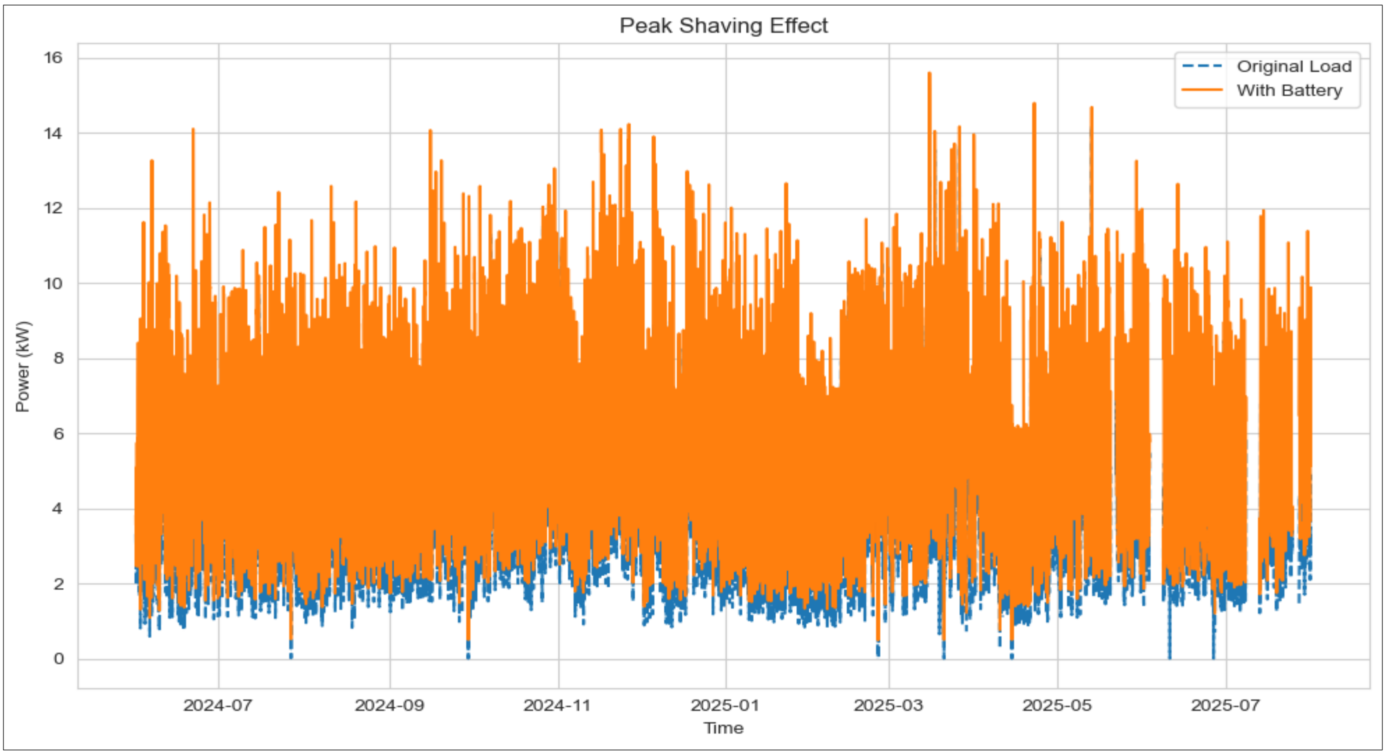

Fig 7 Peak Shaving Effect

➢ *Environmental Impact and Carbon Reduction*

The sustainability of the system shows the importance of hybrid renewable energy systems for carbon mitigation. According to Table 5, when the battery system is integrated, the total emissions are reduced from 154,143.99 $kgCO_2$ (without battery) to 117,357.10 $kgCO_2$ (with battery), representing a reduction of around 23.87%.

This is a result of reduced grid electricity consumption, which is often derived from fossil fuel sources. This energy can be stored and used in a battery system when the demand increases, hence reducing the use of grid electricity. This is an example of the beneficial effect of energy shifting, allowing to use energy from renewable sources that is generated during the day and store it for later use. The results are consistent with studies in Carbon emission reduction in energy systems that show energy storage in photovoltaic systems greatly enhances the carbon mitigation potential (Wang et al., 2024; Chong et al., 2025). In particular, the peak load reduction in the grid by batteries helps to cut down marginal emissions, which occur when the generation is at its peak. Beyond carbon emission reduction, the system's environmental performance heavily depends on the renewable energy capacity. While the system's improvements reduce emissions, there are still large emissions because it is grid dependent. So, storage helps in the environmental performance, but is constrained by the amount of PV capacity. As Saurabh et al. (2025) observe, for this system to decarbonise further, the generation and storage capacity need to increase side by side. EV charging also impacts the environmental outcomes. While EVs are generally considered as a green transportation option, the sustainability of EV charging is source dependent. In this study, EV charging plays a major role in increasing energy demand (29.95%) and therefore, increases emissions when EV is charged using conventional electricity. This shows that EV charging must be coupled with renewable energy sources. Moreover, the results suggest that the system can be used as a green charging station. By integrating EV charging with solar and energy storage, sustainable transportation systems can be enabled. This is in line with recent studies of integrated EV–renewable systems that stress the importance of energy management for sustainable transportation systems (Bilal et al., 2025; Wei et al., 2024).

Table 5 Environmental Impact Assessment

Metric	Value
Emissions With Battery ($kgCO_2$)	117357.1
Emissions Without Battery ($kgCO_2$)	154144
Emission Reduction (%)	23.87

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➢ *System Efficiency and Reliability Metrics*

The hybrid energy system's performance can also be evaluated using other metrics, including battery efficiency, self-consumption, self-sufficiency and system resilience. As shown in Table 6, the battery efficiency is 90.34%, which is in line with the efficiency of lithium-ion batteries reported in the literature (Costa et al., 2023).

The self-consumption of 142,123.33 kWh suggests that a significant amount of the generated renewable energy is used on-site rather than exported to the grid. This demonstrates an enhancement in energy efficiency, as energy generated on-site is used, thus avoiding losses associated with energy transmission and the need for external supply. But the self-sufficiency ratio is low at 25.18%, meaning the system is still heavily reliant on grid electricity to supply the demand.

This is largely due to the insufficient PV generation to meet the total load demand, and the contribution of EV charging. Hybrid renewable energy systems studies show that to improve energy autonomy and independence, appropriate sizing of generation and storage units, as well as smart energy management are necessary (Khan et al., 2025; Giedraityte et al., 2025).

The resilience index of 0.425 offers further information about the system's resilience and ability to operate without grid support. This value indicates that the system has some resilience to continue operation in case of grid outage, but not complete. To improve resilience, storage capacity and load management must be improved, and possibly supplemented by more renewable generation.

The Battery State of Charge (SoC) Profile (Figure 6) also provides insights into the storage system's operation. The bidirectional and rapid change in battery charges suggests a high level of battery usage, responsive to balancing variable demand and generation. This improves the short-term efficiency of the system, but potentially reduces its longevity and lifetime costs.

In terms of system operation, the findings reveal a trade-off between efficiency, cost and lifespan. Intensive battery use enhances economic and energy balancing but could shorten battery lifespan. This is a common insight among energy storage optimisation studies, which call for balanced control strategies that account for economic and technical considerations (Alhousni et al., 2025; León Gómez et al., 2023).

Also, incorporating EV demand adds complexity to the system operation, demanding advanced control strategies for optimal energy management. Emerging technologies such as artificial intelligence and predictive analytics have been suggested to help improve the operation of hybrid energy systems under dynamic conditions (Azad et al., 2025; Kiasari et al., 2024).

Table 6 System Performance Indicators

Metric	Value
Battery Efficiency	0.9034
Self-Consumption (kWh)	142123.3
Self-Sufficiency (%)	25.18
Resilience Index	0.425

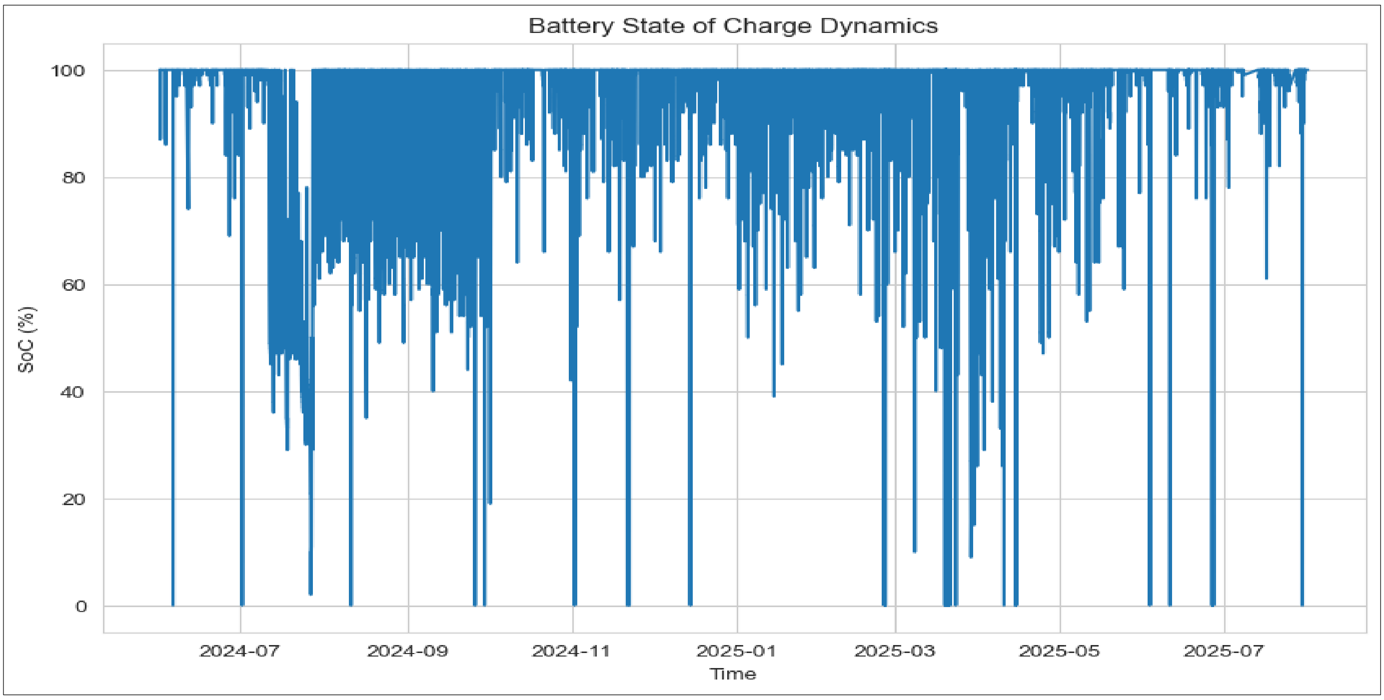

Fig 8 Battery State of Charge

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➢ *Battery Size Optimization Analysis*

A sensitivity study was carried out to identify the economically optimal battery capacity by parametric optimisation over a range of battery size from 0 kWh to 600 kWh (Bamisile et al., 2024; Jakus et al., 2025). The findings are summarised in Table 7 and Figures 9-10.

The cost optimization curve (Figure 9) shows a rapid decline in the system cost as the battery size increases from 0 kWh to 20 kWh. In particular, the total cost reduces from 68.72 to 65.93, which represents a tangible cost reduction (Lin et al., 2024; Díaz-Bello et al., 2024). But beyond this point, the cost curve is perfectly flat, suggesting that there is no further cost improvement associated with additional battery capacity.

This evidently shows the phenomenon of diminishing returns, where the improvement in cost reduction becomes zero due to higher storage capacity (Saurabh et al., 2025; Jakus et al., 2025). So, the optimal size of the battery is approximately 20 kWh. Any excess storage capacity beyond 20 kWh is not fully used and does not help to lower costs.

The same trend can be found in grid import (Figure 10). Grid import is significantly reduced from 385.36 kWh at no storage to 368.43 kWh at 20 kWh. However, larger increases in battery size do not result in a further reduction in grid import. This suggests that the surplus photovoltaic (PV) generation is fully used at relatively small battery capacity sizes.

The findings indicate that the system is more energy-limited than storage-limited; that is, the benefit of increased battery capacity is limited by the lack of excess PV generation (Khan et al., 2025; Giedraityte et al., 2025). This conclusion confirms previous observations that the PV system is relatively small compared to demand.

The findings suggest the need for simultaneous generation and storage capacity sizing in system design (Alhousni et al., 2025; Dosa et al., 2025). A higher battery capacity does not necessarily lead to better system performance, if it is not backed by sufficient renewable energy generation. This finding is consistent with other research on hybrid energy system design and operation, which highlights the importance of holistic system design for economic and operational performance.

Finally, the flatness of the optimization curve suggests that increased investment in larger battery systems would not be economically viable with the current system design (Zhang et al., 2023; Saurabh et al., 2025). Rather improvements to system performance should focus on enhancing the PV generation capacity or incorporating demand-side management to increase the value of stored energy.

Table 7 Optimization Results for Battery Capacity

Battery kWh	Total Cost	Grid Import
0	68.72045	385.36
20	65.9336	368.4257
40	65.9336	368.4257
60	65.9336	368.4257
80	65.9336	368.4257

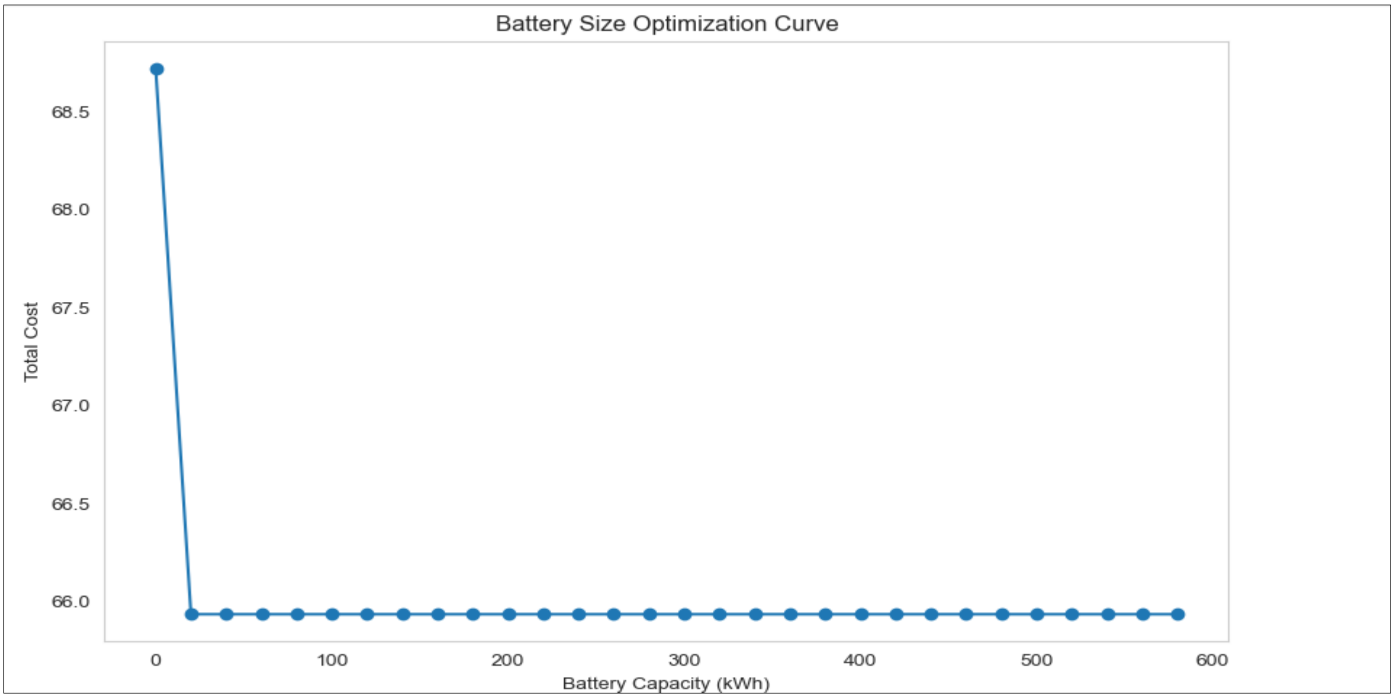

Fig 9 Battery Size Optimization Curve

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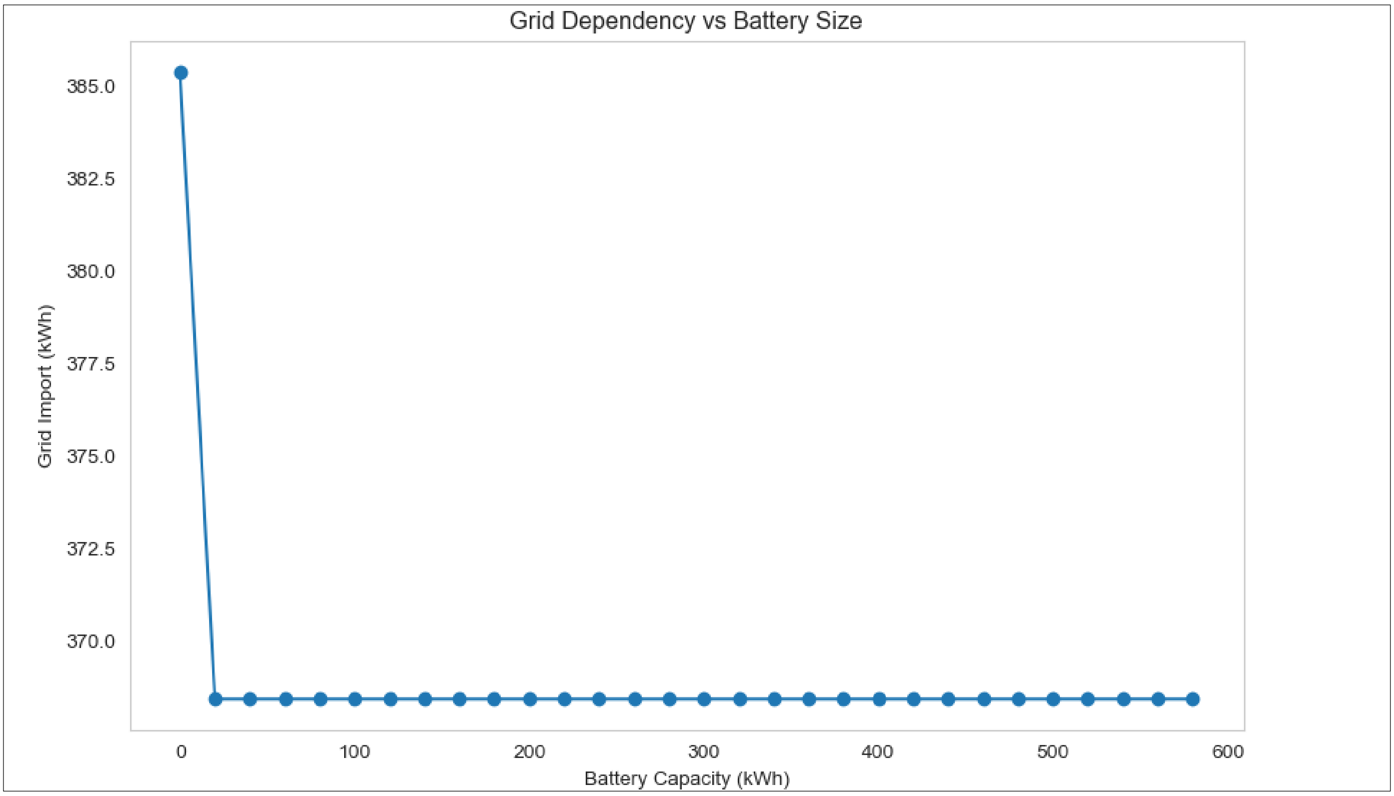

Fig 10 Grid Dependency vs Battery Size

➢ *Comparative Analysis with Existing Studies*

The outcomes are further validated by comparing with results of the previous studies available in the literature to support the robustness and relevance of the proposed hybrid PV–BESS–EV system.

The findings of this study are consistent with the previous results of photovoltaic-battery systems with time of use (ToU) pricing, which showed a 20.64% cost reduction. Guan et al. (2024) showed that energy arbitrage is effective for PV–battery systems with ToU tariffs in metro stations, with a high level of cost savings. Similarly, Lin et al. (2024) have shown that the economic advantages are substantial when scheduling PV–battery systems in industrial applications. Based on this result, the cost savings achieved in this study is consistent with the cost savings reported in the literature, showing that the system is economically viable even if the demand for EV charging is increased.

With respect to grid dependency, the recorded reduction in grid import (23.87%) is similar to Bamisile et al. (2024) who found that grid dependency of hybrid PV–battery system can vary significantly depending on the system configuration and battery size. The system has, however, a relatively high remaining grid import in this study, which further confirms this finding, as there is not enough PV capacity to cover the total demand.

In terms of environmental performance, the 23.87% carbon emission reduction aligns with the findings of Wang et al. (2024) and Chong et al. (2025), who showed that photovoltaic power systems combined with battery storage can significantly improve the potential for carbon emission reduction by decreasing the reliance on grid electricity from fossil fuels. The findings here are consistent with earlier research though: greater decarbonization will be achieved with higher levels of renewable generation capacity, and greater storage deployment.

The decrease in peak demand from 19.222 kW to 15.617 kW shows how well battery storage can mitigate load fluctuations for optimum load management and grid stability. Islam et al. (2024) pointed out that energy storage is crucial for increasing the flexibility and minimising the intermittency of renewable integrated systems. Additionally, Rajendran et al. (2025) observed that advanced energy management strategies enhance peak shaving and system stability, which is evident in the study.

From the perspective of system design, the resulting optimal battery size (~20 kWh) is in alignment with the findings from Jakus et al. (2025) and Saurabh et al. (2025), which emphasized the importance of optimal battery size for economic efficiency. When solar and wind energy supplies are relatively small, these studies show that there is no proportional improvement in performance as battery storage expands.

The overall results of this study are consistent with the majority of the earlier studies conducted on economic, environmental and technical studies. However, this is a key distinguishing feature of this work as it brings EV charging demand into a data-driven hybrid system framework and it is found that EVs make a significant difference to demand (29.95%) and system variability. This underscores the need for synchronised energy management strategies, and the need for a holistic design of energy systems, where generation, storage and demand need to be optimally balanced.

V. CONCLUSION AND POLICY IMPLICATIONS

➢ *Conclusion*

This research offers a data-driven analysis of a hybrid solar photovoltaic (PV) and battery energy storage system (BESS) combined with model-based electric vehicle (EV) charging. The research employed high resolution time series data to evaluate the technical, economic and environmental performance of the system, providing insights for designing and operating distributed energy systems. The results show a significant PV output gap (197,834.8 kWh) to meet a very small portion of demand (564,431 kWh). As a result, there is significant grid dependency, with total grid imports of 293,392.74 kWh. Yet, there is also substantial energy export (55,711.43 kWh) in this system, suggesting a temporal mismatch between energy supply and demand. This is in line with other studies of solar PV systems, where intermittent supply and demand mismatches lead to losses if no storage is present (Aslam et al., 2022; Fezzani et al., 2023). The integration of electric vehicle (EV) charging significantly changes the demand profile, adding 29.95% to the energy demand and increasing the peak load from 16.002 kW to 19.222 kW. This confirms that EVs not only create additional demand, but also variability, which correspondingly increases stress on the system. But the integration of batteries alleviates these issues through load support and energy shifting.

In terms of economics, the use of BESS leads to a cost reduction of 20.64% and a grid import reduction of 23.87%. Such reductions are mainly achieved through energy arbitrage with time of use pricing, where the battery is discharged during periods of high cost. This conclusion is supported by previous research that highlights the economic benefits of PV systems with storage (Díaz-Bello et al., 2024; Lin et al., 2024). However, the study also shows that battery sizing exhibits diminishing returns, suggesting an optimal system design.

From a grid perspective, the system exhibits enhanced stability, reduced variability and peak shaving. The battery lowers peak demand to 15.617 kW and minimises variability, improving system stability. These enhancements are essential for managing renewable energy and EV loads in power systems, as highlighted in Smart grid systems studies (Islam et al., 2024; Rajendran et al., 2025).

In terms of environmental sustainability, the system achieves 23.87% carbon emissions reduction, showing hybrid renewable energy systems' role in decarbonisation. However, the residual emissions indicate storage capacity is not adequate to achieve deep decarbonization without increasing the renewable generation capacity. This finding is in line with research on renewable energy systems that emphasise the need to increase generation and storage capacity together (Saurabh et al., 2025; Wang et al., 2024).

Finally, the studies demonstrate that while hybrid PV-BESS systems improve economic efficiency, grid stability and sustainability, the full energy autonomy can only be achieved with a holistic approach to optimal PV-BESS sizing, control and additional renewable capacity. The inclusion of EV demand also highlights the importance of smart energy management in achieving system performance and sustainability.

➢ *Policy Implications and Recommendations*

This study offers several key insights for policymakers, energy planners, and stakeholders on the deployment of hybrid renewable energy systems.

First, the high reliance on grid electricity even with PV-installed systems underscores the need for policies on system sizing. Governments should implement policies that promote the proper sizing of PV and energy storage to ensure the performance goals of renewable energy deployments are met. Small-sized systems limit the impact of renewable energy integration and introduce inefficiencies.

Second, the proven cost reductions from using batteries provide a clear case for subsidies to promote energy storage adoption. Policymakers should explore subsidies, tax credits or low-interest loans to promote the installation of battery storage, especially in areas with time-of-use electricity rates. This can help drive the shift to a more efficient and sustainable energy future.

Third, the substantial demand impacts of EV charging highlight the importance of managed and smart EV charging policies. Without proper coordination, EV charging can lead to higher peak demands and grid stresses. Thus, incentives for smart charging, encouraging EV owners to participate in demand response and offering time-of-use tariffs to EV owners are crucial. This can help match EV charging demand with renewable energy supply and mitigate grid impacts, as discussed in research on EV-grid interactions (Wei et al., 2024; Neeraja et al., 2025).

Fourth, grid stability and peak load reduction measures show the role of storage systems in enhancing grid flexibility and stability. Policy makers should include energy storage in national grid planning and as a crucial element of the energy system. This finding is in line with Distributed energy resources research which identifies storage as critical to resilient and flexible energy systems (Kulkarni et al., 2024; Pastore, 2026).

Fifth, the environmental studies indicate a need for increased renewable energy uptake for decarbonisation. While storage improves the environment, it requires higher renewable energy. As such, policies should prioritise increasing solar capacity to support storage deployment for decarbonisation. Finally, the high levels of cycling for the battery suggest that lifecycle and degradation impacts should be considered in system operation and policy. Policies should encourage the adoption of smart energy management to achieve economic and environmental benefits.

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➢ *Future Research Directions*

This research provides a valuable insight into hybrid solar PV-BESS systems with integrated EVs, but there is room for improvement.

Future research is needed on new energy management strategies, including artificial intelligence and machine learning techniques. These can enhance the performance of the system through predictive control, load prediction and adaptive battery scheduling, as discussed in Artificial intelligence in energy systems studies (Azad et al., 2025; Kiasari et al., 2024).

In addition, incorporating real EV charging profiles would make the study more applicable. This study assumes a simulated EV charging demand, but real EV charging demand may be more variable and uncertain and require further study.

Further research is also required to explore multi-objective optimisation, considering cost, emissions, reliability and battery degradation. This will provide more comprehensive system design and operation approaches, such as hybrid system optimisation studies (Bamisile et al., 2024; Nassef et al., 2023).

Lastly, hybrid renewable energy systems (consisting of wind and solar) should be considered to reduce variability and enhance reliability. This can help satisfy the energy demand and improve system performance.

Finally, future work needs to consider battery degradation and lifecycle costs to assess the long-term behaviour of storage technologies. This is essential to meet the long-term system operation.

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