Development of PV/Battery Grid-Connected System for Efficient Charging of Plug-in Electric Vehicles in Residential Areas in Thailand

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Received July 11, 2024, Revised May 1, 2025, Accepted May 15, 2025, Published June 30, 2025

Abstract. *This paper explores the development of photovoltaic (PV) and battery grid-connected systems to enhance plug-in electric vehicle (EV) charging in residential areas. The study employs a rooftop PV grid-connected system designed for a residential area with typical monthly electricity consumption, aiming to analyze the impact of power usage on household EV charging. The proposed system evaluates and compares four EV brands with power ratings of 105, 110, 120, and 110 kW. Findings indicate that the average daily power demand is 8 kWh, covering both quick and conventional charging modes. Among the four brands, the second brand exhibited the highest energy consumption for fast charging, totaling 3,096 kWh annually, while the fourth brand consumed the most power for normal charging, reaching 2,859 kWh per year. The annual electricity procurement cost from the grid was calculated at 76.80 kWh. PVsyst analysis revealed a system performance ratio of 76.6%, capable of generating 21,826 kWh/year, with 5,390 kWh/year consumed by AC loads. Financial assessments identified the optimal choice for the 120-kW fast charger from the fourth brand. The study confirms that integrating PV with a battery energy storage system offers an efficient solution for improving plug-in EV charging in residential microgrids.*

Keywords:

Microgrid, PV-rooftop, electric vehicle

1. Introduction

The uncontrolled charging of multiple electric vehicles (EVs) can strain power distribution systems, causing operational challenges for utilities, such as power disturbances, load imbalances, transmission losses, voltage drops, and overloading. The severity of these impacts depends on the number of EVs in use and the existing grid infrastructure [1]. To mitigate these issues, various strategies have been explored. One approach involves implementing smart charging schedules through information technology, which requires substantial investment. Another solution is deploying widespread EV charging stations to accommodate varying charging standards [2]. However, this method may introduce inefficiencies, installation complexities, and higher costs, as it often necessitates integrating additional low-cost renewable energy sources into the grid [3].

Distributed generation (DG) systems, such as photovoltaic (PV) arrays, wind turbines, and fuel cells, can be integrated into EV charging stations to support grid-connected renewable energy solutions. However, while renewable energy penetration enhances sustainability, it can also reduce grid inertia—particularly in residential areas—potentially destabilizing power systems [4]. Meanwhile, the growing adoption of EVs is accelerating the deployment of charging stations to replace conventional internal combustion engine (ICE) vehicles, as illustrated in Figure 1 [5].

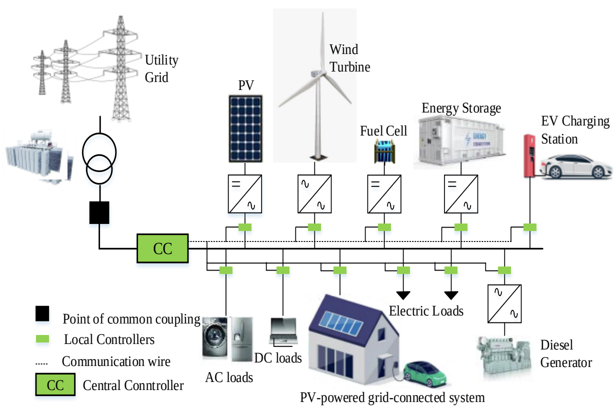

Fig. 1 Configuration of the power system in the residential areas [11].

Depending on application requirements, these renewable sources and loads can be connected to the grid via single- or three-phase power converters [6-9]. Yet, unmanaged EV charging from the grid may lead to power imbalances and increased demand, risking voltage and frequency instability [10]. Such fluctuations strain the power system and could degrade the EV battery lifespan. Further research on PV/battery-powered EV charging infrastructure is essential to improve grid stability in residential areas.

Recent studies have explored various approaches to enhance power system stability in residential areas through vehicle-to-grid (V2G) technology [12-16]. V2G enables bidirectional power flow, allowing EVs to supply active and reactive power to the grid while providing ancillary services. Complementary research has investigated PV-powered grid-connected systems that synergize with V2G to improve overall system stability. These systems employ advanced converters capable of regulating grid voltage and frequency fluctuations through dynamic power exchange while detecting critical grid abnormalities such as blackouts and enabling a seamless transition to islanding mode. This study proposes an integrated PV/battery grid-connected system to optimize plug-in EV charging infrastructure in residential areas. The system architecture incorporates rooftop PV generation with battery storage, enabling localized EV charging while minimizing grid dependence. A key innovation lies in its ability to adapt to stochastic EV charging patterns through intelligent power management. The principal contributions of this work are threefold: (1) development of a comprehensive design framework for PV/battery renewable energy systems in residential microgrids; (2) implementation of an energy management strategy that reduces grid dependency while ensuring reliable EV charging; and (3) optimization of battery storage configuration to meet dynamic power demands, ensuring consistent charging capability regardless of user behavior patterns.

This paper is organized into seven sections. Section 2 analyzes residential power system configurations and their operational characteristics. Section 3 introduces a novel PV-battery grid-connected architecture to enhance power stability in residential microgrids. Section 4 develops a comprehensive methodology for evaluating system efficiency through advanced performance metrics. Section 5 investigates the dual impact of EV proliferation on utility infrastructure and demand-side management. Section 6 describes the experimental framework, including system parameters and validation datasets used to assess the proposed solution's efficacy. Finally, Section 7 synthesizes key findings and discusses their implications for future research and implementation.

2. Power Systems in Residential Areas

This section presents a comprehensive overview of residential electrical power systems, particularly rooftop photovoltaic (PV) systems integrated with battery energy storage (BES). As illustrated in Fig. 2, typical residential power systems incorporate multiple distributed energy resources (DERs), including PV arrays, wind turbines, diesel generators, and various energy storage technologies, serving diverse load profiles. Optimal system design necessitates careful capacity configuration of these components to ensure cost-effectiveness and operational efficiency [17].

Modern residential power systems integrate renewable energy sources, clean energy technologies, and advanced energy storage solutions to form hybrid microgrid architectures. This heterogeneous composition of distributed energy resources demands sophisticated monitoring systems capable of (1) enhancing system reliability through continuous performance assessment, (2) enabling remote configuration and control via standardized communication protocols, and (3) facilitating data-driven operational optimization. The collection and analysis of historical operational data are significant and serve as the foundation for accurate system state forecasting and subsequent control strategy refinement.

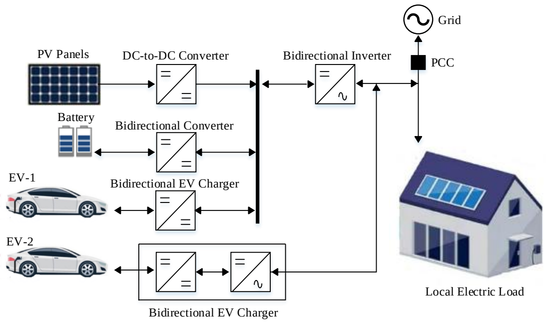

Fig. 2 Configuration of rooftop PV/Battery-powered EV charging system [11].

This study aims to optimize electricity utilization and electric vehicle (EV) charging infrastructure in residential areas, as illustrated in Fig. 2. We evaluate the performance of residential power supply systems incorporating lithium-iron phosphate ($LiFePO_4$) battery technology, with three primary objectives: (1) increasing electricity consumption capacity, (2) reducing grid electricity expenditures, and (3) minimizing EV-related fuel costs. Our case study examines a residential configuration with average daily AC loads exceeding 150 kWh/month [18], employing NASA satellite-linked simulation software to model rooftop PV system performance at the target location.

The research focuses on developing an enhanced energy management system that integrates battery storage for EV charging applications. This approach addresses critical challenges in residential power systems, particularly the grid stress caused by concurrent EV charging demand. We propose an algorithmic framework to (1) determine optimal battery system specifications for residential applications and (2) predict EV charging patterns to accommodate anticipated demand growth. The developed system demonstrates significant potential for mitigating peak load impacts while maintaining charging accessibility.

3. PV/Battery-Powered EV Charging System

The proposed rooftop PV/battery-powered EV charging system offers a sustainable solution for electric vehicle charging while reducing carbon emissions associated with conventional fossil-fuel power generation. This system enables EV charging through solar energy during grid outages or insufficient supply conditions. As demonstrated in Fig. 3, the integrated PV generation combined with vehicle-to-grid (V2G) technology [19] reduces peak demand and improves overall power system stability.

The system architecture consists of several key components: photovoltaic arrays for renewable energy generation, DC-DC converters with maximum power point tracking capability to optimize PV output, bidirectional EV chargers for controlled charging/discharging operations, and bidirectional inverters for efficient power transfer between system components. The charging infrastructure connects to the primary grid through these bidirectional inverters, which manage power flow between the PV system, grid, and local loads. In this configuration, the PV array primarily supplies electricity for EV charging, with excess power either supporting household loads or feeding back into the grid. The MPPT-enabled DC-DC converter ensures maximum energy harvest from the PV array, while the bidirectional charger facilitates optimal energy management of vehicle batteries.

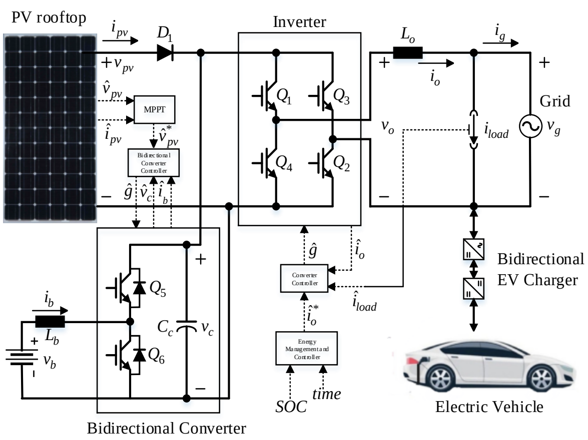

Fig. 3 Structure of rooftop PV-powered EV charging system [20]

4. Charging Behavior for Electric Vehicles

Conductive charging, the predominant method for replenishing electric vehicle (EV) energy, employs wired connections to achieve high efficiency and operational simplicity as the International Electrotechnical Commission (IEC) standardized. This study examines two primary charging modalities: (1) onboard chargers with single-phase AC power ratings ≤7 kW and (2) three-phase quick chargers capable of delivering ≤22 kW. The latter, commonly called DC fast charging (DCFC), utilizes dedicated DC conversion systems coupled with Battery Management Systems (BMS) to enable rapid energy transfer unimpeded by onboard charger limitations. Such high-power systems necessitate three-phase infrastructure and are predominantly deployed in public charging stations where minimal charging duration is critical. The IEC 62196 standard [21] governs these charging system interconnections. However, widespread EV adoption, particularly with high-power fast charging, presents substantial challenges to grid capacity. Transmission system overloads may occur even under conventional charging scenarios, necessitating accurate modeling of EV charging loads. Our simulation framework incorporates the following key parameters: EV specific energy consumption profiles, Travel behavior patterns accounting for vehicle specifications (make/model), battery performance characteristics, and EV market penetration rates and Projected EV adoption growth trajectories.

Given substantial variations across EV manufacturers and models, our methodology aggregates manufacturer-specific data to establish representative power demand profiles. The travel range estimation, derived from mean distance metrics, enables state-of-charge approximation through Equation (1) by incorporating maximum achievable travel distances.

$$BRCV = \frac{\bar{x}_{EV}}{e_{EV} \times \eta} \quad (1)$$

where $BRCV$ is the battery remaining charge volume of EV penetration level, $\bar{x}_{EV}$ is the average distance of EV mileage in daily life, e_{EV} is the energy consumption, and η is energy conversion efficiency, respectively.

The residual charge capacity of the battery within the large-scale power system is quantified by Equation (2). The annualized energy expenditure for EV charging operations is a multivariate function incorporating several key parameters: (1) remaining battery capacity, (2) charging power level, (3) prevailing electricity tariffs, and (4) economic inflation rate. This comprehensive cost relationship is mathematically expressed through Equation (3).

$$BRCV_i = \alpha \times H_{EV} \times BRCV_0 \quad (2)$$

$$Cost_i = BRCV_i \times t \times C_{energy} \times \lambda_{Inflation} \quad (3)$$

where α is the growth rate coefficient of EV, H_{EV} is EV density, i is The yearly period of estimation, t_C is charging time rate, C_{energy} is Energy charging cost in a day, and $\lambda_{Inflation}$ is a collecting factor depending on the economy, respectively.

The charging duration for electric vehicles (EVs) is principally determined by the battery's current state of charge (SOC). Accurate modeling of EV charging patterns requires simulation of multiple charging cycles occurring at different times of day when connected to the grid. As shown in Fig. 4, the EV charging demand profile can be characterized by normally distributed departure and return times. This study further examines the impact of EV adoption on utility power generation systems, contextualized within national objectives for power generation capacity expansion. Our analysis builds upon the 2015 assessment framework while incorporating updated electricity demand projections for 2015-2036 [22].

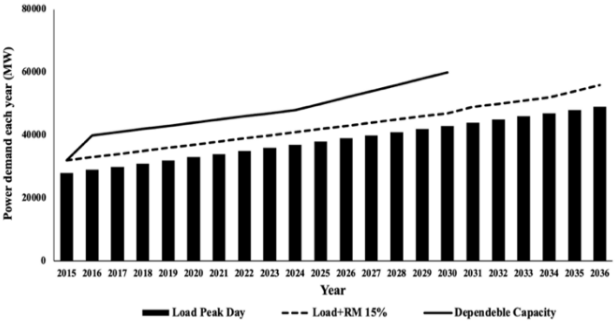

Fig. 4 Maximum power demand each year.

The EV power demand is modeled through a comprehensive framework for heterogeneous EV types and their respective charging characteristics. Our impact assessment focuses on the 2015-2036 timeframe, corresponding to the anticipated significant EV market penetration and adoption period. The analysis integrates national electricity demand projections with temporal EV charging patterns, evaluating system-wide impacts at hourly resolution. Peak demand scenarios are presented in Figures 5 and 6, illustrating the maximum loading conditions resulting from widespread EV charging.

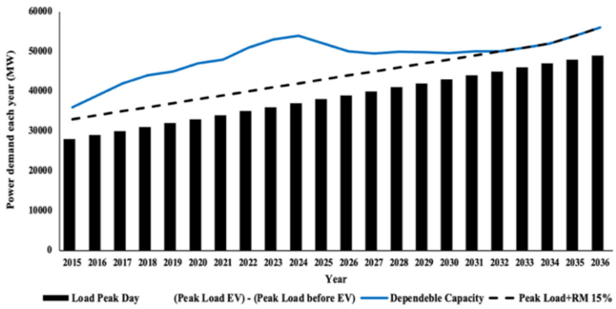

Fig. 5 Maximum power demand each year considering the charging of EVs (probable case).

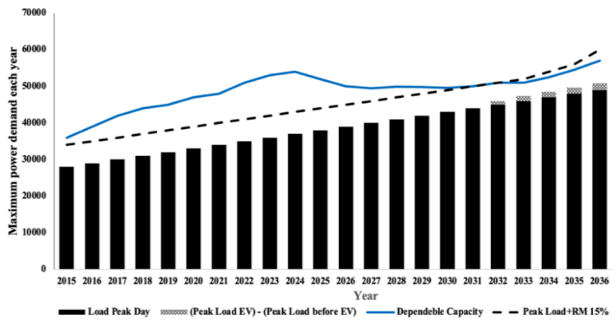

Fig. 6 Maximum power demand each year considering the charging of EVs (extreme case).

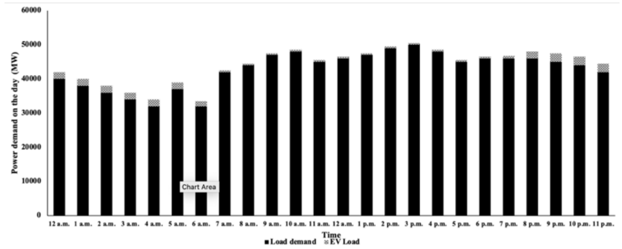

Fig. 7 Power demand on the day.

The analysis reveals that EV adoption will not significantly strain power generation systems, as the projected electricity demand—even when accounting for annual peak loads with a 15% capacity buffer—remains below reliable generation capacity thresholds. Hourly demand assessments demonstrate this finding, with Fig. 7 showing EVs' growing but manageable influence in the 2036 impact scenario. Under normal conditions, peak demand consistently occurs at 2 p.m.; however, exceptional cases show a shift to 8 p.m., indicating a transition of peak consumption from afternoon to evening hours. Although EV charging loads are typically lower than rapid charging demands, the cumulative effect of home charging during evening return periods creates sustained electricity demand. This pattern may reduce available power reserves during early evening hours despite remaining within system capacity limits.

5. Testing Setup and Design

To achieve these objectives, we developed an integrated modeling framework. The system performance is evaluated using PVsyst software, incorporating load profile data from a residential cluster of 119 households with monthly electricity consumption exceeding 150 kWh (2023 data). Our simulation platform integrates multiple parameters into Homer Grid, including (1) PV system production metrics, (2) detailed load profiles, (3) battery storage specifications, and (4) EV charging loads. The analysis examines energy generation from rooftop solar installations and associated operational costs, particularly focusing on battery system requirements to meet residential electricity demand while supporting EV charging infrastructure. As demonstrated in Equations (4)-(5), the proposed framework enables comprehensive techno-economic assessment of microgrid configurations, optimizing both suitability and cost-effectiveness for residential applications.

$$P_{grid}+(P_{PV}\cdot\eta_{PV})+(P_{BESS}\cdot\eta_{BESS})-(P_{EV}\cdot\eta_{EV})-P_{Load}-P_{Loss}=0 \quad (4)$$

$$[P_{EV}\cdot\eta_{EV}]_t=P_{grid,t}+(P_{PV}\cdot\eta_{PV})_t+(P_{BESS}\cdot\eta_{BESS})_t-P_{Load,t}-P_{Loss,t} \quad (5)$$

where P_{grid} is the grid injected power in kW, P_{PV} is the PV demanded power in kW, P_{EV} is the EV demanded power in kW, η_{EV} is the EV efficiency in percentage, η_{PV} is the PV efficiency in percentage, η_{BESS} is the battery efficiency in percentage, P_{load} is the load demanded power in kW, P_{loss} is the total loss power in kW, and $t$is the period in second, respectively.

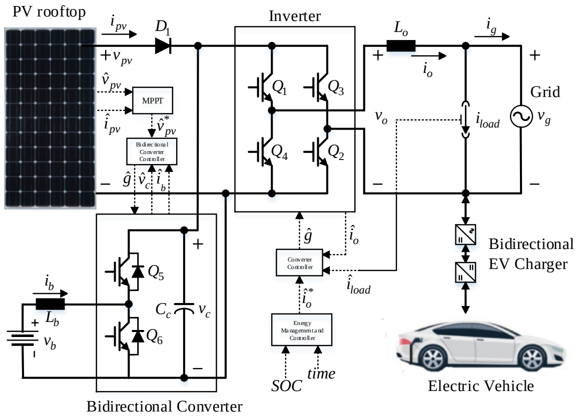

Fig. 8 Structure for supplying an electrical system to the battery of EV.

Figure 8 presents the architectural schematic of the proposed rooftop PV/battery grid-connected system with integrated EV charging infrastructure. The system operation and component interactions were analyzed through detailed software simulations, with key specifications as follows:

1. Photovoltaic Array: 345 Wp solar modules operating at [X] V and 9.55 A, achieving 17.4% panel efficiency (manufacturer specifications).
2. Power Conversion System: Bidirectional, three-phase inverter (400 V, 50 Hz) with MPPT optimization, Grid-tie certified for utility interconnection, and Demonstrated compliance with IEEE 1547 standards for distributed generation
3. DC-DC Conversion: Secondary bidirectional converter for voltage regulation and Steps down PV array voltage to match LiFePO4 battery bank requirements
4. Energy Storage: Lithium iron phosphate (LiFePO4) battery system, 480 V DC output with 50-150 kW power capacity range and Supports both stationary storage and EV charging applications
5. EV Load Characteristics: Four vehicle models representing market segments (105, 110, 120, and 110 kW) [17] and Includes both standard and high-performance variants
6. Residential Load Data: 119-household community with >150 kWh/month consumption and Utility-provided load profiles with temporal resolution

Fig. 9 details the averaged residential load profiles, showing distinct consumption patterns:

- Weekdays (Monday-Friday): blue trendline
- Saturdays: [blood → orange] trendline
- Sundays: red trendline
- Holidays: green trendline
- Monthly peak periods: brown trendline

The Homer Grid simulation platform processed these datasets using peak consumption ranges to model system performance under maximum demand conditions.

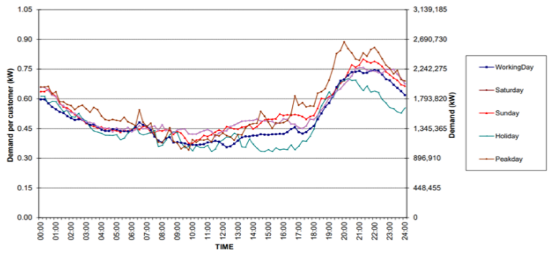

Fig. 9. Data on average power demand in the residential area.

The analysis revealed a peak average daily power consumption of 14.77 kWh for residential units, which served as the basis for dimensioning the rooftop PV system capacity. Our evaluation framework compared two charging scenarios: (1) fast charging using a 120 kW DC charger and (2) conventional charging with an 8 kW AC charger. The study incorporated four representative EV models (Brands 1-4) with rated powers of 105, 110, 120, and 110 kW respectively [17].

Key findings include: Mean daily energy requirement for EV charging: 8 kWh, Fast charging duration: 20 minutes (DC), and Standard charging duration: 8 hours (AC). The proposed microgrid architecture integrates rooftop PV generation with battery storage, which is interconnected with the utility grid. This configuration explicitly addresses the technical requirements for high-power EV fast charging while maintaining grid stability. The experimental setup modeled a 119-household residential cluster, with Fig. 10 illustrating the Homer Grid simulation results showing the characteristic 14.77 kWh daily consumption profile.

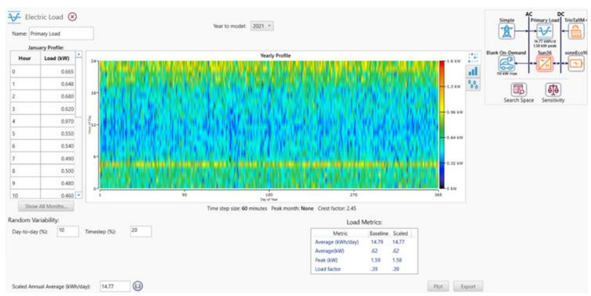

Fig. 10 Electricity consumption data in the Homer Grid.

6. Simulation Results

This study conducted a comprehensive feasibility assessment of a residential microgrid system to support EV fast-charging infrastructure and potential energy trading with utility providers. Using Homer Grid software, we simulated a 15.87 kW rooftop photovoltaic installation and analyzed its performance under two charging scenarios: High-power fast charging (120 kW DC) and Conventional charging (8 kW AC).

The evaluation incorporated four distinct EV models (Brands 1-4) with power ratings of 105 kW, 110 kW, 120 kW, and 110 kW, respectively. Our analysis focused on Comparative energy expenditure between fast and normal charging modes, Peak demand scenarios during evening charging (8 p.m.), Techno-economic viability of 120 kW fast-charging infrastructure, and Break-even analysis for system implementation. The microgrid architecture integrated lithium iron phosphate (LiFePO4) battery storage with PV generation, enabling rapid EV charging (particularly for Brand 1 EVs with 105 kW demand) and potential energy exchange capabilities. System performance was evaluated using actual residential load profiles from PV-equipped households. Key findings regarding energy consumption patterns during high-power EV charging events are presented in Figures 11 and 12.

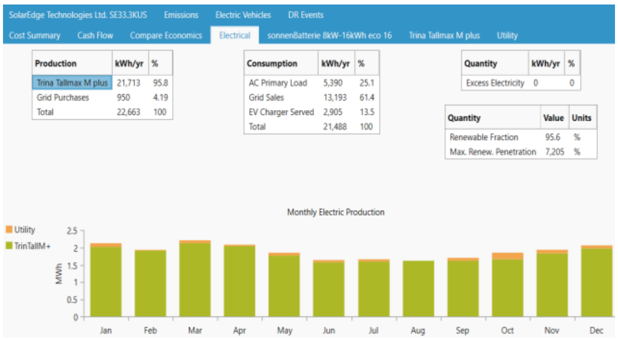

Fig. 11 Energy for charging a 1st brand of EV for a quick 120 kW charger.

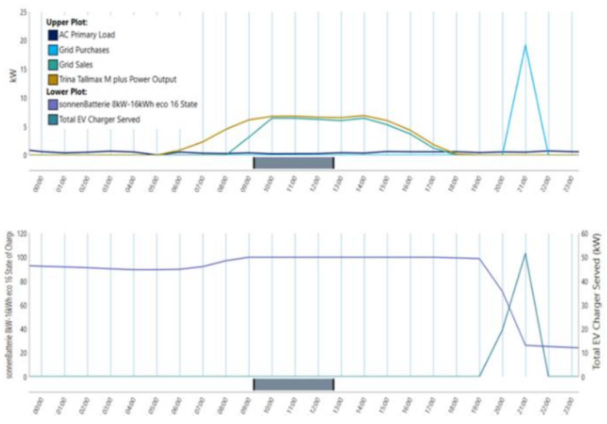

Fig. 12 Energy consumption behavior of 1st brand of EV.

Figure 11 illustrates the operational patterns of battery charging and electricity exchange within the PV-based mi crogrid system. The system demonstrates an annual energy yield of 21,713 kWh from photovoltaic generation, with 950 kWh/year of supplementary grid purchases. The energy allocation comprises 5,390 kWh/year for AC loads and 2,951 kWh/year dedicated to charging Brand 1 electric vehicles.

This distribution highlights the system's capability to simultaneously support residential power demands and EV charging infrastructure while maintaining grid connectivity for ancillary power requirements. The microgrid system demonstrates efficient energy utilization, with an annual renewable electricity generation of 22,663 kWh fully allocated across various functions. Notably, 13,193 kWh/year are exported to the Power Authority through grid interconnection. Figure 12 details the temporal energy production patterns observed between 08:00 and 17:00 hours. The system employs LiFePO4 (LPF) battery discharge to simultaneously power AC loads and support EV fast-charging operations.

Key operational phases include Energy export to the Electric Authority (EAF) from 19:00 to 22:00 hours, peaking at 50 kW, Grid power procurement between 08:00 and 18:00 hours, and Critical load support period from 20:00 to 22:00 hours. This operational strategy optimizes renewable energy utilization while maintaining grid stability through scheduled energy exchanges.

The study analyzes a residential microgrid system incorporating rooftop photovoltaic arrays and lithium-polymer (LiPo) battery energy storage designed to support electric vehicle (EV) charging operations and potential future energy trading capabilities. Our investigation focuses on a configuration optimized for residential applications, specifically examining its capacity to accommodate charging demands for Brand 1 EVs with a 105 kW power rating. The research methodology includes a detailed assessment of energy requirements for standard EV charging using 8 kW Level 2 charging stations, Temporal analysis of charging behavior, modeling typical overnight charging cycles initiating at 20:00 hours with an 8-hour duration, and Stochastic modeling of charging start times to account for user variability. The system performance and energy consumption patterns are further illustrated in Figures 13 and 14, which present the proposed microgrid configuration's detailed operational characteristics and power flow dynamics.

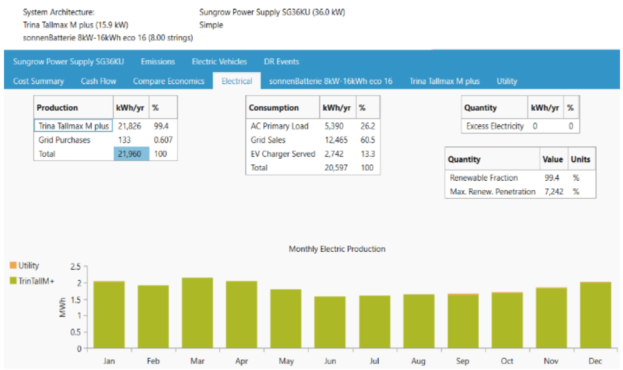

Fig. 13 Energy used of 1st brand EV.

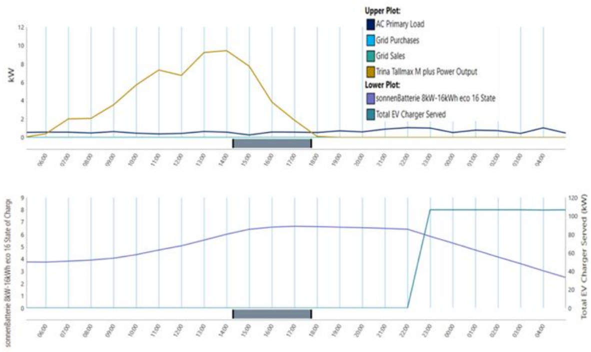

Fig. 14 Energy consumption behavior of conventional 1st brand EV.

The photovoltaic-based microgrid system demonstrates efficient energy utilization with an annual net generation of 21,826 kWh. The system's energy balance comprises Grid imports: 133 kWh/year, AC load consumption: 5,390 kWh/year, Brand 1 EV charging demand: 2,742 kWh/year, and Energy exports to utility: 12,465 kWh/year. The total renewable generation reaches 21,960 kWh/year, utilizing the energy produced entirely. System operation exhibits distinct diurnal patterns: Active power generation phase (08:00-17:00): Characterized by PV production meeting simultaneous loads and Battery discharge phase (22:00-06:00): LiFePO4 (LPF) batteries supply power for AC loads and baseline EV charging, peaking at 106 kW. The study further examines comparative energy economics for High-power fast charging (120 kW DC) and Conventional charging (8 kW AC) across four EV models with measured charging loads of 106.68 kW, 111.90 kW, 121.60 kW, and 110 kW, respectively. Baseline energy consumption approximates 8 kWh/day, equivalent to typical annual EV driving ranges.

7. Conclusions

This study demonstrated the successful development and analysis of a grid-connected PV/battery system designed to optimize plug-in electric vehicle (EV) charging in residential areas. We evaluated system performance across four major EV manufacturers with power ratings of 105 kW, 110 kW, 120 kW, and 110 kW through detailed simulation of a rooftop PV system serving a high-demand residential community. Key findings include:

1. Energy Consumption Patterns: Average daily EV charging demand ranged between 6-8 kWh, Annual fast-charging consumption peaked at 3,096 kWh (Brand 2), and Conventional charging reached 2,859 kWh annually (Brand 4).
2. System Performance: Achieved 76.6% performance ratio (PVsyst analysis), Annual generation: 21,826 kWh with 5,390 kWh AC load consumption, and Minimal grid dependence (76.80 kWh annual purchase)
3. Economic Viability: Financial analysis identified the 120-kW charging system (Brand 4) as optimal and Demonstrated the cost-effectiveness of PV/battery integration

These results confirm that hybrid PV-battery microgrid systems represent a technically and economically viable residential EV charging infrastructure solution. The system effectively addresses peak demand challenges while reducing grid dependence, with particular advantages for high-power fast-charging applications. Future work should explore scalability and grid-interaction dynamics under higher EV penetration scenarios.

Acknowledgements

This work was supported by the National Science, Research and Innovation Fund (NSRF), and Thailand Science Research and Innovation (TSRI) through Rajamangala University of Technology Thanyaburi (Grant No.: FRB680045/0168, Project Code: FRB68E0707).

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