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Aydın ATALAR[1]

[1]*Iğdır İl Özel İdaresi, Iğdır, TÜRKİYE*

aydnatalar76@gmail.com—ORCID 0000-0002-4431-7953

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Corresponding Author: Aydın ATALAR

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RESEARCH ARTICLE

Modelling PV system with Electric Vehicles in a Micro Grid

Aydın ATALAR[*1]

[*1]*Iğdır İl Özel İdaresi, Iğdır, TÜRKİYE*

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ABSTRACT

The growing deployment of plug-in hybrid electric vehicles (PHEVs) alongside residential photovoltaic (PV) systems introduces new operational complexities for modern power grids, particularly concerning load balancing and voltage regulation. This paper presents a comprehensive modeling framework that integrates a detailed PHEV demand model and a probabilistic PV generation model to assess security-related constraints in a microgrid environment. The proposed PHEV model accounts for user-specific behavior, including demographic employment patterns, brand-based vehicle specifications, and varying charging routines across weekdays and weekends. In parallel, the PV generation model simulates output using a stochastic clearness index and diverse panel configurations. The models are implemented on an expanded IEEE 33-bus distribution network to evaluate system performance under different conditions, focusing on voltage deviations, reverse power flow thresholds, and generation adequacy. Findings underscore the importance of transformer ratings and reverse power limitations, especially in the absence of grid export capabilities. Moreover, the study examines cost-effective strategies through capacity adequacy analysis, highlighting the need for optimized local trading mechanisms. The results offer valuable guidance for integrating variable solar energy with rising electric vehicle demand in microgrid settings, contributing to future work on grid resilience and energy planning.

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1. INTRODUCTION

In recent years, the swift evolution of clean energy technologies—particularly photovoltaic (PV) systems and electric vehicles (EVs)—has brought about a significant transformation in energy infrastructure and consumption models. Residential-scale PV installations have become increasingly popular as decentralized generation tools, utilizing otherwise idle surfaces such as rooftops to contribute to local energy supply. Simultaneously, the growing uptake of electric mobility, including plug-in hybrid electric vehicles (PHEVs), reflects a global effort to reduce urban emissions and transition toward more sustainable transport options [1-3].

Despite their environmental benefits, integrating these distributed energy resources into conventional power distribution systems introduces operational complexities. Among the key challenges are load-generation imbalances, increased voltage fluctuation risks, and potential overloading of network assets, particularly in distribution feeders with limited flexibility. These issues can undermine both the reliability and efficiency of power systems, particularly in high-penetration scenarios [4-6].

In response, this study develops a detailed modelling framework aimed at evaluating the simultaneous integration of PV systems and PHEVs within a residential microgrid context. The research introduces two core components: (i) a probabilistic PV generation model that considers panel-specific characteristics and irradiance variability through a stochastic clearness index, and (ii) a dynamic PHEV load model that incorporates demographic factors, brand-specific energy consumption patterns, and variable charging behavior across the week. All simulations are parameterized for the West Midlands region of the UK, ensuring contextual realism [7-9].

A modified 33-bus radial distribution network serves as the testbed for system-level assessment. The impact of increasing PV and PHEV penetration is explored through detailed analysis of voltage deviations, reverse power flow constraints, and generation adequacy. Simulations are performed using DIgSILENT-PowerFactory software to ensure technical accuracy. Additionally, economic considerations such as cost-effectiveness of PV installations are evaluated to assess the viability of proposed system configurations [9-12].

This research offers several original contributions: it introduces a fine-grained PV generation model capable of capturing environmental uncertainty; it presents a data-driven PHEV demand model reflective of user diversity and load variation; and it delivers a joint analysis of security and economic trade-offs in mixed-resource microgrids. Collectively, the study contributes toward the design of more resilient, efficient, and policy-aligned renewable energy systems that can support the ongoing transition to a low-carbon future.

2. METHODOLOGY

2.1. Generation modelling

The modeling of photovoltaic (PV) generation has been extensively studied, with various approaches developed to forecast solar power output using different techniques. This study introduces an innovative PV generation model designed to address specific gaps in existing methodologies. The proposed model is capable of calculating power generation at one-minute intervals over an entire year, making it highly adaptable for diverse power system analyses. A key distinguishing feature of this model is its incorporation of technical specifications from commercially available PV panel brands, ensuring practical relevance and accuracy.

The model simulates the minute-by-minute power output of a solar panel over a 24-hour period, which is then utilized to characterize PV generation in DIgSILENT simulations. Additionally, it aggregates daily power output data to compute monthly and annual generation profiles, enabling the development of a stochastic PV generation model for assessing generation adequacy.

2.1.1. Input Parameters:

The model requires several input parameters, including:

- Geographic coordinates (latitude and longitude) of the location.
- The specific day of the year (n) for simulation.
- Start and end dates of daylight-saving time.
- Clearness index (CI), which accounts for atmospheric conditions.
- Slope (SoP) and azimuth (AoP) angles of the PV panel.
- Panel surface area (S) and system efficiency (η).

For this study, the geographic coordinates of West Midlands, UK. (latitude: 52.48° N, longitude: 1.83° W), are used as the reference location. The slope and azimuth angles of the PV panel are set to 30° and 0°, respectively. The panel area and system efficiency are derived from the technical specifications of commercially available PV brands, ensuring a diverse and representative dataset.

The model begins by calculating solar time, accounting for the difference between local standard time and solar time. In the UK, local standard time aligns with solar time during winter, while daylight saving time advances the clock by one hour. The local standard time meridian (LSTM) for West Midlands 0.00°.

The Equation of Time (ET), which quantifies the variation between a 24-hour day and a solar day due to the Earth's elliptical orbit, is computed as follows [12-16]:

$$ET = 9.87 \cdot \sin(2B) - 7.53 \cdot \cos(B) - 1.5 \cdot \sin(B) \quad (1)$$

Where

$$B = (360 / 365) \cdot (n - 81). \quad (2)$$

The time correction factor (TC) is then calculated to adjust for longitudinal variations:

$$TC = 4 \cdot (Lo - LSTM) + ET \quad (3)$$

The hour angle (HRA), which represents the Sun's position in the sky, is derived using:

$$HRA = 15 \cdot (LT + (TC / 60) - 12) \quad (4)$$

where LT is the local time in hours. The extra-terrestrial radiation (ER) incident on the Earth's surface is estimated as:

$$ER = 1367 \cdot (1 + 0.033 \cdot cos((360 \cdot n) / 365)) \quad (5)$$

Finally, the optical depth (OR), which accounts for atmospheric attenuation of solar radiation, is expressed as:

$$OR = 0.174 + 0.035 \cdot sin\left(\frac{(360 \cdot (n - 100))}{365}\right) \quad (6)$$

These calculations form the foundation of the PV generation model (Figure 1), enabling precise simulation of solar power output under varying environmental and operational conditions. By integrating stochastic elements such as the clearness index (Figure 2) and real-world PV panel characteristics, the model provides a robust framework for analysing the impact of solar generation on grid stability and reliability.

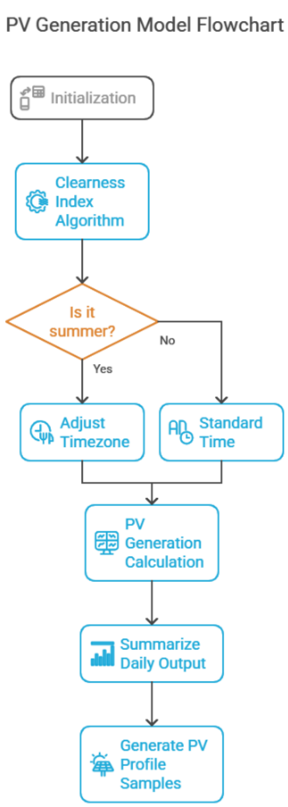

Figure 1. PV Generation Model

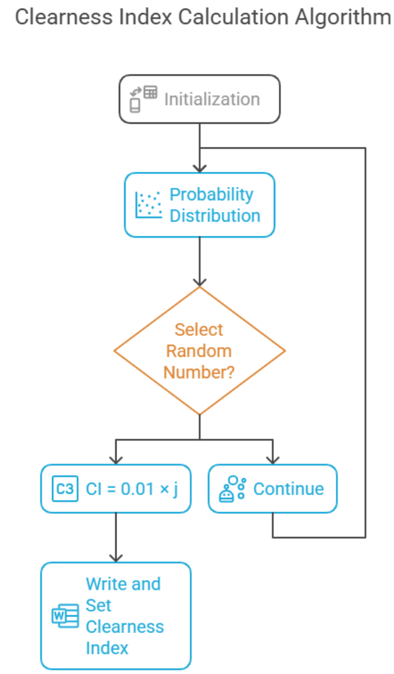

Figure 2. Clearness Index flowchart

2.2. PHEV modelling

Research on electric vehicle (EV) demand modeling has advanced significantly, with numerous studies analyzing the electricity demand of EVs from various perspectives. However, many existing models focus primarily on technical aspects and often overlook external factors that significantly influence the charging behavior of plug-in hybrid electric vehicles (PHEVs). These external factors, such as user demographics and electricity pricing, play a critical role in determining the distribution of charging times and power demand. This study aims to develop a comprehensive PHEV power demand model that simulates daily power consumption patterns for different demographic groups. By incorporating the proportion of people in various age categories and considering piece-wise electricity pricing, the model provides a realistic estimation of PHEV power demand distribution.

2.2.1. Input Parameters

The model (Figure 3) utilizes the following key parameters:

- **Battery capacity of PHEV**: Determines the energy required for charging.
- **Type of charger**: Influences the charging power and duration.
- **Electricity price levels**: Includes peak, shoulder, and off-peak rates, which affect charging behaviour.
- **Demographic distribution**: Based on the British population age structure, categorized into three groups:
  - Under 18 years (18.9% of the population).
  - Between 19 and 64 years (63.1% of the population).
  - Above 65 years (18% of the population).
- **Charging time and date:** Reflects the variability in charging patterns across weekdays and weekends.

2.2.2. Electricity Pricing Structure

The model incorporates a time-of-use (TOU) pricing scheme to simulate the impact of electricity costs on charging behaviour. The pricing levels are defined as follows:

- **Peak price**: Applies from 3:00 PM to 9:00 PM on weekdays.
- **Shoulder price**: Applies from 7:00 AM to 3:00 PM and from 9:00 PM to 10:00 PM on weekdays, and from 7:00 AM to 10:00 PM on weekends.
- **Off-peak price**: Applies from 10:00 PM to 7:00 AM every day.

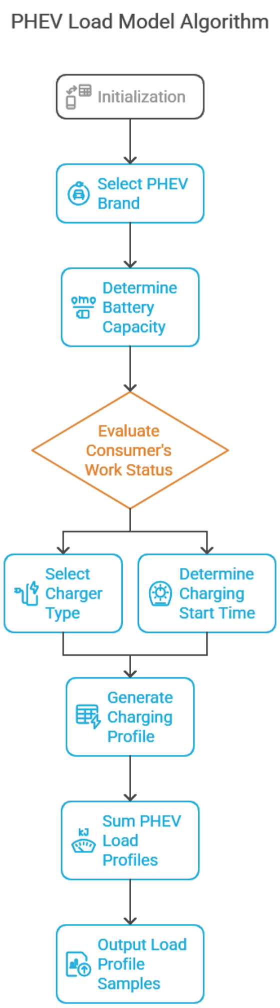

Figure 3. PHEV load model

3. CASE STUDIES

3.1. 33-Bus system topology

The simulation is conducted on a 12.66 kV, 33-bus radial distribution system, as illustrated in Figure 4. This test system has a total peak load of 3715 kW and 2300 kVAr, making it a suitable benchmark for validating the proposed renewable energy integration scheme. The primary focus of the simulation is to assess the stability and reliability of the system, ensuring that the implemented solution is feasible and effective.

A key component of the test system is the modified analysis block, highlighted in a red box in Figure 5. This block represents a low-voltage (LV) bus serving a residential community. The community comprises several households, each equipped with essential electrical components, including PHEV loads, household appliance loads, and PV generation systems. The characteristics of this block, such as time-dependent behavior and scaling factors, are adjusted to reflect real-world community conditions. By modifying the parameters of these components, various test scenarios can be simulated to evaluate system performance under different conditions.

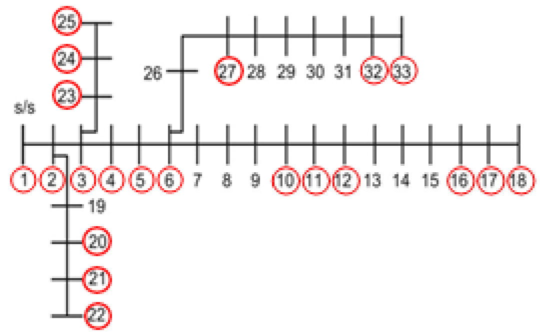

Figure 4. Utilized 33-bus system topology

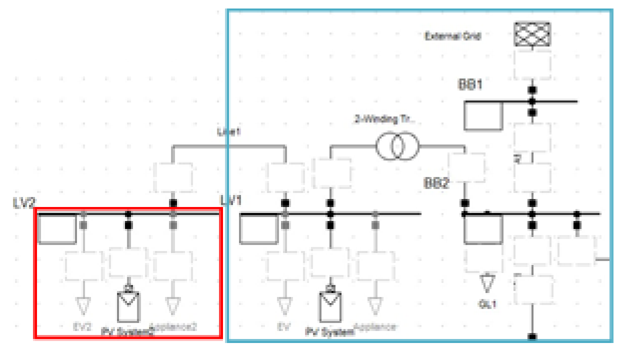

Figure 5. A schematic diagram presents modified buses

3.2. Case 1: Voltage impact of the distributed system

The case study 1 evaluates the integration of solar-powered homes and PHEVs in a 33-node distribution system with 21 LV buses connected to HV buses. Transformers are rated at 1 MVA, and two constraints are applied: PV output must not exceed transformer capacity, and voltage increase must stay within 5%.

3.2.1. Key Findings

PV Integration:

Buses near the utility grid (HV1-HV6, HV20-HV27) are limited by transformer capacity, with voltage increases remaining stable. Buses at the system's end (HV10-HV12, HV16-HV18, HV32-HV33) are constrained by voltage fluctuations. The maximum PV capacity for the system is 14.9978 MW.

PHEV Integration:

Under zero PV generation, only select buses (HV1-HV5, HV20-HV24) can handle additional loads without voltage drops. The maximum additional load is 7.7771 MW (4.908 MW appliances, 2.863 MW PHEVs).

System Constraints:

Voltage fluctuations are minimal near the grid but increase toward the system's end. Maximum PHEV charger capacity is 2.863 MW, considering voltage limits. This analysis highlights the importance of strategic placement and capacity planning for PV and PHEV integration to maintain grid stability.

3.3. Case 2: Generation Adequacy

3.3.1. Objective

This case study evaluates the generation adequacy of a residential microgrid system integrating photovoltaic (PV) panels and plug-in hybrid electric vehicles (PHEVs). The goal is to determine the optimal installed capacity of PV panels that maximizes revenue and efficiency while minimizing costs and losses under varying levels of PHEV penetration.

3.3.2. Methodology

The study is divided into three scenarios based on PHEV penetration levels:

- **Zero PHEV Load:** Total system load is 3.715 MW (base load only).
- **Half PHEV Load:** Total system load is 4.748 MW (base load + 50% of maximum PHEV capacity).
- **Full PHEV Load:** Total system load is 6.578 MW (base load + 100% of maximum PHEV capacity).

For each scenario, the following metrics are calculated:

- **Expected Energy Not Supplied (EENS):** Represents the energy deficit due to insufficient generation.
- **Loss of Load Probability (LOLP):** Indicates the likelihood of the system failing to meet demand.

The EENS is derived from the Expected Demand Not Supplied (EDNS) using the formula:

$$EENS = EDNS \times 8760 \ (MWh/year) \quad (7)$$

$$P\_n = R\_n - C\_n \quad (8)$$

where:

$$R\_n = P\_grid \times (EENS\_n - 1 - EENS\_n) \quad (9)$$

Eq. 9 represents the marginal revenue. C_n is the marginal cost of PV installation. The study assumes PV installation cost: £5 per watt and grid electricity price: £0.5 per watt. The intersection of marginal cost and marginal revenue curves indicates the optimal PV capacity:

Zero PHEV Penetration: Optimal capacity is ~25 MW.

Full PHEV Penetration: Optimal capacity is ~30 MW.

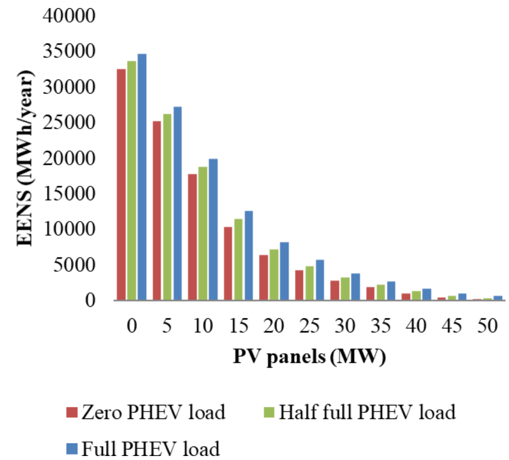

Figure 6. EENS with capacity of PVs

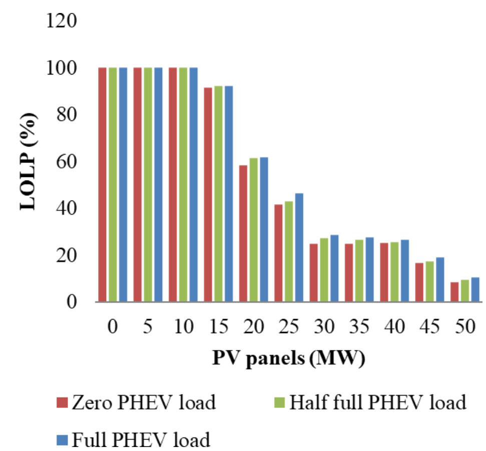

Figure 7. LOLP with capacity of PVs

3.3.3. Key Findings

Optimal PV Capacity:

- The optimal installed capacity of PV panels is approximately 30 MW, balancing cost-effectiveness and system reliability.
- Beyond 30 MW, the marginal cost exceeds the marginal revenue, making additional PV installations economically unviable.

System Reliability:

- PV capacities between 15 MW and 30 MW significantly improve system reliability by reducing LOLP.
- However, the marginal efficiency of PV panels decreases beyond 15 MW, highlighting the trade-off between reliability and economic returns.

Impact of PHEV Integration:

PHEV load has a minimal impact on LOLP trends but increases the overall system load, requiring higher PV capacity to maintain reliability.

4. CONCLUSION

This research explores the technical boundaries and system-level implications of integrating residential photovoltaic (PV) systems and plug-in hybrid electric vehicles (PHEVs) into distribution networks. By employing a probabilistic PV generation model—based on a stochastic clearness index—and a behaviorally-informed PHEV demand model, the study conducts a set of simulations on an IEEE 33-bus distribution system to assess the operational feasibility and limitations of such integration strategies.

In the first scenario, various combinations of high-voltage (HV) and low-voltage (LV) buses were analyzed to determine the allowable PV output and PHEV load capacities. Findings indicate that transformer capacity and voltage regulation constraints are primary limiting factors in systems where grid-export is permitted. Conversely, when reverse power flow to the main grid is restricted, the reverse power limit emerges as the dominant bottleneck for PV integration. For PHEV loads, the results show that abrupt increases in charging demand can cause notable voltage instability, making user behavior and temporal demand profiles critical to planning efforts.

The second part of the study focuses on long-term generation adequacy under different PV installation levels and PHEV penetration scenarios. Simulations demonstrate that while higher PV capacity can reduce metrics such as Expected Energy Not Supplied (EENS) and Loss of Load Probability (LOLP), the marginal benefit declines beyond approximately 30 MW. At this point, additional investment in PV capacity offers limited returns and becomes economically inefficient due to rising marginal costs.

To summarize, this study presents a multi-dimensional evaluation of residential PV and PHEV integration, identifying both technical constraints and economic thresholds. Key insights point to voltage control, transformer loading, and reverse flow limits as dominant factors in system design. Additionally, the research emphasizes the importance of balanced capacity planning to avoid overinvestment while ensuring system reliability. These conclusions support future efforts in policy formulation, smart grid design, and sustainable urban energy development.

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