Simulation-Based Analysis of PV Generation, Load Profiles, and Battery SOC Dynamics in Residential Energy Systems Using Simulink

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***Abstract*—This project investigates the behaviour of residential solar power systems using a detailed simulation built in MATLAB Simulink. The model represents a small neighbourhood with multiple households (4 households), each equipped with photovoltaic (PV) systems, battery storage, and unique electricity consumption profiles. The simulation runs for 7 continuous days with a 1-second time step, allowing high-resolution analysis of solar generation, household load, and energy storage dynamics.**

Solar irradiance forecasts are used to generate realistic PV production patterns, including daily cycles and sudden changes such as cloud cover. The system's response to these changes is observed through key variables like PV output, battery state of charge (SoC), and grid power exchange. Instead of implementing real-time control logic, the study focuses on how adjusting battery parameters such as capacity and operating thresholds can influence self-consumption and reduce reliance on the power grid.

The simulation results provide insights into how solar variability and diverse household demands interact with storage systems, and how thoughtful battery sizing can improve the performance of decentralised residential energy systems.

I. INTRODUCTION

The transition toward decentralised and renewable energy systems has led to a significant rise in the adoption of rooftop photovoltaic (PV) installations within residential neighbourhoods. While these systems offer environmental and economic benefits, they also introduce complexity into power system operation due to their non-dispatchable and weather-dependent nature. In particular, the variability of solar irradiance and the diversity of household electricity usage patterns make it challenging to maintain efficient and stable grid interaction.

To address these challenges, detailed time domain simulation is essential for analysing how residential PV systems behave under realistic conditions. This study presents a MATLAB Simulink-based simulation model of a small neighbourhood comprising multiple households, each equipped with a PV system, battery storage, and individualised load profiles. The simulation is conducted over a continuous 7-day period using a 1-second time step to capture high-resolution dynamics, including transient PV fluctuations and daily load behaviour.

Instead of implementing active control or real-time optimisation logic, the focus of this study is on evaluating the performance of the system under different battery parameter configurations. By adjusting battery size, state-of-charge limits, and other key settings, the simulation explores how system performance, particularly grid reliance and PV self-consumption, can be improved.

A. The research is structured around the following core questions:

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- **Q1:** To what extent do variations in simulated solar irradiance profiles influence photovoltaic (PV) power output, and how accurately does the model capture real-world diurnal solar generation characteristics?
- **Q2:** How do diverse residential electricity consumption profiles affect the level of grid reliance when integrated with rooftop PV and battery storage systems?
- **Q3:** To what extent do varying tariff levels influence cumulative energy cost across households with different load and battery configurations?
- **Q4:** To what degree can household PV self-consumption be enhanced through strategic battery hyperparameter tuning within the simulation framework?

This study aims to provide insights into the design and tuning of decentralised residential energy systems, with a focus on how storage characteristics interact with generation and demand at the household level.

II. THEORETICAL BACKGROUND

A. Photovoltaic (PV) Power Generation and Solar Irradiance

Photovoltaic systems generate electricity by converting solar irradiance into direct current (DC) electrical power using semiconductor materials. The output of a PV system depends primarily on the incident irradiance, temperature, and panel characteristics. Under clear sky conditions, solar irradiance follows a bell-shaped diurnal profile, peaking around midday.

However, weather effects such as cloud cover introduce variability and transients into this pattern.

In residential systems, PV output is typically converted from DC to AC using an inverter and can either supply the household load directly, charge a battery, or export excess power to the grid. Accurate modelling of irradiance and its effect on PV output is essential for simulating real-world performance and understanding generation behaviour across different timescales.

B. *Load Profiles in Residential Energy Systems*

Residential electricity consumption typically follows a two-peak pattern, with higher usage in the early morning and evening due to occupant routines and appliance use. These patterns vary across households and days.

In this simulation, load profiles were generated using an AI-based method designed to replicate realistic residential behaviour. [1]. Each household was assigned a unique, non-repeating profile featuring characteristic morning and evening peaks. This diversity enables a more accurate assessment of how varying demand patterns impact PV self-consumption, battery usage, and grid reliance within the neighbourhood model. [2].

C. *Battery Energy Storage and Self-Consumption*

Battery storage plays a critical role in residential PV systems by enabling self-consumption, the use of locally generated PV energy to meet local demand. During periods of excess PV generation, energy is stored in the battery. When generation is low or demand is high, the stored energy is discharged to meet the load or reduce grid dependency.

Key battery parameters considered in this study include:

- **Capacity (kWh)**: total energy the battery can store
- **State of Charge (SoC)**: the current level of stored energy
- **Charge/discharge rates**: limits on how fast energy can be stored or released
- **Initial charge condition**: the starting SoC at the beginning of simulation

In this study, no real-time control algorithm is implemented. Instead, battery behaviour is observed under different parameter configurations (e.g. varying capacity) to assess its impact on grid reliance and self-consumption.

D. *M*

odelling Framework Using MATLAB Simulink Simulink provides a graphical environment for modelling, simulating, and analysing dynamic systems. Its time-domain simulation capabilities make it suitable for evaluating the interaction between PV generation, household demand, and storage over extended periods.

The model developed in this study uses a 1-second time resolution to simulate 7 days, capturing fine-grained changes in energy flow and system behaviour. Each household is modelled as an independent system with its irradiance input, PV generation unit, battery, and load profile. Data sources such as solar forecasts and randomised loads are introduced using MATLAB scripts and integrated into the model via workspace connections [3].

By using Simulink, it is possible to visualise real-time dynamics and evaluate how different system configurations, especially battery-related parameters, influence energy performance.

III. Methodology and Model Setup

A. *Simulation Overview*

The simulation environment models a decentralised residential energy system consisting of four independent households. Each household includes a photovoltaic (PV) generator, a battery energy storage system, and a unique load profile. The model was developed in MATLAB Simulink and executed with a 1-second fixed time step over a continuous 7-day period, enabling high-resolution observation of dynamic energy behaviour.

The system components were modelled using the **Carnot Toolbox**, a Simulink-based library tailored for modelling thermal and electrical energy systems. Carnot provides standardised blocks for PV panels, batteries, electric meters, inverters, and control logic, which allows for modular and physically consistent system design [4].

At the core of the simulation is a base household model, shown in Fig. 1, which integrates key subsystems: PV generation, inverter, load consumption, battery management, and bidirectional grid connection. This base model was duplicated across the other three households, with each instance customised using:

- A unique AI-generated load profile
- Individual PV generation capacities
- Different battery sizes and parameter tuning
- Slightly varied irradiance profiles to reflect spatial diversity

Each household's model independently calculates PV production, grid export/import, battery state-of-charge (SoC), and consumption metrics. At the neighbourhood level, these outputs are aggregated to compute net grid interaction and total energy flows, as shown in Fig. **??**.

This structure enables both individual household analysis and collective system evaluation under realistic decentralised energy conditions.

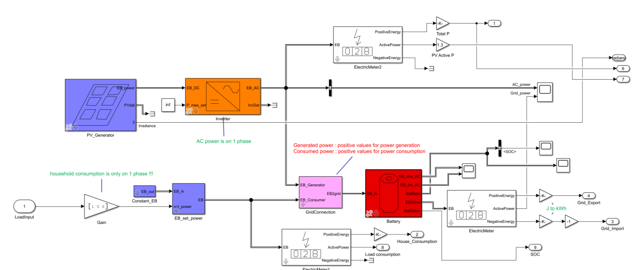

Fig. 1. Base household model including PV generator, load, battery, and grid interface.

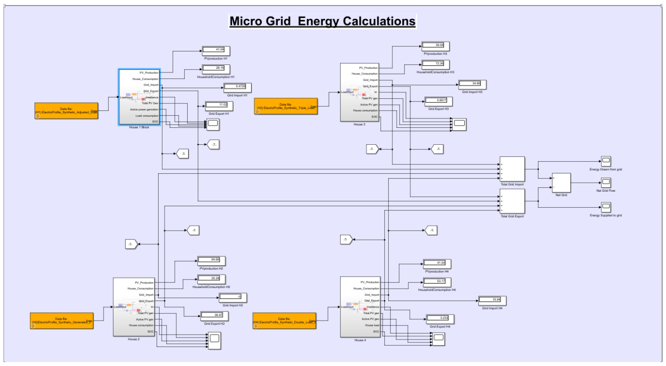

Fig. 2. Multi-household energy system layout with total grid import/export aggregation.

B. PV System and Irradiance Forecast Input

Each household in the simulation is equipped with a photovoltaic (PV) system, paired with a battery energy storage unit rated at 3 kWh. The PV subsystem is driven by real-world irradiance data specific to Gummersbach, Germany. This data was retrieved from the API provided by open-meteo.com and includes global horizontal irradiance (GHI) values at a 1-minute resolution over a continuous 7-day period. . [5].

The irradiance time series was processed in MATLAB and integrated into Simulink using a `From Workspace` block. The PV generation subsystem converts the irradiance data into DC power output, which is then passed through a single-phase inverter to simulate household AC generation.

Figure 3 illustrates the MATLAB function used to fetch and prepare irradiance data from the Open-Meteo API, generate household variants, and store them as '.mat' files for Simulink integration.

```
function irradiance_matrix = getGummersbachSolar()

    lat = 51.0261;
    lon = 7.5647;

    % Construct the API URL
    url = sprintf(['https://api.open-meteo.com/v1/forecast?', ...
                   'latitude=%.4f&longitude=%.4f&hourly=shortwave_radiation&timezone=auto'], ...
                   lat, lon);

    try
        % Fetch data
        data = webread(url);
        irradiance = data.hourly.shortwave_radiation;

        % Clean invalid values
        irradiance = double(irradiance);
        irradiance(~isfinite(irradiance)) = 0;

        % Create time vector in seconds
        n = length(irradiance);
        time = (0:n-1)' * 3600;

        % Base irradiance matrix
        irradiance_matrix = [time, irradiance(:)];

        % Generate 4 variants
        irr_H1 = irradiance_matrix;  % base
        irr_H2 = [time, irradiance(:) * 1.03];  % +3%
        irr_H3 = [time, irradiance(:) * 0.95];  % -5%
        irr_H4 = [time, circshift(irradiance(:), 1)];  % time shifted

        % Save to file for Simulink
        save('house_irradiance_profiles.mat', 'irr_H1', 'irr_H2', 'irr_H3', 'irr_H4');

        fprintf('✅ Irradiance profiles saved as house_irradiance_profiles.mat\n');

    catch ME
        warning('Failed to fetch or parse data: %s', ME.message);
        irradiance_matrix = [0, 0];  % fallback
    end
end
```

Fig. 3. MATLAB script for fetching and processing irradiance data from Open-Meteo API.

Figure **??** displays the irradiance and corresponding PV active power output for Household 1. The observed profiles exhibit consistent daily solar patterns and transient variability, reflecting realistic weather-influenced generative behaviour.

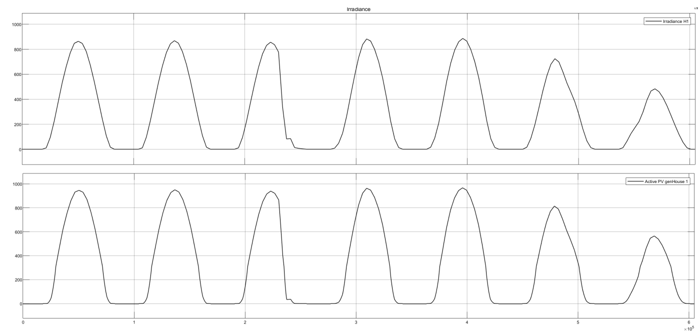

Fig. 4. Irradiance profile VS Active PV gen for Household 1 (7-day period, Gummersbach).

C. Load Profiles and Households Modelling

Each household in the simulation is assigned a unique electricity consumption profile, generated using an AI to reflect realistic residential behaviour. The load curves exhibit characteristic two-peak patterns corresponding to morning and evening usage and are non-repeating across the 7-day simulation window.

To simulate diversity, every household receives a distinct load profile with variations in amplitude and timing. This variation allows the study to analyse how different consumption patterns impact PV self-consumption and battery performance.

The system behaviour governing energy flow follows a realistic control logic. When there is no PV generation (typically during nighttime), the household load is supplied by the battery. If the battery is depleted or reaches its minimum State of Charge (SoC) threshold—set at 10%—the system begins drawing energy from the grid. Conversely, during daytime when PV generation is active, the load is first served directly by the PV output. Any surplus generation is then used to charge the battery, and once the battery is full, the remaining energy is exported to the grid.

Initial battery charge conditions were also varied to assess their influence on system performance. In this simulation, Households 1 and 3 begin with a 40% SoC, while Households 2 and 4 start at 50%.

D. Tariff Calculation

A tariff calculation module was included to compute the economic impact of grid energy import and export for each household. The logic was implemented using a `MATLAB Function` block and is applied individually to all four houses. The function uses a time-of-day-based pricing scheme with separate rates for daytime and nighttime periods.

- **Daytime (6 AM to 6 PM)**: Import tariff = €0.25/kWh, Export credit = €0.08/kWh
- **Nighttime (6 PM to 6 AM)**: Import tariff = €0.15/kWh, Export credit = €0.05/kWh

The function takes `current_time`, `grid_import`, and `grid_export` as inputs and returns the calculated `consumption_cost` and `export_credit`. These values are used to compute the net grid-related cost or savings for each household.

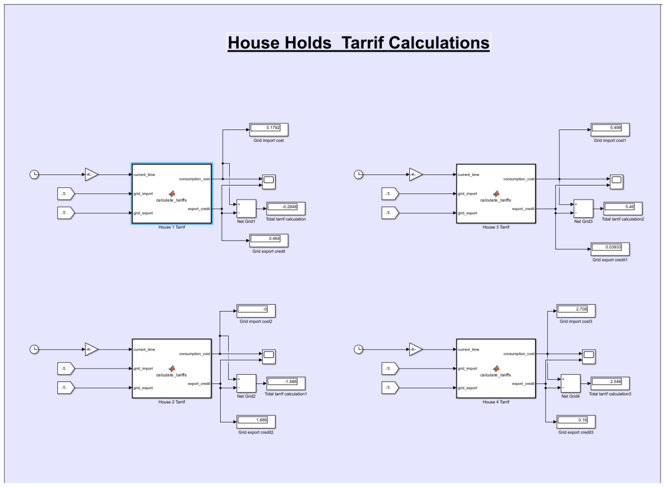

Fig. 5. Tariff calculation logic for individual households using a MATLAB Function block.

Figure 6 shows the MATLAB code used within the simulation to perform this time-dependent tariff logic.

```
function [consumption_cost, export_credit] = calculate_tariffs(current_time, grid_import, grid_export)
    % Define time-based tariff rates
    if current_time >= 6 && current_time < 18
        % Daytime tariff (6 AM - 6 PM)
        consumption_rate = 0.25;  % EUR/kWh
        export_rate = 0.08;       % EUR/kWh
    else
        % Nighttime tariff (6 PM - 6 AM)
        consumption_rate = 0.15;  % EUR/kWh
        export_rate = 0.05;       % EUR/kWh
    end

    % Calculate consumption cost and export credit
    consumption_cost = grid_import * consumption_rate;
    export_credit = grid_export * export_rate;
end
```

Fig. 6. Math function Block Script for Tariff calculation logic.

E. Simulation Configuration

The simulation was configured to run over a continuous period of 7 days, totalling 604,800 seconds. A fixed-step solver was used with a constant time step of 1 second to capture high-resolution system dynamics throughout the simulation period.

IV. Results and Discussion

A. Q1: To what extent do variations in simulated solar irradiance- ance profiles influence photovoltaic (PV) power output, And how accurately does the model capture the real-world diurnal solar generation characteristics?

To assess how solar irradiance variations influence photovoltaic (PV) output and whether the simulation accurately represents diurnal solar behaviour, irradiance and active PV power profiles were analysed for all households. Figure 7 illustrates the irradiance and resulting active PV power for House 1 over a representative 24-hour cycle.

The irradiance data used in this simulation was sourced via API integration from open-meteo.com, capturing location-specific values for Gummersbach, Germany. The PV response is modelled using Carnot Toolbox's `PV_Module_simple`, configured with a peak generator power of 1000 W, a temperature coefficient of 0.0047 1/K, and an efficiency field accounting for diode, mismatch, and dirt losses (approx. 9% in total).

The PV power output closely follows the irradiance profile, both exhibiting a clear bell-shaped curve typical of diurnal solar behaviour. Power generation begins shortly after sunrise, peaks near solar noon, and declines smoothly toward sunset. These dynamics are consistent with real-world solar energy profiles documented in the literature [**?**], reinforcing the model's credibility.

Households were assigned slightly varied irradiance signals (±5%) to reflect localised effects such as microclimate and partial shading. Despite these differences, all households showed a proportional and coherent PV response, confirming the model's robustness.

Overall, the results demonstrate that the PV subsystem accurately captures real-world solar generation characteristics and produces output that is strongly and consistently correlated with irradiance. This validates both the source data and the simulation model's capability to represent realistic PV behaviour in time-varying conditions.

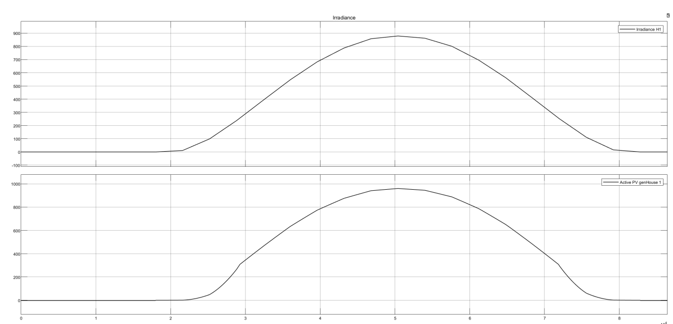

Fig. 7. Irradiance and active PV power output for House 1 over one day.

B. Q2: How do diverse residential electricity consumption profiles affect the level of grid reliance when integrated with rooftop PV and battery storage systems?

To evaluate the impact of household consumption behaviour on grid reliance, four distinct residential profiles were simulated, each using the same PV system and a 3 kWh battery with slightly varied initial SoC levels. Table I summarises the total energy use, generation, battery interaction, and grid dependence for each household over a 7-day simulation.

TABLE I
Comparison of Load Profiles and Grid Dependence

House	Load (kWh)	PV Gen (kWh)	Grid Import (kWh)	Export (kWh)	Self-Consumed PV (kWh)	Cost (€)
1	28.19	36.73	0.89	7.05	29.22	-0.21
2	25.28	58.17	0.00	30.44	27.73	-1.52
3	72.36	34.90	38.53	0.66	34.24	5.77
4	53.17	36.73	19.12	2.41	34.32	2.748

House 2 exhibited the **lowest grid reliance**, importing no energy from the grid while exporting 30.44 kWh. Its low load (25.28 kWh) and high PV generation (58.17 kWh) allowed the system to be fully energy-independent, even charging the battery for later use. This resulted in the most favourable energy cost, with a net credit of €1.52.

House 1 followed a similar trend but with a smaller generation surplus and slightly higher grid import (0.89 kWh), likely occurring during the early morning hours before PV ramp-up. The house still achieved full load coverage and returned a minor credit.

By contrast, House 3 displayed the **highest grid reliance**, importing 38.53 kWh due to its high load (72.36 kWh) and limited PV generation (34.9 kWh). Although the system maximised the use of its available PV energy (self-consuming 34.24 kWh), the shortfall required substantial grid support, leading to the highest energy cost at €5.77.

House 4 showed intermediate behaviour, importing 19.12 kWh, self-consuming a similar amount of PV as House 3, and experiencing a moderate net energy cost.

These results confirm that **household consumption patterns strongly influence grid interaction**, even when PV and battery systems are present. Households with lower demand and load-shifting patterns that align with PV production tend to self-consume more, export more surplus, and achieve energy independence. Conversely, higher or poorly timed loads significantly increase reliance on the grid.

C. Q3: To what extent do varying tariff levels influence cumulative energy cost across households with different load and battery configurations?

To evaluate the economic performance of each household under a shared time-varying tariff structure, the total energy cost and export credit over the 7-day simulation were compared across all four households. Table II summarises the energy consumption, PV generation, battery setup, and financial outcomes for each household.

The tariff structure was uniform for all houses: during daytime hours (6:00–18:00), the grid import cost was set to €0.25 per kWh, and the export credit was €0.008 per kWh. During nighttime (18:00–6:00), import cost dropped to €0.15 per kWh, and export credit was reduced to €0.005 per kWh.

TABLE II
TARIFF PERFORMANCE SUMMARY ACROSS HOUSEHOLDS

House	Load (kWh)	PV Gen (kWh)	Import (kWh)	Export (kWh)	Cost (€)	Credit (€)	Init. SoC (%)
1	28.19	38.80	1.16	9.11	0.174	0.456	40
2	25.28	61.34	0.00	33.63	0.000	1.682	50
3	72.36	36.91	36.79	0.80	5.519	0.040	40
4	53.17	38.80	17.85	2.86	2.678	0.143	50

The results show a clear divergence in economic outcomes based on household configuration and energy behaviour. House 2 achieved the most favourable outcome, with zero energy cost and the highest export credit (€1.682), despite having a relatively modest load (25.28 kWh). This performance can be attributed to its high PV generation (61.34 kWh), no grid import, and a higher initial state of charge (50%), which allowed the battery to absorb excess PV output during low-load periods.

House 1 also maintained a positive energy balance with low consumption cost (€0.174) and significant export credit (€0.456), reflecting a well-balanced PV-to-load ratio and minimal reliance on the grid.

In contrast, House 3 experienced the highest consumption cost (€5.519) and negligible export revenue, despite having a similar PV system. This is explained by its significantly higher load (72.36 kWh), high grid import (36.79 kWh), and lower initial battery charge (40%), which led to more frequent grid dependence during high tariff hours.

House 4 showed moderate grid dependence and cost, with a mid-range load profile and performance between the two extremes.

Overall, the analysis demonstrates that under a common tariff structure, cumulative energy cost is strongly influenced by the interplay between load demand, PV production, and battery behaviour. Higher initial battery SoC and larger PV surplus allow households to avoid grid imports during high-tariff periods and maximise credit from exports, even in the absence of explicit optimisation logic.

D. Q4: To what degree can household PV self-consumption Can it be enhanced through strategic battery hyperparameter tuning within the simulation framework?

To assess the effect of battery tuning on photovoltaic (PV) self-consumption, three configurations were tested for House 1, varying battery capacity and initial state of charge (SoC) while keeping the PV generation and load profile constant. The configurations included:

- **Test A (Baseline):** 3 kWh battery, 40% initial SoC
- **Test B:** 5 kWh battery, 80% initial SoC
- **Test C:** 2 kWh battery, 20% initial SoC

TABLE III
BATTERY CONFIGURATIONS AND RESULTING GRID INTERACTIONS

Config	Imp. (kWh)	Exp. (kWh)	Cost (€)	Credit (€)
A (Baseline)	0.1077	2.450	0.0162	0.1229
B (Larger Bat)	0.0000	3.181	0.0000	0.1591
C (Smaller Bat)	0.7720	3.617	0.1159	0.1808

Test B achieved complete grid independence, with zero import over the full day. The larger capacity and higher initial SoC allowed the battery to fully meet nighttime demand and store surplus PV for later use. In contrast, Test C—configured with a smaller battery and conservative SoC settings—showed the highest grid import and cost, indicating early battery depletion and inability to buffer excess PV energy effectively.

Although Test C achieved slightly higher export credit, this came at the expense of increased reliance on the grid, which under dynamic tariff conditions would be less favourable. The baseline Test A sat in between, demonstrating moderate performance.

These results highlight that strategic battery tuning—especially sizing and initial SoC can significantly enhance PV self-consumption and reduce grid dependence, even without explicit optimisation logic.

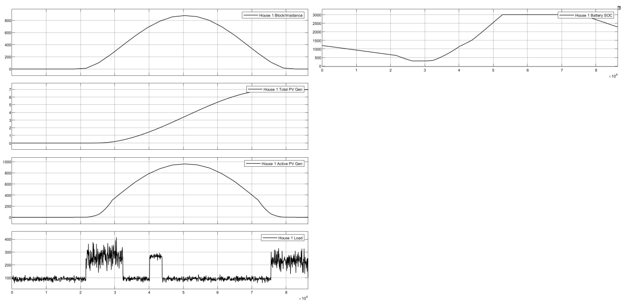

Fig. 8. Battery SoC and PV performance in Test A (baseline).

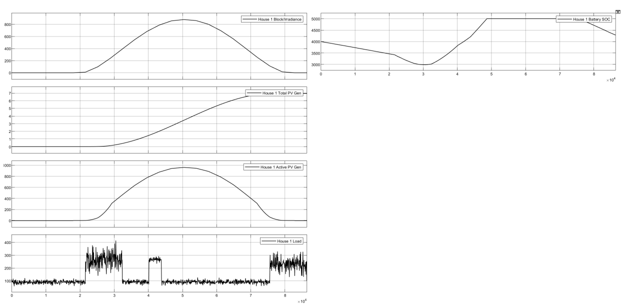

Fig. 9. Battery SoC and PV performance in Test B (larger battery, 80% SoC).

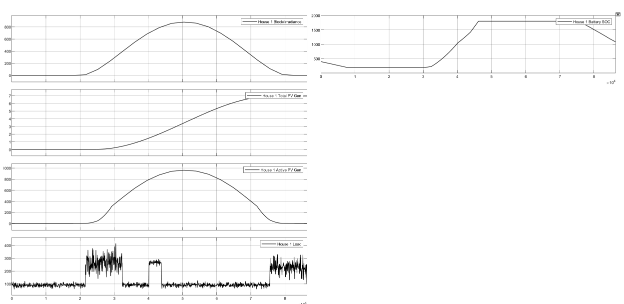

Fig. 10. Battery SoC and PV performance in Test C (smaller battery, 20% SoC).

V. Conclusion

This study presents a comprehensive, high-resolution simulation of residential energy systems integrating rooftop PV, battery storage, and diverse load profiles using MATLAB Simulink. By modelling four distinct households over a continuous 7-day period with 1-second resolution, the research captures fine-grained dynamics of PV production, storage behaviour, and grid interaction under realistic conditions.

The findings confirm that system performance is shaped not just by PV availability, but also by household-specific factors such as load demand, timing, and battery configuration. Variation in solar irradiance was shown to directly influence PV output, and the model successfully reproduced real-world diurnal generation behaviour. Furthermore, battery presence consistently reduced grid dependence, especially in households with favourable PV-to-load ratios.

Households with low consumption or better-aligned usage patterns (e.g., House 2) achieved near or total energy independence. Conversely, households with high or poorly timed demand (e.g., House 3) remained reliant on the grid despite having similar PV setups. The tariff analysis further revealed that strategic battery sizing and initial SoC choices could meaningfully reduce energy costs, even without advanced optimisation logic.

Finally, controlled experiments on battery hyperparameter tuning (capacity and SoC thresholds) demonstrated that thoughtful system configuration can significantly enhance PV self-consumption, reduce grid imports, and improve financial outcomes. These results reinforce the importance of integrated design thinking in residential energy systems and show that detailed simulation models are valuable tools for evaluating and optimising decentralised grid participation.

References

[1] A. Mellit and S. A. Kalogirou, “Artificial intelligence techniques for photovoltaic applications: A review,” *Renewable and Sustainable Energy Reviews*, vol. 13, no. 9, pp. 2189–2205, 2009.

[2] F. Rahimi and A. Ipakchi, “Demand response as a market resource under the smart grid paradigm,” *IEEE Transactions on Smart Grid*, vol. 1, no. 1, pp. 82–88, 2010.

[3] S. Nema, R. Nema, G. Agnihotri, *et al.*, “Matlab/simulink based study of photovoltaic cells/modules/array and their experimental verification,” *International Journal of Energy and Environment*, vol. 1, no. 3, pp. 487–500, 2010.

[4] H. Drück, D. Müller, C. Nytsch-Geusen, and M. Schmidt, *Carnot Toolbox – A MATLAB/Simulink Library for Building Energy Systems*, 2024.

[5] N. Herweg, “Open-meteo: Free weather forecast api,” 2024. https://open-meteo.com/.