

Optimizing BES Costs Through P2P Energy Trading in PV and Wind Communities for Stable Grid

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Abstract—The increasing energy consumption is stressing utility companies significantly, challenging their ability to meet demand and threatening power system stability. As a result of grid loading, the frequency decreases, exacerbating these issues. End users can mitigate these challenges by participating in energy generation; however, integrating renewable energy sources (RES) introduces variability and uncertainty and necessitates battery energy storage (BES) integration which adds to an increase in the overall cost. Peer-to-peer (P2P) energy trading offers a solution by reducing the additional costs of BES. This paper explores innovative strategies for minimizing the cost of BES through P2P energy trading within energy communities, particularly those utilizing photovoltaic (PV) and wind turbine technologies. This paper will explore the fundamentals of P2P energy trading, highlighting its potential to reduce storage costs by enabling direct energy exchanges between community members to enhance the grid's stability. Key sessions will cover the technical aspects of integrating PV and wind turbines and the economic benefits of P2P trading. The case study takes residential loads consisting of 15 consumers and 15 prosumers with specific load demands and integrates PV and Wind turbines at 40% of total demand with BES. Then the cost of BES is optimised through P2P energy trading. The result shows the effective strategy for avoiding the challenges related to the BES integration through how P2P trading can revolutionize energy storage economics, paving the way for more sustainable and financially viable energy communities.

Keywords—renewable energy sources, battery energy storage, Peer-to-peer (P2P) energy trading

I. INTRODUCTION

A good level of living and general well-being depend on energy. The world's population is growing at an accelerated rate, which is driving up energy consumption. Utility companies face difficulties due to this increase, particularly those that depend on conventional energy sources like fossil fuels. These resources are limited, detrimental to the environment, and prone to price swings. A move toward renewable energy sources (RES) is required due to these concerns. Investing in sustainable alternatives like hydro, wind, and solar energy is essential to meet rising energy demand and reduce greenhouse gas emissions. However, maintaining a steady and dependable energy supply is severely challenged by the intrinsic unpredictability and fluctuation of RES. To reduce RES uncertainties and preserve a balanced electricity grid, energy storage system integration is essential. These resources are usually distributed, changing from conventional customers to pro-consumers, who can manage their own energy production, use, and storage. Under the well-known feed-in-tariff policy, so-called Peer-to-grid (P2G) mode, prosumers can sell their excess power directly to

the grid for a set amount of money. However, various challenges must be addressed in advance while using the energy storage technologies, particularly battery energy storage (BES), which can be extensively used. These include high initial capital expenditures, technical difficulties in monitoring and control, the need for regular maintenance, environmental issues, and long-term deterioration.

In the context of decentralized power generation, integrating hybrid RES, such as wind and solar power, is critical for improving energy supply. By allowing end users and prosumers to actively engage in peer-to-peer (P2P) energy sharing, surplus energy may be directly shared among consumers, avoiding the need for large-scale battery energy storage systems. This technique not only maximizes the use of RESs but also reduces the need for large storage capacity to satisfy variable load needs. Furthermore, P2P improves grid stability by increasing the system's resilience during outages by facilitating direct energy trades between customers and assuring a continuous supply [1].

As P2P energy sharing promotes local power generation, it dramatically minimizes transmission losses by reducing the distance electricity must travel across the grid. This localized strategy increases total energy efficiency, reduces dependency on centralized infrastructure, and promotes a more resilient, sustainable, and cost-effective energy environment. Moreover, P2P energy sharing encourages the use of RES by allowing local generation and consumption, thus reducing carbon footprints [2]. This promotion is due to the gain of larger financial returns through competitive pricing and decreased energy costs since prosumers can sell surplus energy directly to consumers. [3] Because of all these benefits of P2P energy sharing, various demonstration projects have already been developed, including the Sonnen Community in Germany and TeMiX in the United States [4].

Many research publications investigate P2P energy trading from a variety of perspectives, such as market mechanisms and technologies [5], and barriers and challenges covering political, economic, social, technical, legal, and environmental issues[6]. However, this research takes another perspective and investigates novel ways for lowering the cost of BES and improving the system stability through peer-to-peer energy trading within energy communities, including those that use solar PV and wind turbine technology. To find the best dispatch and pricing methods, the formulation of a multi-objective optimisation problem is formulated that takes into account both technical and economic factors. The impact of community size and generator mix on energy shortfalls and grid interactions is investigated in a simulated residential case study. This research also analyses the foundations of P2P

energy trading, stressing its potential to minimize storage costs by permitting direct energy swaps between community members, hence improving grid stability.

II. MATHEMATICAL MODELLING OF THE SYSTEM

A. Power Balance

The power balance indicates that the total power generated from diverse sources of prosumers must always match the total power consumed by consumers, prosumers, and network losses to maintain the power system's stability [7], [8]. Prosumers can sell power via P2P sharing and purchase electricity from other prosumers when their supply is inadequate; hence, the power balance can be expressed as [9]:

$$\begin{aligned} & \sum_{i=1}^{NP} P_{PV}^i(t) + \sum_{i=1}^{NP} P_{WT}^i(t) + \sum_{i=1}^{NP} P_{dis}^i(t) + \sum_{i=1}^{NP} P_{bou}^i(t) \\ & + \sum_{i=1}^{NC} P_{bou}^i(t) = \sum_{i=1}^{NP} P_{load}^i(t) + \sum_{i=1}^{NC} P_{load}^i(t) + \sum_{i=1}^{NP} P_{ch}^i(t) \\ & + \sum_{i=1}^{NP} P_{sold}^i(t) + \sum_{i=1}^{NP} P_{loss}^i(t) \end{aligned} \quad (1)$$

$$P_{bou}^j(t) + P_{P2P}^j(t) = P_{load}^j(t), 1 \leq jN_C \quad (2)$$

The addition of P2P to the equations represents power bought (>0) or sold (<0) through P2P energy sharing, respectively.

B. Solar Photovoltaic (PV) Modelling

The output of a PV array depends on the radiation intensity and temperature factors. The power generated by the PV module at MPPT decreases as the temperature rises. Furthermore, an increase in radiation intensity may result in an increase in produced power at a PV module's maximum power point. The PV power is denoted as follows [10]:

$$P_{pv} = I(t) \times A_{pv} \times \eta_{pv}(t) \quad (3)$$

Where: $I(t)$ is solar irradiation in (kW/m²), A_{pv} is the area occupied by PV panels (m²), $\eta_{pv}(t)$ is represents the PV panel's instantaneous efficiency [10].

$$\eta_{pv}(t) = \eta_r \times \eta_t \times [1 - \beta \times (T_a(t) - T_r) - \beta \times I(t) \times \left(\frac{NOCT-20}{800}\right) \times (1 - \eta_r \times \eta_t)] \quad (4)$$

Where: η_r is the reference efficiency of the MPPT equipment, η_t is the efficiency of the MPPT equipment, β is the temperature coefficient of the efficiency. $T_a(t)$ is the ambient temperature of the PV cell (°C), T_r is the PV cell reference temperature (°C), and NOCT is the nominal operating cell temperature (°C).

C. Wind Turbine (WT) Modelling

Wind and solar PV hybridization complement each other during a day and night cycle. Strong winds often occur during the nighttime period and on cloudy days. Alternatively, during bright days, low winds occur, whereas solar PV output happens during the day. Thus, this hybridization is used to provide load demand with higher reliability and continuity of supply regardless of its intermittent, natural limitation. The output power of the wind generator has three scenarios based on wind velocity, as shown in the following equation [10].

$$P_{wind} = \begin{cases} 0, & V(t) \leq V_{ci}, V(t) \geq V_{co} \\ a \times V(t)^3 - b \times P_r, & V_{ci} \leq V(t) < V_r \\ P_r, & V_r \leq V(t) < V_{co} \end{cases} \quad (5)$$

Where: $V(t)$ expresses the wind speed, P_r is the rated power of the wind turbine generator, V_{ci} is the cut-in speed, V_{co} is cut-out speed, V_r is the rated wind speed, while a and b are two constants expressed as

$$\begin{cases} a = \frac{P_r}{(V_r^3 - V_{ci}^3)} \\ b = \frac{V_{ci}^3}{(V_r^3 - V_{ci}^3)} \end{cases} \quad (6)$$

The rated power of the wind turbine generator can be obtained as

$$P_r = 0.5 \times \rho \times A_{wind} \times C_p \times V_r^3 \quad (7)$$

Where: ρ is the air density (kg/m³), A_{wind} is the swept area of the wind turbine (m²), and C_p is the maximum power coefficient, ranging from 0.25 to 0.45% [10].

D. Battery Energy Storage System (BESS)

Due to the intermittent nature of wind and PV energies and to support the reliability of the system, we need a BESS. The capacity of these batteries can be modelled as follows:

$$C_{bat} = \frac{E_l \times AD}{DOD \times \eta_{inv} \times \eta_{bat}} \quad (8)$$

Where: E_l is the electric energy demand of the load, AD is Autonomy Days, DOD is the depth of discharge of the battery (80 %), η_{inv} is the inverter efficiency (95 %), and η_{bat} is the battery efficiency (85 %) [10]. Battery SoC can be defined as follows: [9]

$$SOC^i(t) = \frac{E_B^i(t)}{E_{B,N}^i} \times 100\% \quad (9)$$

$$SOC^i(t + \Delta t) =$$

$$\begin{cases} SOC^i(t) + \frac{P_{ch}^i(t) \times \Delta t \times \eta_{ch}}{E_{B,N}^i} - \frac{P_{sf-dis}^i \times \Delta t}{E_{B,N}^i} \\ SOC^i(t) - \frac{P_{dis}^i(t) \times \Delta t}{E_{B,N}^i \times \eta_{dis}} - \frac{P_{sf-dis}^i \times \Delta t}{E_{B,N}^i} \end{cases} \quad (10)$$

As shown in this equation, the reduction in E_l due to P2P energy sharing leads to a corresponding decrease in the required battery capacity, thereby lowering storage costs. This reduction can be achieved through the hybridization of energy sources, such as wind and solar PV, which complement each other to minimize the need for energy storage systems by enabling energy imports from the grid when necessary.

III. ENERGY DISPATCH STRATEGY

Prosumers have several sources of energy supply and demand. Power dispatching using a Home Energy Management System (HEMS) is fundamental to effectively balancing energy supply and demand. This section examines fundamental energy dispatching in the P2P energy trading through the energy communities having PV and wind turbines. The energy strategy is implemented, and the operational principle flow chart is depicted in Fig. 1.

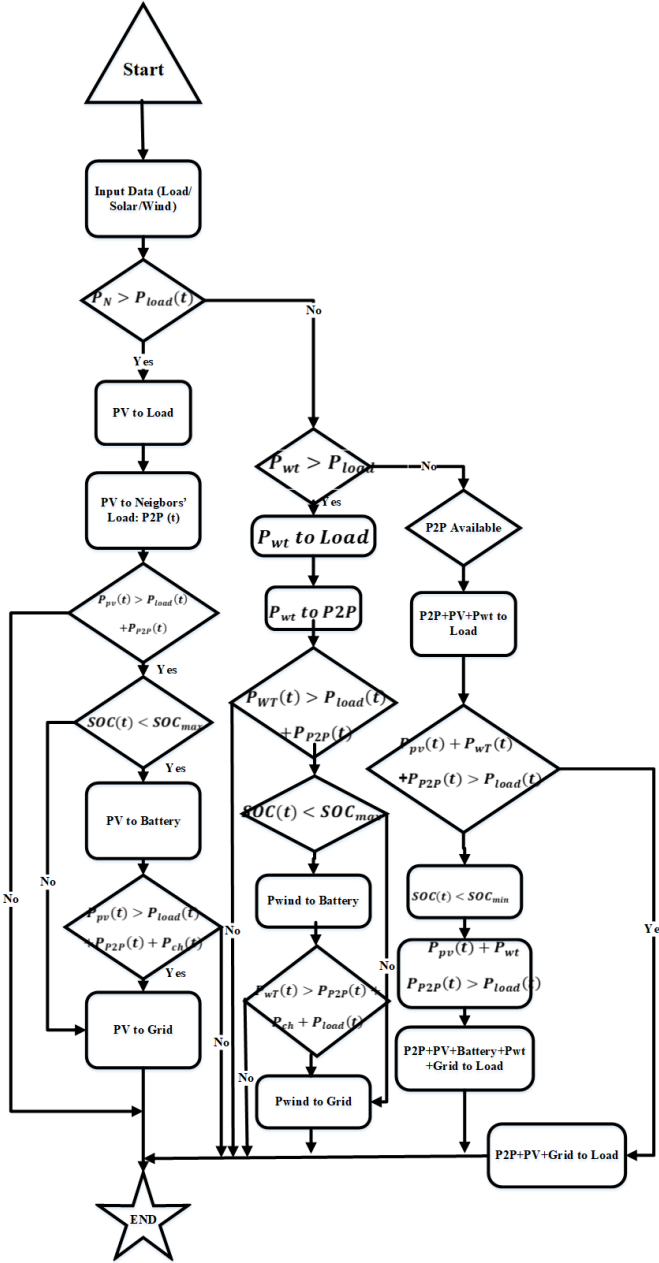


Fig. 1. Flow chart of energy management through the P2P energy trading

At time t , if the photovoltaic (PV) power exceeds the load demand, it will initially fulfil the prosumer's load, with any excess distributed among peers via P2P energy sharing. Subsequently, if the state of charge (SOC) of the battery has not reached its upper limit, the surplus PV power will charge the battery, and any remaining excess will be fed into the grid. When photovoltaic power is inadequate or unavailable at night, the prosumer may initially obtain electricity from a wind turbine or neighbours through peer-to-peer energy sharing, subsequently utilising battery discharge if extra energy is available; otherwise, the prosumer must procure electricity from the grid to meet the net load. As consumers do not implement photovoltaic and storage systems, their energy dispatch strategy remains uncomplicated. In the presence of surplus photovoltaic power within the community, users will first acquire this excess energy via peer-to-peer sharing to meet their load requirements. Otherwise, users will obtain power from the utility grid to satisfy the net load.

The P2P energy sharing and pricing mechanisms determine whether electricity and revenue are properly distributed among peers. The price of P2P energy sharing must fall between the feed-in and retail rates for homes to generate income. The continuous double auction (CDA) process establishes varying trade prices for a succession of P2P energy trading contracts inside each trading session, resulting in inequity. In a P2P energy trading market utilising CDA, the average trading price for a certain trading session is significantly correlated with the energy supply-demand ratio (SDR). Given that the P2P trading price must align with the feed-in tariff and retail price, a consolidated pricing function is derived by analysing the average trading prices of CDA.

$$Pr_{P2P}(t) = \frac{Pr_{\text{retail}} + Pr_{\text{fit}}}{2} + \frac{Pr_{\text{retail}} - Pr_{\text{fit}}}{2} \times \frac{1 - \text{SDR}(t)^{0.5}}{1 + \text{SDR}(t)^{0.5}} \quad (11)$$

$$\text{SDR}(t) = \frac{\text{TSP}(t)}{\text{TDP}(t)} \times 100\%$$

$$\begin{cases} \text{TSP}(t) = \sum_{i=1}^{N_P} P_{\text{net}}^i(t), P_{\text{net}}^i(t) > 0 \\ \text{TDP}(t) = \sum_{i=1}^{N_P} P_{\text{net}}^i(t) + \sum_{j=1}^{N_C} P_{\text{net}}^j(t), P_{\text{net}}^j(t), P_{\text{net}}^j(t) < 0 \end{cases} \quad (12)$$

Optimizing flexible load operation in DSM requires balancing three key objectives: minimizing the community's total cost (economic efficiency), reducing power fluctuations to ensure grid stability (reliability), and ensuring fair revenue distribution during P2P energy sharing (equality) to encourage household participation. Existing studies often overlook these aspects. The overall power expenditure for the community comprises the expenses of photovoltaic generation, Wind turbine generation, battery storage, grid electricity procurement, and the income from electricity sales (expressed as a negative value), computed as follows:

$$\min C_{\text{com}} = \sum_{i=1}^{N_P} C_{\text{bou}}^i + \sum_{j=1}^{N_C} C_{\text{bou}}^j + \sum_{i=1}^{N_P} C_{\text{PV}} + \sum_{i=1}^{N_P} C_{\text{WT}} + \sum_{i=1}^{N_P} C_{\text{bat}}^i + \sum_{i=1}^{N_P} R_{\text{sold}}^i \quad (13)$$

$$C_{\text{PV}}^i = \sum_{t=1}^T \text{LCOE}_{\text{PV}} \times P_{\text{PV}}^i(t) \times \Delta t \quad (14)$$

$$C_{\text{WT}}^i = \sum_{t=1}^T \text{LCOE}_{\text{WT}} \times P_{\text{WT}}^i(t) \times \Delta t \quad (15)$$

$$C_{\text{bat}}^i = \sum_{t=1}^T \text{LCOB} \times P_{\text{dis}}^i(t) \times \Delta t \quad (16)$$

Here, (LCOE) is the levelized cost of electricity, (LCOS) is the levelized cost of the Battery.

Algorithm 1: Multi-Objective Optimization for Flexible Load Operation

1. *Initialize:*
 Input flexible load operation constraints and initial flexible operation data, including P2P sharing parameters.
 Set iteration counter $k=0$.
2. *While $k \leq k_{max}$:*
 - a. *Genetic Operations:*
 - Perform Tournament Selection to choose candidate solutions.
 - Apply Crossover for offspring generation.
 - Apply Mutation to introduce diversity.
 - b. *Evaluate Objective Functions:*

$$\min C_{com} = \sum_{i=1}^{N_P} C_{bou}^i + \sum_{j=1}^{N_C} C_{bou}^j + \sum_{i=1}^{N_P} C_{PV}^i + \sum_{i=1}^{N_P} C_{WT}^i + \sum_{i=1}^{N_P} C_{bat}^i + \sum_{i=1}^{N_P} R_{sold}^i$$

$$C_{PV}^i = \sum_{t=1}^T LCOE_{PV} \times P_{PV}^i(t) \times \Delta t$$

$$C_{WT}^i = \sum_{t=1}^T LCOE_{WT} \times P_{WT}^i(t) \times \Delta t$$

$$C_{bat}^i = \sum_{t=1}^T LCOB \times P_{dis}^i(t) \times \Delta t$$
 - c. *Non-Dominated Sorting and Crowding:*
 - Perform non-dominated sorting to categorize solutions.
 - Compute the crowding distance to maintain diversity.
 - d. *Generate New Population:*
 Use the sorted solutions and crowding distance to create new flexible operation data.
 - e. *Check Termination:*
 - If $k = k_{max}$, proceed to Step 3.
 - Otherwise, increment $k = k_{max} + 1$ and repeat Step 2
3. *Output Pareto-Optimal Solution Set:*
 - Return the Pareto-optimal solutions representing trade-offs among C , F , and E/I .

The costs of photovoltaic generation may be determined by the levelized cost of electricity (LCOE) of the photovoltaic system across its whole life cycle, as outlined [11]. The power fluctuation factor quantifies the influence of community power dynamics on the utility grid and is computed as [12]:

$$\min F = \frac{1}{T} \sum_{t \in T} \left[\left(\sum_{i=1}^{N_P} P_{bou}^i(t) + \sum_{j=1}^{N_C} P_{bou}^j(t) - \sum_{i=1}^{N_P} P_{sold}^i(t) \right) - P_A \right]^2 \quad (17)$$

$$P_A = \frac{1}{T} \sum_{t \in T} \left(\sum_{i=1}^{N_P} P_{bou}^i(t) + \sum_{j=1}^{N_C} P_{bou}^j(t) - \sum_{i=1}^{N_P} P_{sold}^i(t) \right) \quad (18)$$

Homans' social exchange theory posits that distributive justice is attained in an exchange relationship when each individual's output corresponds proportionally to their input [13]. Consequently, assessing the equity of income allocation between prosumers and consumers in P2P energy sharing necessitates an examination of the correlation between inputs and outputs. This study defines the input as the quantity of power contributed by households engaged in P2P sharing, while the output is the corresponding decrease in household electricity expenses. This study delineates the output-input ratio (OIR) indicator as follows:

$$OIR_i = \frac{(C_{P2G}^i - C_{P2P}^i) / \sum_{i=1}^{N_P} (C_{P2G}^i - C_{P2P}^i)}{E_{P2P}^i / \sum_{i=1}^{N_P} E_{P2P}^i} \sum_{i=1}^{N_C} E_{P2P}^i \quad (19)$$

$$OIR_j = \frac{(C_{P2G}^j - C_{P2P}^j) / \sum_{j=1}^{N_C} (C_{P2G}^j - C_{P2P}^j)}{E_{P2P}^j / \sum_{j=1}^{N_C} E_{P2P}^j} \sum_{j=1}^{N_C} E_{P2P}^j \quad (20)$$

The output-input ratio (OIR) for prosumer i and consumer j indicates energy balance, with values closer to 1 reflecting a better match. Deviations from 1 define the inequity index (IEI), which combines the degree of OIR deviation for all households, as shown in (19). Given the variation in household inputs, the weight factor w representing each household's input proportion to the total input is expressed in (20) and (21). Prosumers, due to their higher PV installation investment, are assigned a weight multiplier to ensure fair benefit distribution and higher revenue in P2P energy sharing.

$$\min IEI = \sum_{i=1}^{N_P} |1 - OIR_i| \times \omega_i + \sum_{j=1}^{N_C} |1 - OIR_j| \times \omega_j \quad (21)$$

Here

$$\omega_i = \left(E_{P2P}^i / \sum_{i=1}^{N_P} E_{P2P}^i \right) \times n \quad (22)$$

$$\omega_j = E_{P2P}^j / \sum_{j=1}^{N_C} E_{P2P}^j \quad (23)$$

This study utilises the non-dominated sorting genetic algorithm (NSGA-II) to effectively construct the operational schedule with variable loads. Algorithm 1 presented above utilises a genetic algorithm to enhance convergence and maintain population diversity using rapid non-dominated sorting and elitist selection techniques[14]. In contrast to single-objective optimisation, multi-objective optimisation identifies a group of optimum solutions referred to as the Pareto front. Due to the inability to ascertain the weights of

the three objectives beforehand, the entropy-weight approach and the methodology for order preference by resemblance to an ideal solution (TOPSIS) are employed to identify the optimal solution from the Pareto front.[15]. The entropy weight approach is utilised to determine the weights of the evaluation indices based on the degree of variation in each index value. This approach provides an objective means of calculating index weights devoid of human influence. The optimal solutions on the Pareto front are evaluated using the TOPSIS approach to identify the most effective flexible load scheduling scheme.

IV. CASE STUDY AND RESULT

Fig. 2 shows the power generation profiles of photovoltaic (PV) and wind energy sources, as well as the resulting hybrid power output and load demand for 24 hours. The PV power generation (red line) follows a typical daily solar radiation pattern, commencing in the morning, peaking about midday, and dropping into the evening, with no generation at night. Wind power generation (blue line) fluctuates throughout the day, with significant contributions in the afternoon and evening, indicating its complementary nature to solar energy. The hybrid power output (green line) illustrates the combined contributions of PV and wind energy, resulting in a more stable and improved total power generation profile.

The load demand (black dashed line) follows a dynamic pattern, beginning with a low level in the early hours, growing in the morning, peaking in the evening, and gradually declining at night. This is the load data taken from the Ref. [9]. This demonstrates the effectiveness of hybrid energy integration in optimizing storage requirements and enhancing energy self-sufficiency as the hybrid power system closely aligns with the load demand pattern, significantly reducing the need for large-scale battery storage or grid dependence. The energy deficit, represented by the area under the curve, is minimized to 48.14 kWh in the hybrid system, compared to 198.86 kWh in the PV-only scenario and 72.86 kWh in the wind-only scenario. However, during the night and early morning hours, when both PV and wind contributions are low, energy storage or grid imports are required to provide supply dependability. This research emphasizes the capabilities of hybrid renewable energy systems to improve grid stability, optimize battery consumption, and reduce dependency on external energy sources through a well-balanced combination of PV and wind power.

Fig. 3 and Fig. 4 show how growing community size affects power exchange with the grid (Pgrid) and total daily energy drawn from the grid, assuming a constant local generation scenario. In all situations, only 30 homes have PV power, and one home runs a wind turbine, while the total number of households ranges from 10 to 100. This configuration represents a common imbalance between energy producers (prosumers) and consumers in a community.

Fig. 3 depicts the hourly fluctuation of Pgrid. Negative numbers imply power imported from the grid since local generation is insufficient to fulfill demand. As the number of households increases, so does the total load while generation stays constant, resulting in larger negative peaks in Pgrid at peak demand hours, particularly in the late afternoon and early evening. During noon, when PV output

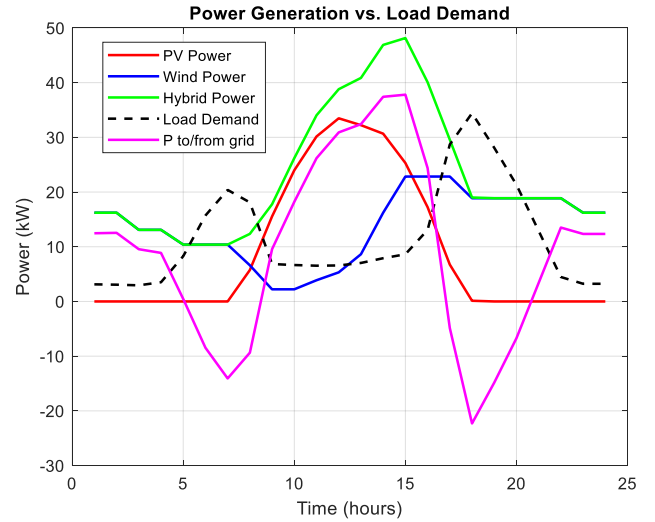


Fig. 2. Power generation vs. load demand at 30 homes

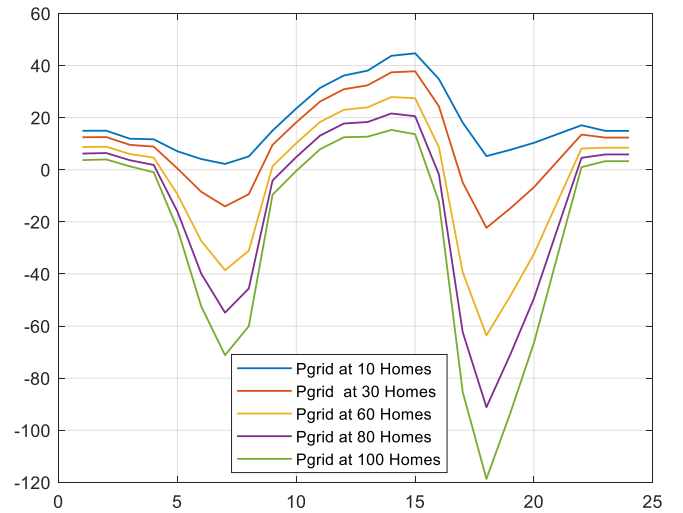


Fig. 3. Power exchange between the grid and homes at different home numbers.

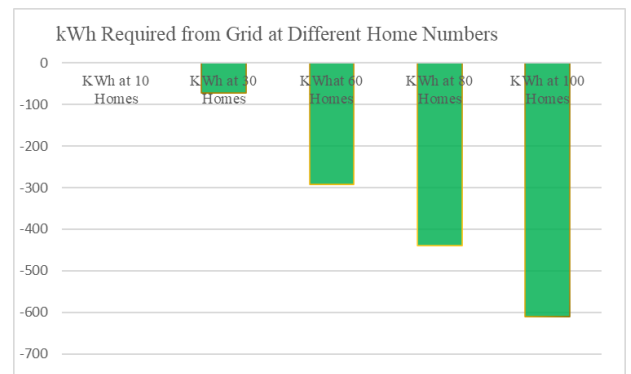


Fig. 4. kWh Required from Grid at Different Home Numbers

is maximum, grid imports are lowered but remain negative, suggesting that even peak local generation does not entirely fulfill the wider community's need. The overall daily energy exchange, shown in Fig. 4 verifies this pattern. The negative values of cumulative energy (kWh) required from the grid rise in size as the number of households increases—from around -73 kWh at 30 homes to roughly -650 kWh at 100 homes. This

depicts the rising energy shortfall, emphasizing the importance of battery BES or increasing the P2P energy sharing of the communities to maintain system stability as community size grows without equivalent increases in generation. These findings highlight the necessity of maximizing the number of prosumers and implementing successful BES tactics. While P2P energy sharing helps to better share the community's limited renewable power, it cannot totally balance growing demand as additional non-generating houses are added. As a result, to maintain a stable and robust system, particularly at larger sizes, additional generation sources, magnify P2P networks, or cost-optimized BES systems must be implemented.

However, this P2P integration of PV and WT systems decreases the demand for BES, but it also poses both economic and technological difficulties. Economically, due to the integration of many technologies, which might result in significant upfront capital expenditures as well as continuing operations and maintenance expenses. Market instability and sometimes inadequate frameworks for P2P trading or auxiliary services make revenue creation challenging. Moreover, the investment risk of complex hybrid projects, as well as legislative and regulatory uncertainties, will arise, i.e. grid compatibility, regulatory limits, and communication infrastructure are essential to facilitate this integration [16]. Technically, how to manage the intermittency and variability of both sources through advanced forecasting using advanced tools such as AI to facilitate energy management. The design and size of optimal systems require careful component and layout choices to maximise energy production and preserve grid stability. Furthermore, technical challenges in terms of controlling voltage and frequency, making up for decreased inertia, and modifying protection plans. For cybersecurity, fault ride-through, and real-time optimisation, a sophisticated energy management system is essential [17].

V. CONCLUSION

This study emphasizes the important benefits of implementing a hybrid renewable energy system through a P2P trading system to better match the dynamic pattern of residential load demand. The hybrid design had a substantially lower energy deficit (48.14 kWh) than the PV-only (198.86 kWh) and wind-only (72.86 kWh) configurations, highlighting its efficiency in reducing storage requirements and increasing energy self-sufficiency. Despite the requirement for battery backup or grid imports during low-generation times (night and early morning), the hybrid system offers a balanced, robust solution that enhances grid stability and optimizes battery use.

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