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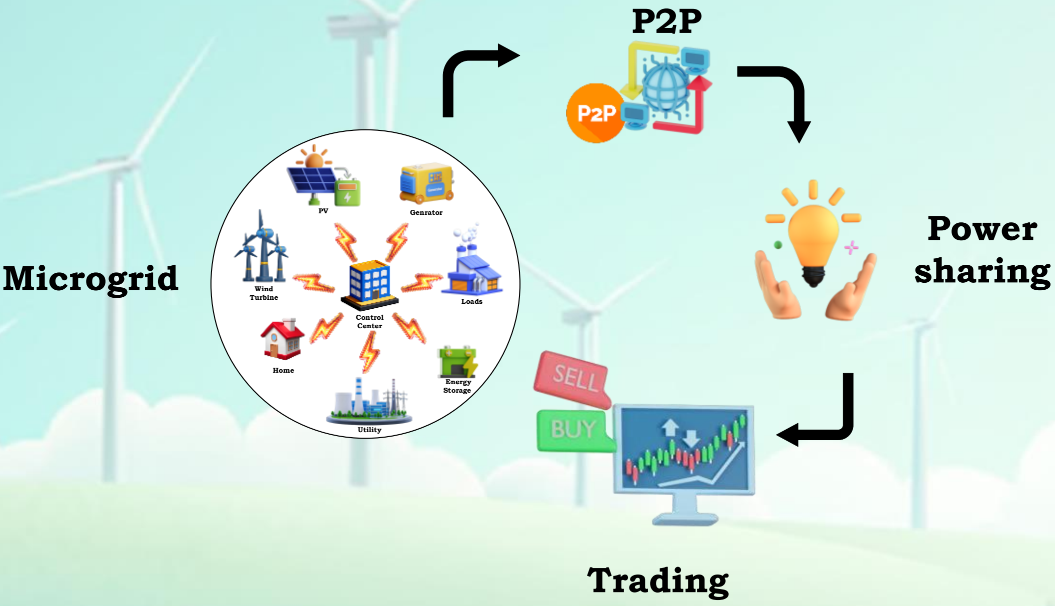
An Electricity Market Pricing Model Based on Load Demand in a Microgrid Using a Community Peer-To-Peer Approach

Arash Rahimi

Highlights

- Proposes an energy exchange method and models energy pricing.
- Balances user and microgrid interests using game theory to encourage microgrid participation.
- Accounts for uncertainties in wind and solar energy production, impacting market pricing.
- Assigns fair prices for energy loads based on the unique characteristics and facilities of each microgrid.

Graphical Abstract



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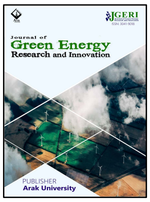

An Electricity Market Pricing Model Based on Load Demand in A Microgrid Using a Community Peer-To-Peer Approach

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ABSTRACT

In this paper, a new peer-to-peer (P2P) pricing mechanism based on Flexi User and Pool Hub schemes is proposed in a community of buyers using battery storage systems to ensure that all customers in a community enjoy economic benefits. The proposed mechanism does not only consider the power surplus and shortage relationship, but also considers the power grid Real-Time Price (RTP) and Feed-in Tariff (FiT), which reflects the power system demand, where the price is high during peak demand and lower during off-peak. Demand is then implemented by a demand response (DR) program to encourage consumers to manage energy consumption, reduce stress on the power grid, and ensure that energy exchange between peers does not violate grid constraints. Results show that in addition to demand response in the grid, in the Flexi User scenario, the total savings to society from the combination of storage and P2P collaboration lead to a 24.25% reduction in electricity bills compared to a reference case (neither storage nor P2P trading). While the monetary savings in the Pool Hub market is up to 25.53%, this requires more direct P2P trading of distributed energy resources.

1. Introduction

Due to the requirements of sustainable development and reducing the emission of environmental pollutants, today's power grids have undergone huge changes and developments to provide a new low-carbon decentralized infrastructure [1]. The use of distributed energy resources, jointly with information and communication technology and energy system management for homes and residential buildings, has forced us to rethink our approach to the operation of the power system. In particular, going down to the lower levels of the network, a new type of agent appears, i.e., sellers, with the ability to produce and consume (and most likely store in the very near future) [2]. Renewable energy, which is also called reversible energy, refers to a type of energy that, unlike non-renewable or fossil energy, has the source of producing that type of energy with the ability to be regenerated in a short period of time by nature [3]. The warming of the earth and the depletion of fossil fuels have caused the electrical energy systems to become new systems and use renewable energy. Over the past ten years, the cumulative global wind energy capacity has increased 6.58 times, from 74 GW in 2006 to 487 GW in 2016, while photovoltaic (PV) power has also increased by 43.14 times from 7.0 GW in 2006 to 302 gigawatts increased in 2016. Therefore, the unique characteristics of renewable and clean energy sources compared to fossil fuels, such as compatibility with the environment and relatively unlimited resources, have caused an increase in the demand for the use of such new energies. So that it is predicted that the use of clean energy will surpass other traditional methods in the coming years [4]. On the other hand, the flexibility of distribution networks is an issue that has been further enhanced by the evolution of these networks from a unidirectional flow of electricity (from large centralized generators) to a system of bidirectional power flow between traditional generators and increasingly small-scale producers. Manufacturers often use distributed energy resources (DER), which are intermittent and allow them to play a more active and dynamic role in electricity consumption and production. In the meantime, electric energy storage devices will play a significant role in increasing the flexibility of the network [5].

Today, vast changes are emerging in power systems. Day by day, the presence of solar resources, wind farms and geothermal resources at the transmission level and small renewable energy sources such as fuel and solar cells at the distribution level is increasing. This presence of renewable resources in distribution systems has created a new structure of networks called microgrids [6].

Microgrids (MGs) are introduced as DER, energy storage systems (ESSs) and a group of controllable and uncontrollable loads. MGs can be used in different modes including grid connection and island mode. By connecting to the grid and taking power from the grid or giving power to the grid, MG plays a key role in adjusting the power balance as well as supply and demand. In stand-alone mode, MG is located away from the grid and customers buy power from MG according to DG offers [7,8]. In Figure 1, a schematic of a microgrid is shown.

One of the new platforms for economic exploitation in microgrids is energy exchange between self-production consumers, which can be peer-to-peer (P2P) with other self-production consumers or with the upstream network. Produced renewable energy can be used for self-consumption, storage or exchange with others [9]. One of the new topics raised in relation to self-production consumers is P2P energy exchange, in such a way that consumers can provide for their required power. They should use the products of self-producing consumers in the network whose energy production is more than their required power consumption [10]. P2P energy exchange is more economical than energy exchange only with the upstream network. In [11], a local electricity market for P2P energy exchange is presented. Consumers self-determine residential generation, generation capacity or consumption capacity to minimize their electricity bills and dependence on the upstream grid. Two types of competition in P2P energy exchange are discussed. First, the competition to determine the appropriate price between the sellers, which is determined according to the solar energy purchase tariff and the energy purchase price from the upstream network, and it should be such that the first choice of the buyers is to buy from the self-produced consumers. The second is the competition between buyers to choose the right seller to make the most economical choice [12]. In general, the research conducted in the field of peer-to-peer approach can be divided into two categories: double auction model [13-17] and analytical model [18-21]. The research conducted using the dual auction (DA) model is such that peers (sellers and buyers) can interact with each other to trade their energy in a step-by-step manner. On the other hand, the researches based on the analytical model are focused on estimating the energy generated from DERs in a local market based on specific rules.

Also, in [22] the concentrates were on the planning of price-based unit commitment (PBUC) managed by Virtual Power Plants (VPPs) over a day. The proposed framework effectively formulates strategies for VPP market production and consumer engagement, particularly with load-shedding capabilities. The research crucially investigates the effects of uncertainties on VPP strategies using probability density functions and the Monte Carlo method. The model proves effective for strategizing VPP market production and consumer interaction in simulations without energy price and demand uncertainties. However, when these uncertainties are included, VPP profits are impacted by market volatility, and increased price and demand fluctuations can significantly alter VPP strategies, occasionally leading to losses.

A P2P energy network can be defined as a network, where network members can share part of their resources (for example, renewable energy and storage space and information) to achieve energy-related goals such as maximizing renewable energy consumption, electricity cost reduction, load modification, network operation reduction and investment cost minimization. Each member can be an energy provider or receiver and communicate directly with the network without any intervention from a third controller. In addition, a new peer can be added to an old peer without changing the operational structure of the system. Today, the presence of the consumer in the load supply chain can play an important role in reducing costs and increasing the stability of the network, and the consumer is in two situations of virtual production and consumption.

Figure 1. The general structure of a microgrid [7].

Therefore, by increasing the storage, the load is provided faster. In order to participate in the load in the chain, the demand side resources should be used. Reducing the cost of electricity supply, reducing the cost of electricity consumed by consumers, reducing investment to build new power plants, preserving the environment, improving reliability is a suitable tool for providing system security in emergency situations and reducing blackouts among the benefits of demand side management programs. Demand side management programs are either short-term or long-term. Among these resources, we can mention load response programs. Load response programs are short-term programs whose effects are visible both in the short term and in the long term. In general, load response programs are divided into two main categories: time-based programs and price-based programs [23,24].

The main purpose of this paper is to encourage subscribers to install renewable systems for self-consumption, storage and their participation in electricity markets to earn money by selling excess energy to the upstream grid or other consumers. The participation of consumers in the production side brings many benefits both for the network and for the consumers themselves. Consumers in a smart micro-grid using renewable systems can have on-site production and in addition to supplying the electrical energy, they can also supply the energy of their neighbors and reduce their dependence on the upstream network. The goal is to determine the appropriate energy prices according to the renewable energy purchase tariff by the upstream network and encourage participation in P2P production and energy exchange programs and self-consumption, which ultimately leads to the minimization of self-produced consumer costs. Therefore, the main contributions and novelty of this paper can be stated as follows:

- Providing an energy exchange method and modeling energy pricing
- Considering the benefits of microgrids in addition to the interests of the user, that is, taking into account the interests of the user and microgrids at the same time, using game theory, which encourages microgrids to participate in these projects.
- Considering the uncertainty for the production of wind and solar systems, which causes changes in market pricing.
- Considering different prices for the load being exchanged between each of the microgrids and the operator based on the different characteristics of each microgrid, which makes the prices assigned to the microgrids fairer according to their different facilities.
- The use of energy storage devices along with the transmission network and by determining the optimal planning under the Flexi User and Pool Hub strategies

The structure of this paper is as follows: In section 2, system modeling and problem formulation are discussed. In section 3, the formulation of energy sharing by P2P method is proposed. In section 4, the simulation results are presented, and in section 5, the conclusion will be expressed.

2. Problem model

In order to efficiently use renewable resources in the microgrid and improve the performance of P2P trading, we use two distinct local electricity market designs in the producer and consumer communities. Therefore, we use two different systems in using the battery for storage and subsequently we consider the rules for prices, P2P trading and the amount of battery consumption. For this purpose, we consider a set of n consumers who are connected through a local electricity distribution network. In this model, each customer has wind energy production technology or solar panel. The purpose of this market is to minimize the cost of electricity consumption from the transmission network by prioritizing self-sufficiency. This is possible by incentivizing direct P2P trading within the community (marketplace) or using batteries for balancing. Figure 2 schematically shows a community of four houses where a battery storage is either decentralized at the house level (a) or centrally located in the community (b). Also Figure 3, shows the flowchart of proposed model of study.

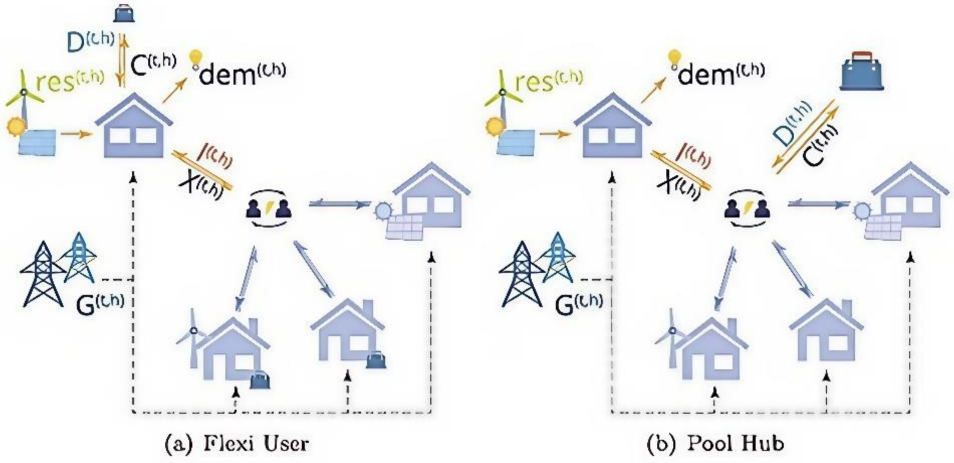

Figure 2. Schematic of the proposed problem [2].

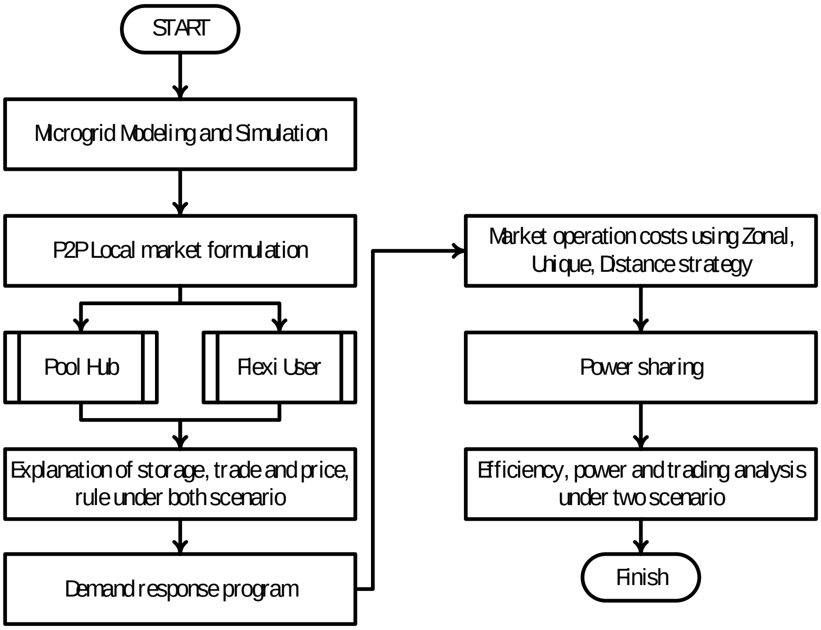

Figure 3. The flowchart of proposed model of study.

Designing the market includes determining the rules of market operation and checking its actions. This design lays down rules that aim to ensure the efficient and fair functioning of the market. Hence, to examine the value of storage and P2P trading in a local market, we define and compare trading rules and how to manage storage according to different sets of rules to bring the most benefit to the community. These two separate plans are called Flexi User and Pool Hub in the market [25,26].

As seen in Figure 2, the Flexi User strategy is designed for individual battery configurations at the consumer level; This is while the existing structure in Pool Hub considers a large battery at the community level. For both plans, trading of locally generated electricity within the community is allowed, with the ability to sell excess electricity from renewable energy sources to peers. Each of these two settings gives a specific role to the storage entity, which leads to distinct market design definitions as follows:

Decentralized storage - Flexi User market:

This market design imposes rules on system setup with individual batteries. Producers and consumers in a community can dynamically trade locally generated energy at a local P2P price. Private storage is also recharged by DG from producers within the community.

Centralized storage - Pool Hub Market:

This market design applies the rules in setting up a system with a common battery. Producers and consumers can trade locally with the same dynamic local P2P pricing as with User Flexi. Unlike User Flexi, there is only one large storage unit that is centrally located and owned by the community. Battery charging can only be done and compensated by renewable energy producers in the community. Battery discharge is available to all - producers and consumers - at a slightly higher charge compensation rate.

In order to create a fair market, these two plans include special rules for prices. To incentivize local trade, introduce a price mechanism for P2P trade in a way that guarantees low electricity prices at the local level. Apart from the main rules in determining the price and accessibility of storage, the battery is allowed to be charged only from DG sources and it is assumed that the producers cannot feed into the grid. On the one hand, the arbitrage potential that can be obtained when changing network consumption using batteries is reduced. On the other hand, this reduction comes with limitations. In addition to the rules related to storage, trading and prices defined in market design, assumptions should also be considered due to the complexity of the model and computational effort. Hence, we assume unlimited supply from the network at any time. Physically, battery degradation and power distribution characteristics such as load current are ignored. DG investment costs are also not included in the calculation model. Although we are aware of the uncertainty in power generation through RES, no certainty is assumed in production or prices.

3. Formulation

3.1. P2P market-based problem formulation

The problem model for load distribution between network components using P2P is expressed as follows which directly expresses the limitations of microgrid, according to [27], in the context of a P2P market [2]. Equations (1-9) represent a mathematical model for the problem of load distribution in P2P networks. The model includes an objective function for cost optimization and a set of constraints related to power balance, network limitations, and operational conditions of various network components.

$$\min_{P, p_{n\in\Omega}, \theta_{i\in N}} \sum\nolimits_{n\in\Omega} f_n(p_n) \tag{1}$$

$$P = -P^T \tag{2}$$

$$p_n = \sum\nolimits_{m\in\omega_n} p_{nm} \qquad n\in\Omega \tag{3}$$

$$\underline{p_n} \le p_n \le \overline{p_n} \qquad n\in\Omega \tag{4}$$

$$p_{nm} \ge 0 \qquad n\in\Omega_g \tag{5}$$

$$p_{nm} \le 0 \qquad n\in\Omega_c \tag{6}$$

$$\underline{p_n} \le p_{nm} \le \overline{p_n} \qquad n\in\Omega_p \tag{7}$$

$$\omega_n$$

$$p_n = \sum\nolimits_{m\in\omega_n} p_{nm}$$

$$p_{nm} = 0$$

$$q_{ij} = Y_{ij}(\theta_j - \theta_i) \le C_{ij} \qquad (i,j)\in L \tag{8}$$

$$\sum\nolimits_{n\in N_i} p_n = \sum\nolimits_{(i,j)\in L} q_{ij} \qquad i\in N \tag{9}$$

In the proposed network, the entry of electric lines *L*, which Y_{ij} is mentioned for the connecting node of line *i* and *j*. It is classically assumed to be driven by their inductance in the presence of pure sinusoidal voltage and current. This assumption leads to real power currents q_{ij} is proportional to the voltage angle difference, which θ_i at node i, is noted between the two ends of the line as in Equation (8). To prevent any damage to the transmission lines, their flow is limited by thermal limits related to the heat they can dissipate. In addition, a power balance Equation (9) must be maintained at each node *N* of the network between the line currents and the power injection of the agents connected to it, so N_i at node *i*.

The objective of the P2P market, Ω, with size of N_Ω, is to minimize the total cost, which sums all the individual cost functions as in Equation (1). To minimize the cost function f_n, agent (customer) *n* can optimize its transaction volume p_n within the flexibility range defined by a lower $\underline{p_n}$ and an upper bound $\overline{p_n}$, as expressed in Equation (4-7). If agent *n* sells electricity, the value of the transaction is positive and when buying, it becomes negative. Considering multilateral transactions requires the division of net powers, according to [28], into a set of multiple bilateral transactions p_{nm}. Every possible bilateral power trade within the market can be condensed into a matrix *P* such that in Equation (10):

$$P = \begin{pmatrix} p_{11} & \cdots & p_1 N_\Omega \\ \vdots & \ddots & \vdots \\ p N_\Omega 1 & \cdots & p N_\Omega N_\Omega \end{pmatrix} \tag{10}$$

It is necessarily p_{nm} equal to zero if *m* in the business partnership set is not representative of *n* in the set ω_n. Then the net power $p_n = \sum\nolimits_{m\in\omega_n} p_{nm}$ is obtained as in Equation (3). As seen in Equation (2), *P* is symmetric to guarantee the power balance of each transaction, so $p_{nm} = 0$. This allows prices to potentially be customized in each equation.

3.2. P2P energy sharing mechanism

The P2P energy exchange mechanism is designed to motivate residents to participate in the energy market. Accordingly, in this paper, a new P2P pricing mechanism is presented to ensure all customers that they will enjoy more economic benefits, unlike the traditional electricity market. The proposed pricing mechanism can be applied to any P2P energy sharing model. The proposed mechanism does not only consider the power surplus and shortage relationship, but also considers the power grid RTP and FiT, which reflects the power system demand, where the price is high during peak demand and lower during off-peak. A Demand Response (DR) program is then implemented to encourage consumers to manage energy consumption, reduce stress on the power grid, and ensure that energy exchanges between peers do not violate grid constraints. Accordingly, for each time period, the total surplus energy to the P2P market that is imported by n customers is equal to Equation (11):

$$E_S(t) = \sum_{i=1}^{n} E^i_{surplus}(t), \ \forall t\in[0,T] \tag{11}$$

Also, the lack of energy purchased by customers is also defined as follows in Equation (12):

$$E_D(t) = \sum_{i=1}^{m} E^i_{deficiency}(t), \ \forall t\in[0,T] \tag{12}$$

Since P2P prices depend on the relationship between the shortage and surplus of energy to be traded in the P2P market, this measure is defined by the ratio α as follows in Equation (13):

$$\alpha = \frac{E_D - E_S}{E_D + E_S} \quad , \alpha \in [-1,1] \tag{13}$$

When $\alpha = 0$, excess energy is equal to deficiency ($E_S(t) = E_D(t)$). Also, when $\alpha \approx -1$, there is no shortage ($E_D(t) = 0$)or the surplus is much greater than the shortage ($E_S(t) \gg E_D(t)$). Also, when $\alpha \approx 1$ there is no excess energy ($E_S(t) = 0$) or the excess is much smaller than the deficiency ($E_S(t) \ll E_D(t)$).

In the proposed model, according to the reality of electricity consumption, the energy price of the main grid fluctuates during the day. Demand is higher in peak periods and lower in off-peak periods, which affects domestic P2P prices. Therefore, the relationship between import price and FiT can be expressed as Equation (14):

$$\beta = \frac{r_{ex}}{r_{ex} + r_g} \quad , r_{ex} < r_g \tag{14}$$

In this equation, r_g is equal to RTP of the main network and r_{ex} is equal to FiT. Therefore, the P2P market price is calculated according to the values (α) and (β)as Equation (15-16) [1]:

$$r_b = \begin{cases} \left(\dfrac{r_g - r_{ex}}{2}\right) \dfrac{(2-\beta)e^{2\alpha} + \beta e^{-2\alpha}}{e^{2\alpha} + e^{-2\alpha}} + r_{ex} & , \alpha \geq 0 \\ \left(\dfrac{r_g - r_{ex}}{2}\right) \dfrac{(1+\beta)e^{2\alpha} + (1-\beta)e^{-2\alpha}}{e^{2\alpha} + e^{-2\alpha}} + r_{ex} & , \alpha < 0 \\ r_g & , E_s(t) = 0 \end{cases} \tag{15}$$

$$r_s = \begin{cases} \left(\dfrac{r_g - r_{ex}}{2}\right) \dfrac{(1+\beta)e^{2\alpha} + (1-\beta)e^{-2\alpha}}{e^{2\alpha} + e^{-2\alpha}} + r_{ex} & , \alpha \geq 0 \\ \left(\dfrac{r_g - r_{ex}}{2}\right) \dfrac{(2-\beta)e^{2\alpha} + (\beta)e^{-2\alpha}}{e^{2\alpha} + e^{-2\alpha}} + r_{ex} & , \alpha < 0 \\ r_{ex} & , E_D(t) = 0 \end{cases} \tag{16}$$

3.3. Problem formulation

To model the characteristics of local business interactions, we focus on the interaction of four main operational supply-demand decisions:

- Consumers/vendors demand electricity from the main grid
- Vendors use their own distributed resources
- P2P trading takes place within the community
- Battery storage is balanced

Hence, a community of producers (sellers) and consumers face business decisions based mainly on RES surplus power, battery flexibility, network and commercial prices. Therefore, using a multi-period linear programming model, these decisions are optimized in half-hour intervals (t) in a time horizon. The objective function includes electricity costs for the entire community and is subject to supply, battery, and trade constraints.

In this model, houses (h ∈ H) have diversity in demand and production profiles. Every house needs to balance supply and demand. This means that supply from renewable resources $res^{(t,h)}$, network consumption $G^{(i,h)}$, battery discharge $D^{(i,h)}$ and direct P2P purchase means $I^{(i,h)}$ must be combined with the sum of demand $dem^{(i,h)}$, battery charge $C^{(i,h)}$ and P2P sales i.e. $X^{(i,h)}$ for each house h ∈ H in Each time step t ∈ T is considered. In short, based on Equation (17), more supply than demand is considered [29]:

$$\begin{gathered} RES + Grid + Battery\ discharge + P2P\ \ purchase \geq \\ Demand + Battery\ \ charge + P2P\ \ sale \\ res^{(t,h)} + G^{(t,h)} + D^{(t,h)} + I^{(t,h)} \geq dem^{(t,h)} + C^{(t,h)} + X^{(t,h)} \end{gathered} \tag{17}$$

- Specific market restrictions:

The battery decisions and objective functions of these two different schemes assume distinct rules for the availability, capacity, and pricing of storage in the community. Therefore, the models of each scheme optimize slightly different objectives under different constraints for the storage entity. For all considered models, the general objective is to minimize the cost subject to supply-demand, P2P trading and various storage constraints [29].

- Flexi User scenario

In the User Flexi market with decentralized storage, costs are incurred when a customer buys from the network or buys from a peer. However, in P2P trading, the selling peer earns money, thereby reducing electricity costs for the entire community. Since an amount is paid by one person and an amount is received by another person, we exclude these conditions from optimization.

Therefore, the objective function for this case, which minimizes the total consumption costs of the network $G^{(t,h)}$, is equal to Equation (18) [29]:

$$\min \sum_{h} \overset{\text{Grid consumption}}{\sum_{t}} [p_G^{(t)}.G^{(t,h)}] \tag{18}$$

Minimizing the cost of this model depends on the balance of supply and demand, i.e. Equation (17), commercial constraints Equations (19-22), and the constraint for private batteries. Based on this, the community is continuously designed to allow producers to communicate directly with their peers. Active trading must follow certain rules. The total amount of sales $X^{(t,h)}$ for each house h ∈ H as the sum of electric currents $X_p^{(t,h\rightarrow p)}$ from this house h ∈ H to its counterparts p ∈ H, as Equation (19) is defined as [29]:

$$X^{(t,h)} = \sum_{p \neq h} X_p^{(t,h \rightarrow p)} \tag{19}$$

Where

$$I_p^{(t,h \rightarrow p)} = \psi^{P2P}.X_p^{(t,p \rightarrow h)}) \qquad \forall p \neq h \tag{20}$$

The change in flow direction indicates the purchase of $I_p^{(t,h\leftarrow p)}$ of a house h ∈ H from its counterpart p ∈ H. The total amount purchased in each house, $I^{(t,h)}$ is defined by Equation (21) [29]:

$$I_p^{(t,h)} = \sum_{p \neq h} I_p^{(t,h \leftarrow p)} \tag{21}$$

Since no grid input is considered, the amount of energy sold and purchased can only remain in the community. The total sales in all houses must be equal to the purchases of that house, which is expressed as Equation (22) [28]:

$$\sum_{h} \psi^{P2P}.X^{(t,h)} = \sum_{h} I^{(t,h)} \qquad \forall t \in T \tag{22}$$

Private batteries form the basis of certain physical characteristics. The lower limit s and the upper limit s of the storage level $S^{(t,h)}$ in each battery are limited according to Equation (23) [29]:

$$\underline{s} \leq S^{(t,h)} \leq \bar{s} \tag{23}$$

The charging and discharging of the battery are limited to a certain amount of α and β, respectively. These rates are shown mathematically in Equations (24,25) [29]:

$$0 \leq C^{(t,h)} \leq \alpha \tag{24}$$

$$0 \leq D^{(t,h)} \leq \beta \tag{25}$$

The total storage level of the battery in a time step t is determined by Equation (26) with charge $C^{(t,h)}$ and discharge $D^{(t,h)}$. This period depends on the efficiency coefficients η^c and η^d.

$$S^{(t,h)} = S^{(t-1,h)} + \eta^c.C^{(t,h)} - (1-\eta^d).D^{(t,h)} \tag{26}$$

- Pool Hub scenario

In the Pool Hub scenario with a centralized storage, the total cost in the cost vector is three components: network consumption, P2P trading and centralized battery drain. In addition, we deduct the fees charged to customers and consider their income from P2P trading. Hence the Pool Hub objective function, Equation (27), requires two additional components that add the battery discharge costs $D^{(t,h)}$ and the charge compensation $C^{(t,h)}$ [29].

$$\min \sum_{h} (\sum_{t} [p_G^{(t)}.G^{(t,h)}] + \sum_{t} [p_D^{(t)}.D^{(t,h)}] - \sum_{t} [p_C^{(t)}.C^{(t,h)}]) \tag{27}$$

The large battery is limited to the physical constraints formulated in Equations (23-25) with constants $\underline{s}$ ‹$\bar{s}$ ‹α ‹β ‹η^c and η^d for a more centralized storage entity. The total storage level will not depend on the charging or discharging of a house, but will take into account the total current from the battery to the houses. Equation (28) includes the amount of discharge $D^{(t,h)}$ and charge $C^{(t,h)}$ of the concentrated battery and adds these to the total storage level $S^{(t)}$ [29]:

$$S^{(t)} = S^{(t-1)} + \eta^c.\sum_{h} C^{(t,h)} - (1-\eta^d).\sum_{h} D^{(t,h)}, \ \forall t \in T \tag{28}$$

3.4. Case study

In order to implement the proposed method, we use a case study that includes the basic information of the problem. The case study is a 500-unit residential complex in Italy with a total volume of 230,000 cubic meters, the energy supply of its facilities and equipment throughout the year is specifically provided by the grid. In these buildings, a number of houses are equipped with solar panels, in addition to this, the possibility of storing energy in batteries (due to their capacity and erosiveness) is also available for subscribers. Also, digital technologies and smart grids are assumed to be installed and capable of P2P trading. The main energy supply system in this complex is CHP. The generating unit (CGU) consists of an internal combustion engine (ICE) that is fueled by natural gas. These engines are the most common prime movers for medium-scale (100-5000 kW) CHP applications [30].

The nominal electrical power capacities considered for this motor (Pcgu) are from 600 kW to 1600 kW, with discrete intervals of

100 kW. Therefore, the lower power capacity is equal to 50% of the nominal power capacity and the load efficiency is considered according to the Equations (29,30):

$$\eta_{E,CGU} = \eta_{E,CGU,nom}\left(1.126L - 0.126\right) \tag{29}$$

$$\eta_{H,CGU} = \eta_{Q,cguCGU,nom}\left(0.8253L + 0.1747\right) \tag{30}$$

The load factor is defined as $L = F_{CGU} \cdot \eta_{E.CGU,nom} / P_{CGU}$. Also, nominal efficiency and heat rate to power of CGU are given in Table 1.

The investment cost of combustion units is significantly affected by the "scale effect". For this reason, the cost relationship of CGU according to its size is considered as Equation (31):

$$C_{TI,CGU} = 15460 P_{CGU}^{0.7247} \tag{31}$$

where $C_{TI,CGU}$ should be in Euros and power (P_{cgu}) in kilowatts.

As stated above, hourly average values are adopted to represent energy load demand. Figure 4 shows the load length curves of electrical and thermal demands of the residential complex. This data is obtained from 12 typical days, corresponding to 4 typical weeks. For each week, representing seasonal weather periods, one weekday and two weekend days (Saturday and Sunday) are considered. It is necessary to explain that the residential complex in this simulation plays the role of supplying energy and ancillary services. Therefore, by using new technologies such as blockchain, which are based on P2P behavior in the electricity market, it is possible to reduce the annual energy costs in addition to providing the amount of load required for supply to customers. From this roof, the uncertainty in the annual energy load demand is considered through normal distributions. Therefore, 20% relative standard deviation is used for both electrical and thermal requirements. Such a value corresponds to 8 consecutive years of energy demand data measured in the tested residential complex.

As mentioned, the use of energy storage devices along with the transmission network and by determining the optimal planning in both Flexi User and Pool Hub scenarios is an innovation of this research. In the following, the results of this issue will be examined.

4. Results

Simulation results for all CGU sizes and operational strategies are shown in this section. 10,000 iterations were performed for each combination of design configuration and operational strategy, so that reliable results and limited uncertainty in the output indicators can be obtained. On the other hand, in Table 2, the specifications of the electrical energy storage system are presented in order to receive renewable energy, store it, and sell it to the grid (interaction with the grid).

Table 1. Main specifications of the production unit.

Parameter	Value
$\eta_{E,CGU,nom}$	38.5%
$\eta_{Q,CGU,nom}$	34.4 %
HPR_{nom}	0.894
CGU Design Lifetime	20 years
Nominal power of natural gas boiler	$\eta_{boi} = 0.9$
Fuel cost per unit of thermal energy	$c_F = 0.04\ \epsilon/kWh$
Price of buying and selling electricity based on P2P transactions	$c_{PEG} = 0.15\epsilon/kWh$ $c_{SEG} = 0.05\ \epsilon/kWh$

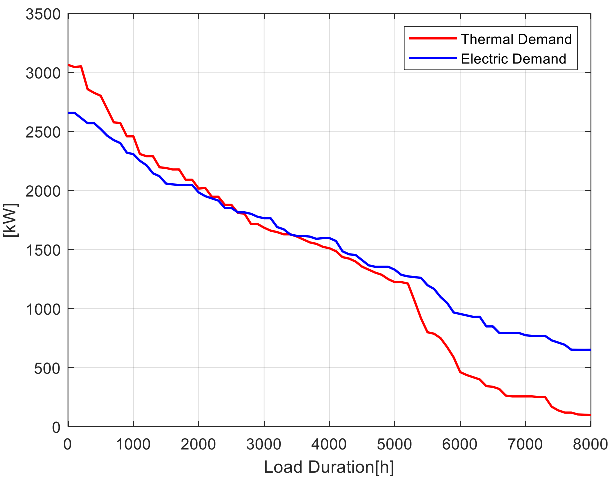

Figure 4. Length curve of electrical and thermal demand.

Table 2. Specifications of electric energy storage devices.

Parameter	Value
Capacity	100 Kw.h
Charging power	50 Kw
Discharging power	50 kw
Charging efficiency	0.85 %
Discharging efficiency	0.85 %

In the following, we have presented the model's supply and demand decisions on how to cover each of the sample houses (customers) on a day in spring. In this simulation, the following are observed:

- Interaction and storage reduce network consumption
- P2P transactions allow the community to cover all demand through renewable energy sources for many parts of the day.
- Storage covers a large share of demand, especially at peak times

This spring sample day shows how P2P trading and energy storage are used by the community to cover their demand. A pure consumer (House 1) covers the demand mainly with P2P purchases due to the exploitation of cheaper local P2P prices. Figures 5 and 6 show the problem results for both Flexi User and Flexi User scenarios, respectively. Pool Hub is presented in the first house and in terms of using all three conditions of PV, Wind and Battery in interaction with the grid. In economics, a graph of supply and demand serves as an instrument to comprehend the correlation between the amount of a product that sellers are willing to offer and the volume that buyers intend to purchase. This concept is rooted in the principle of supply and demand, which posits that the cost of a product or service will recalibrate until the demanded quantity aligns with the supplied quantity. Figures 5, and 6 illustrates the consumption sources for the houses exemplified, captured on a typical spring day under two mentioned scenarios. The following observations can be made:

- A significant portion of the demand in the Pool Hub market is met through interaction and storage.
- Prosumers exhibit a tendency to deplete the battery at varying times.
- Consumption from the grid during peak hours is substantially reduced and rescheduled to late night or early morning.
- During the evening peak, the house utilizes the battery or DG to evade high grid prices. On the selected day, which sees substantial wind-generated electricity, house 1 has the opportunity to sell and recharge the battery at high compensations during the morning and evening, and deplete it at low rates during the day. The consumer largely meets its demand through P2P purchases and draws from the grid during times of high demand and low generation. It is only during periods of intense demand that it becomes necessary to draw from the grid at the highest rate.

The two suggested market models, Flexi User and Pool Hub, integrate market regulations concerning prices, P2P transactions, and battery utilization. The variation in rules originates from the difference in ownership of the deployed battery storage. The enforcement of these rules encourages the use of different market features (battery storage or direct P2P trade) within their configurations. Consequently, the supply-demand decisions of the community vary among the cases examined. Figures 5, and 6 display the average source of supply for the exemplified community over a single day, considering the total time span of nine months. Under the Flexi User market rules, the community predominantly consumes directly from the renewable sources during the day, and employs the storage in the evening to decrease grid consumption (Figure 5). The regulations of a Pool Hub market design result in slightly different supply-demand decisions (Figure 6). The community consistently discharges a minor amount of electricity from the centralized battery during the day and a marginally larger share in the evening. This subsequently leads to a higher demand for grid consumption in the evening. The direct consumption from renewable generation is more substantial during the day as P2P trade is also extensively utilized.

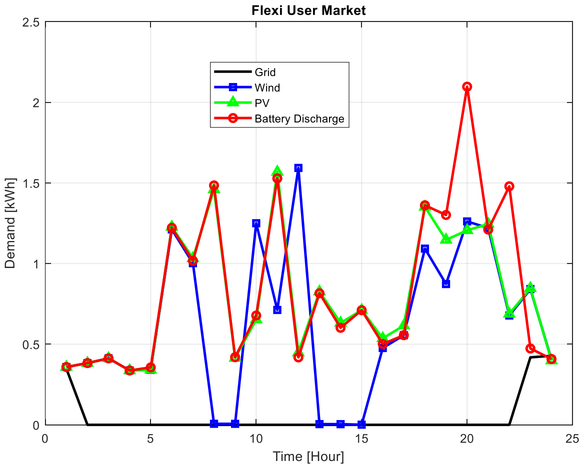

Figure 5. Demand supply graph for house 1 on a spring day in the Flexi User market.

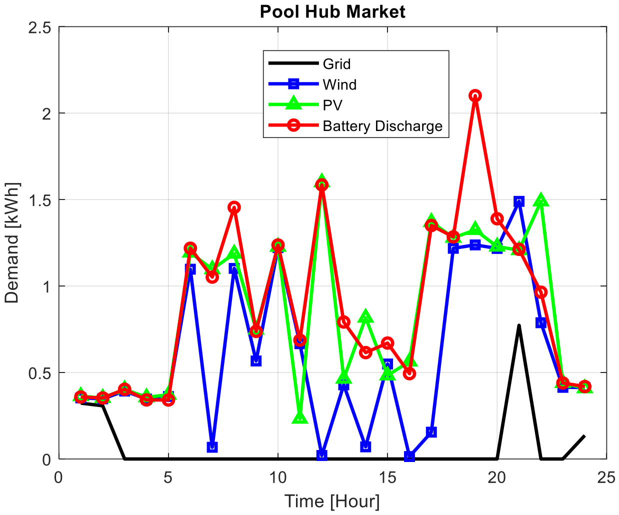

Figure 6. Demand supply graph for House 1 on a spring day in the Pool Hub market.

All producers can use their own production and store surplus electricity for later use. Offloading power from the grid is only necessary during the evening peak when local power generation, particularly from the PV source, is relatively low or absent. At night, when prices are low, buyers also cover the demand by consuming from the grid and use their own production to charge the battery. Since the selected day provides a good supply of wind, it can be seen that House 1 has met a major part of the demand in the community. The generation from DG will vary between seasons, thereby greatly affecting storage utilization, as charging is assumed to be possible only from local DG.

Figures 7 and 8 also show typical examples of how the simulated energy system works and the detailed outputs of the simulations by considering energy storage devices in planning the load demand in the studied residential complex. Figure 7 shows the electricity demand in 72 consecutive hours. Figure 8 also shows the same type of result for thermal demand. As we can see in Figure 7, the demand fluctuates significantly, reaching peaks that align with the CGU production at several points, suggesting moments when production meets demand. CGU production also shows fluctuations but maintains a level close to the peaks of the blue line, indicating a correlation between demand and CGU production capacity. In other hands, the energy purchased by the grid has smaller peaks compared to the other lines, showing less frequent and lower quantity purchases from the grid. Also, the energy sold to grid has even smaller peaks than the red one, indicating infrequent and low-quantity sales to the grid. This graph visually represents how energy production compares with consumption over time and how much energy is traded with the electrical grid.

Figure 8, shows output thermal power exchanged in the P2P market over the 72-hours. As we can see, ehe 'Demand' line has sharp peaks and troughs, indicating significant fluctuations over time. The 'CGU Production' line has a more consistent pattern with slight undulations around the middle of the y-axis range. The 'Boiler Production' line shows a trend that generally increases and then decreases, with its peaks being much lower than those of the demand.

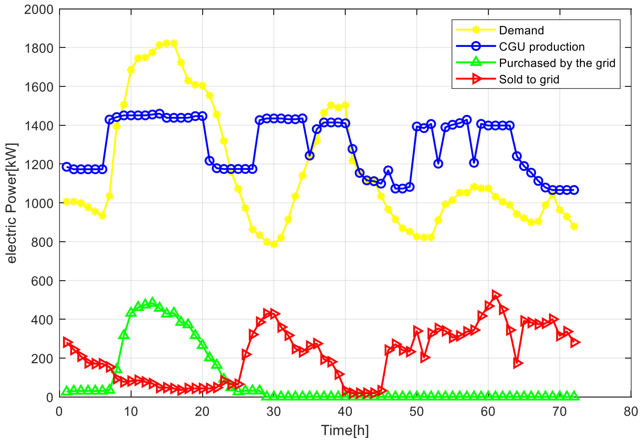

Figure 7. Output electrical power exchanged in the P2P market.

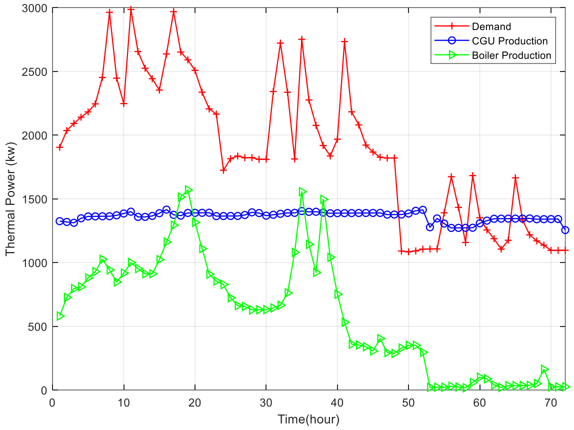

Figure 8. Output thermal power exchanged in the P2P market.

In the following, using the peer-to-peer or P2P approach, modeling of the electricity market and determination of the power level and the exchange of electrical energy sales have been discussed. P2P markets rely on the matching of supply and demand based on multilateral negotiations between all agents (or agent actions). These markets can transmit a complete map of exchanges to the network, and hence enable the sharing of costs related to the use of shared infrastructure and services. In this article, such costs are attributed through exogenous network loads to several alternative methods, uniformly, based on the electrical distance between agents and regions. This covers a variety of basic network physical and regulatory settings. Since attribution mechanisms are defined in an exogenous manner to affect any P2P business, they ultimately change the subject of the market to cover the costs of operating the network. It should be noted that the market fee is modeled based on the following three approaches:

- Zonal: Based on this plan, the power grid is divided into several areas associated with distinct regional unit costs. Each zone can be managed by a different system operator. A high-price area encourages foreign agents not to trade with domestic agents and drives domestic agents to self-consumption. In this sense, regional cost allocation policy allows to isolate a region economically. However, its effectiveness is highly dependent on the design of the areas.
- Unique: According to this plan, the way to allocate costs is to divide them equally among the members of the community.
- Distance: Based on this plan; in order to make the allocation of costs more accurate, network charges can be used according to the electrical distance between agents.

Figure 9 shows that when unique and regional network costs are too high, agents tend to leave the market. Because, the electrical distance policy does not guide transactions between partners connected to an electrical node. Hence, Agents 21 and 31 continue to trade with each other, even with high distance unit costs. In Figure 10 also, as expected, the costs of electrical distance and regional unit allow eliminating all power exchanges between regions. This clearly shows that, unlike unique cost allocation, electrical distance and regional cost allocation allow economic separation of regions. It was also found that the proposed network costs affect bilateral transactions in a way that may lead to sub-optimates. According to Figure 11, considering network costs, if possible, worsens the optimality of the settlement compared to the free market without network restrictions.

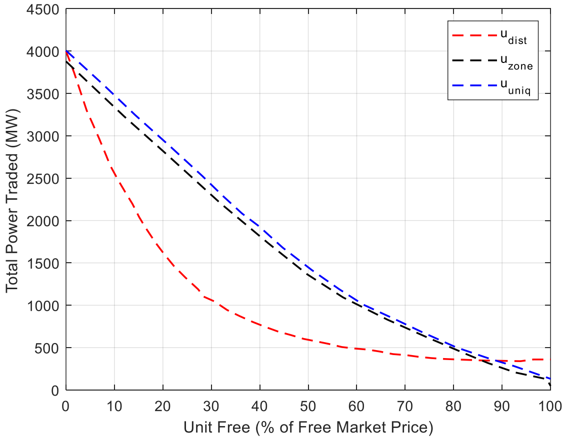

Figure 9. The total amount of power traded in the market.

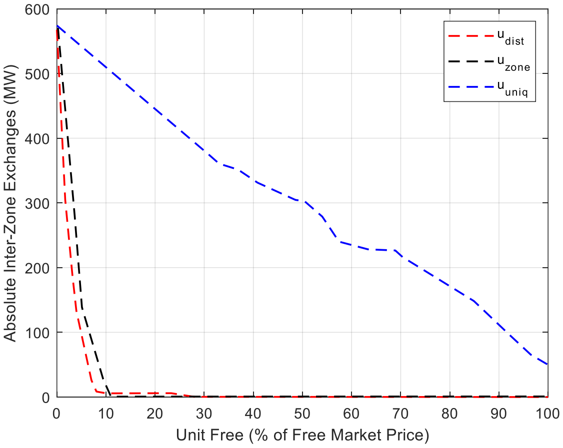

Figure 10. Total amount of power exchanged between different regions.

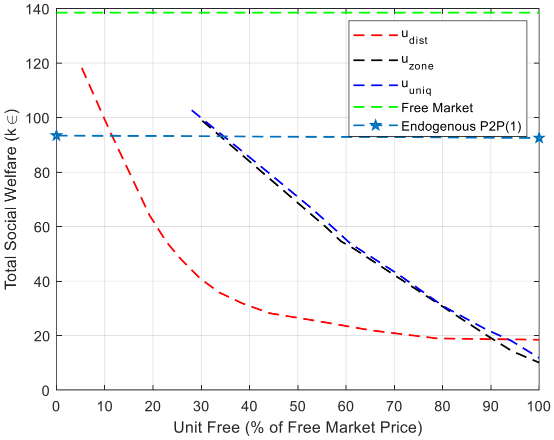

Figure 11. Exogenous P2P market efficiency.

5. Conclusion

A P2P energy network can be defined as a network, where network members can share part of their resources (for example, renewable energy and storage space and information) to achieve energy-related goals such as maximizing renewable energy consumption, electricity cost reduction, load modification, network operation reduction and investment cost minimization. Each member can be an energy provider or receiver and communicate directly with the network without any intervention from a third controller. In addition, a new peer can be added to an old counterpart without changing the operational structure of the system. In this paper, a load demand-based electricity market pricing model is presented in an integrated microgrid using a community-based P2P market model. The design of a community manager that manages business activities within the community as well as communication between the community and the rest of the system is formed. In this paper, the end-user benefits of electricity storage in the presence of P2P trading in local electricity markets with smart grid features are evaluated. Two market designs, Flexi User and Pool Hub, have been used in a community of buyers using battery storage systems. The results show a very interesting trade-off between the independence of the main network and the use of two added features - peer-to-peer trading and storage - for a community of customers. In the Flexi User scenario, the total savings to society from the combination of storage and peer-to-peer collaboration reached a 24.25% reduction in electricity bills compared to a reference case (neither storage nor peer-to-peer trading). While the monetary savings in the Pool Hub market is up to 25.53%, this requires more direct peer-to-peer trading of distributed energy resources.

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Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Bibliography

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