Received: 3 April 2024 | Revised: 2 July 2024 | Accepted: 7 August 2024

IET Generation, Transmission & Distribution

DOI: 10.1049/gtd2.13257

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Designing a decentralized multi-community peer-to-peer electricity trading framework

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Funding information
European Union's Horizon 2020 Research and Innovation Program, Grant/Award Number: 957852

Abstract

Electric power systems are currently undergoing a transformation towards a decentralized paradigm by actively involving prosumers, through the utilization of distributed multi-energy sources. This research introduces a fully decentralized multi-community peer-to-peer electricity trading mechanism, which integrates iterative auction and pricing methods within local electricity markets. The mechanism classifies peers in all communities on an hourly basis depending on their electricity surplus or deficit, facilitating electricity exchange between sellers and buyers. Moreover, communities engage in energy exchange not only within and between themselves but also with the grid. The proposed mechanism adopts a fully decentralized approach known as the alternating direction method of multipliers. The key advantage of this approach is that it eliminates the need for a supervisory node or the disclosure of private information of the involved parties. Furthermore, this study incorporates the flexibility provided by residential heating systems and energy storage systems into the energy scheduling of some prosumers. Case studies illustrate that the proposed multi-community peer-to-peer electricity trading mechanism effectively enhances local energy balance. Specifically, the proposed mechanism reduces average daily electricity costs for individual prosumers by 63% compared to scenarios where peer-to-peer electricity trading is not employed.

1 | INTRODUCTION

The UK, and many other countries have set a target of reaching net zero emissions by around 2050 [1]. Achieving this goal requires a major transformation of the electricity sector, which is responsible for a significant proportion of the countries' greenhouse gas emissions (GHG). In 2022, global renewable electricity capacity witnessed a substantial rise, with the introduction of nearly 295 GW of renewable electricity sources resulting in a 9.6% increase in the overall renewable power stock. Moreover, renewable power sources contributed to 83% of worldwide power additions [2]. Distributed renewable electricity resources (DRER), particularly solar panels, played a crucial role in this growth.

The trend in DRER involves a shift towards localized power generation through sources like rooftop solar panels and small wind turbines. While promising, this trend poses challenges to the electricity system [3]. Technical challenges include intermittency and grid stability, as many distributed sources are dependent on weather conditions [4]. Economic and market challenges include pricing models and lack of incentives, hindering the seamless integration of distributed renewable electricity into the existing system [5]. Addressing these challenges is crucial for realizing the full potential of distributed renewable electricity and ensuring an optimal, sustainable, and resilient electricity system.

The concept of peer-to-peer (P2P) electricity trading has gained significant attention due to its potential to enhance flexibility, diversity, locality and promote environmentally friendly electricity supply and consumption. This increased interest is driven by the growing integration of distributed electricity resources (DERs) into the existing electricity grids [6, 7].

P2P electricity trading enables customers to directly trade surplus electricity generated from their DERs among themselves, allowing for the possibility of feeding excess electricity back into the grid or exchanging it with other customers [8]. Such trading mechanisms offer various benefits, including the ability for consumers to sell their excess renewable electricity, facilitate supply and demand balancing, and incentivize the adoption of renewable electricity sources. Furthermore, P2P trading has the potential to reduce the dependence on costly electricity storage solutions, thereby contributing to a more cost-effective integration of renewable electricity into the grid infrastructure [9].

The market clearing methods employed in the P2P trading pose some notable challenges. The approaches to market clearing can vary depending on factors such as market structure, player behaviour, specific rules and underlying assumptions [10]. Decentralized optimization approaches are favoured over centralized methods in addressing challenges within P2P trading for several compelling reasons [11], although centralized methods, such as those described in [12, 13], are commonly used to clear such markets. Firstly, decentralized approaches align naturally with the inherent structure of P2P trading wherein a central coordination unit is unnecessary, and peers can directly engage in communication with one another [14]. Secondly, decentralized approaches are designed to efficiently distribute the communication load among individual nodes, reducing the burden and risk on any single unit, in contrast to centralized methods that concentrate the communication load at the central unit [15]. Furthermore, because of the nature of centralized methods, it is unattainable for them to ensure the privacy of individual players.

As a result, various distributed methods have been utilized for the market clearing of P2P trading, including the primal-dual gradient method [16, 17], the alternating direction method of multipliers (ADMM) [18, 19], consensus-based methods [20, 21], and decentralized Ant-Colony optimization [22].

In consideration of privacy concerns and the inherent limitations of communication, it is customary for entities to exchange a limited corpus of information. The ADMM serves as a distributed algorithm dedicated to addressing the challenges encountered in multi-entity optimization scenarios, where individual problems are optimized independently, while adhering to local constraints. Some studies have employed a partially decentralized implementation of ADMM, where a supervisory node acts as a coordinator for the players [19, 23]. However, other studies have fully decentralized ADMM without the involvement of a supervisory node [11].

A dual-layer game optimization strategy involving the distributed system operator and prosumers is introduced in [24], which integrates a risk price guidance mechanism within the P2P energy market. Notably, this approach accommodates the privacy requirements of participants by limiting information sharing between the upper and lower layers. The study utilizes the ADMM with an adaptive penalty factor to resolve the equilibrium within the decentralized P2P energy market.

A decentralized framework for the implementation of the P2P market utilizing the ADMM is developed in [25], which upholds the constraints of the distribution system, accounting for the independent nature of agents. Convergence among agents is achieved with minimal information exchange, while ensuring adherence to network constraints, such as voltage and current limitations. A methodology is advanced in [26] to optimize the scheduling of household appliances, aiming to reduce the collective electricity expenses of the community while prioritizing the privacy of participants. This is achieved through the integration of non-cooperative energy game theory within time-of-use tariffs and incentive structures. The proposed ADMM approach seeks to effectively tackle the dual challenge of enhancing social welfare and safeguarding participants' privacy within the decentralized distribution of power in the P2P market.

Authors in [27] introduce a decentralized P2P energy trading market employing the ADMM, enabling the exchange of electricity among consumers. Within this market framework, individual consumers act as autonomous agents, determining their willingness to maximize social welfare by offering surplus energy production in the P2P market.

Additionally, the emergence of the P2P market engenders another technological advancement known as the demand-side flexibility market. Operated by the distribution system operator within the local P2P market framework, the demand-side flexibility market becomes active. In instances of congestion forecasted for the following day, the operator solicits flexibility from the demand-side to alleviate congestion.

The existing literature primarily focuses on single-community systems or single local electricity markets, but it is inevitable to address the P2P trading in the context of multi-community systems. The expansion of research to encompass multi-community systems is necessary to fully understand and address the complexities and opportunities associated with P2P electricity trading across interconnected communities. Table 1 provides a comparative analysis between current work and previous studies. Some studies adopt a method that does not achieve full decentralization, employing a supervisory node to coordinate players. In contrast, a fully decentralized approach does not utilize any supervisory node.

Multi-community electricity systems provide numerous advantages over single-community systems [28]. They offer advantages such as enhanced resilience, improved electricity efficiency, cost savings, increased renewable electricity integration, flexibility in load balancing, community engagement and empowerment, environmental benefits and support for net-zero emissions goals [29]. Interconnecting communities ensure a robust electricity supply, and lower overall costs [8]. They facilitate sustainability and reduce GHG emissions.

It merits consideration that within multi-community systems aiming to enhance flexibility through the utilization of electric heaters and energy storage systems (ESSs), two challenges are associated with market clearing prices within the domain of P2P electricity trading. The first challenge involves market clearing prices within communities, and the second pertains to market clearing prices between communities, which have received less attention. This paper addresses these gaps by developing a fully decentralized ADMM-based model to tackle the issue of market clearing prices within and between interconnected communities in multi-community electricity systems.

The contributions of this paper are detailed as follows.

- Firstly, to enhance the flexibility of the system, the integration of electric heaters (EH) and ESSs has been strategically

TABLE 1 Comparison of the current work with existing studies.

	Market clearing mechanism							
Ref.	**Centralized**	**Decentralized**	**Fully-decentralized**	**Flexibility**	**Multi-community**	**ESS**	**EH**	**Upstream grid**
8	√	–	–	√	√	√	√	√
18	–	√	–	–	–	–	–	√
20	–	√	–	–	–	–	–	√
22	–	√	–	√	–	√	–	√
24	–	√	–	–	–	√	–	√
25	–	√	–	–	–	–	–	√
26	–	√	–	–	–	√	–	√
27	–	√	–	√	–	√	–	√
Current work	–	–	√	√	√	√	√	√

Abbreviations: EH, electric heater; ESS, energy storage systems.

incorporated within the framework of a comprehensive and fully decentralized multi-community P2P electricity market.

- Secondly, a fully decentralized ADMM-based approach is implemented to clear the proposed P2P electricity trading market, considering both within-community and between-communities transactions. The employed ADMM approach ensures that the private information of prosumers remains undisclosed, while simultaneously guaranteeing the attainment of a feasible and globally optimal solution for all individual local players involved in the market.

The rest of the paper is organized as follows: Section 2 introduces the problem formulation. Section 3 discusses the case studies and presents the simulation results. Finally, Section 4 presents the concluding remarks.

2 | FORMULATIONS OF THE PROBLEM

This section will describe the overall framework and explain the problem formulation from both the sellers' and buyers' points of view.

2.1 | Multi-community P2P electricity trading framework

This work's primary focus is on P2P electricity trading within geographically proximate communities, referred to as local electricity trading. This approach may encompass multiple communities; however, the overall number of such communities will remain relatively limited. Figure 1 shows the proposed multi-community P2P electricity trading framework. In this figure, blue arrows show the flow of information and red arrows indicate the flow of electricity. In a multi-community system, some peers have generation resources like solar panels and wind turbines; some are just consumers. Therefore, every hour, according to whether each peer has excess electricity or a lack of electricity, they are placed in the group of sellers (n = 1, 2, …, N) or buyers (m = 1, 2, …, M). Excess electricity of each seller can be sold to buyers within the same community ($P^{Ex}_{n_k,m_k,t}$ [kW]) in $\lambda_{n_k,m_k,t}$ [£/kWh] price, and/or to the supplier ($P^{ExG}_{n_k,t}$ [kW]) in $\lambda^{CG}_{k,t}$ [£/kWh] price, and/or to other communities ($P^{ExC}_{n_k,i,t}$ [kW]) in $\lambda^{C}_{k,i,t}$ [£/kWh] price. The deficit of

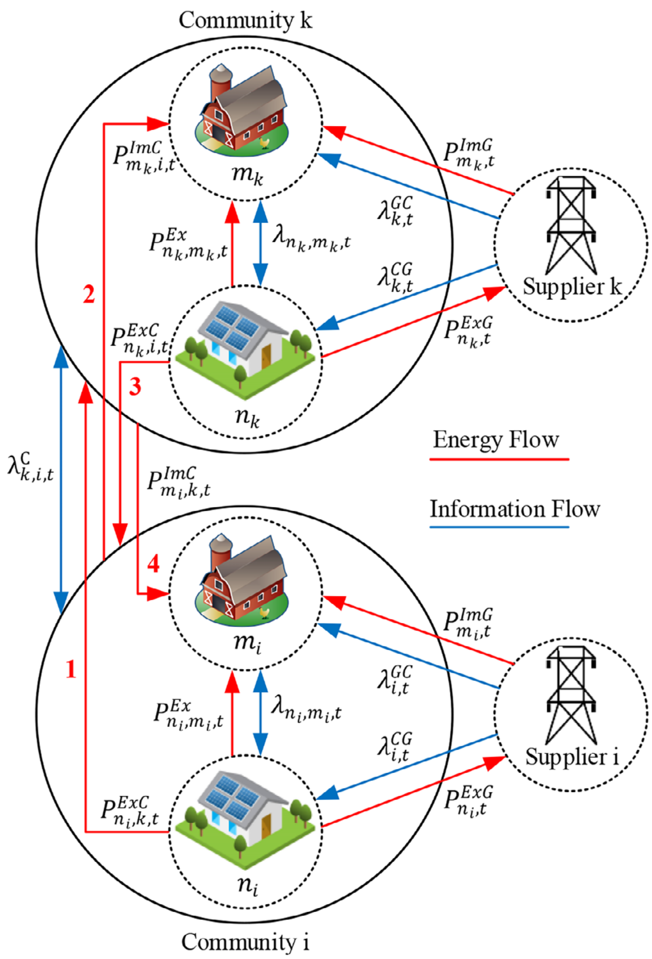

FIGURE 1 Multi-community peer-to-peer electricity trading framework.

electricity of each buyer can be bought from the sellers from the same community ($P^{Im}_{m_k,n_k,t}$ [kW]) in $\lambda_{n_k,m_k,t}$ [£/kWh], and/or from the supplier ($P^{ImG}_{m_k,t}$ [kW]) in $\lambda^{GC}_{k,t}$ price, and/or from other communities ($P^{ImC}_{m_k,i,t}$ [kW]) in $\lambda^{C}_{k,i,t}$ [£/kWh] price.

To elaborate on the left-hand red arrows, it should be noted that two of the four red arrows represent flows from community k to community i, and the other two represent flows in the opposite direction. Specifically:

- Arrow 1, denoted as $P^{ExC}_{n_i,k,t}$, represents the amount of electricity that seller peer n in community i sells to community k.
- Arrow 2, denoted as $P^{ImC}_{m_k,i,t}$, represents the amount of electricity that buyer peer m in community k purchases from community i.
- Arrow 3, denoted as $P^{ExC}_{n_k,i,t}$, represents the amount of electricity that seller peer n in community k sells to community i.
- Arrow 4, denoted as $P^{ImC}_{m_i,k,t}$, represents the amount of electricity that buyer peer m in community i purchases from community k.

Trading prices are simultaneously cleared within communities and between communities. It is imperative to acknowledge that the elucidation of the method is presented from the standpoint of community k (and the same can be applied to community i).

2.2 | A seller's perspective

As mentioned earlier, each peer is placed in the group of sellers or buyers at any hour. As depicted in Figure 1, the seller has the capability to sell its surplus electricity to consumers residing within the same community, other communities, and the grid. The objective function of a seller is specified by (1). In this equation, the revenue of the peer n in community k at time t is denoted by $R_{n_k,t}$ [£], which should be maximized. The total electricity that community k exports to community i is specified by (2).

$$\text{Max } R_{n_k,t} = \sum_{m_k=1}^{M_k} P^{Ex}_{n_k,m_k,t} \Delta t \lambda_{n_k,m_k,t} + \sum_{\substack{i=1 \\ i \neq k}}^{K} P^{ExC}_{n_k,i,t} \Delta t \lambda^{C}_{k,i,t} + P^{ExG}_{n_k,t} \Delta t \lambda^{CG}_{k,t} \quad (1)$$

$$P^{ExCC}_{k,i,t} = \sum_{n_k=1}^{N_k} P^{ExC}_{n_k,i,t} \quad (2)$$

The first term in (1) indicates the income from exporting electricity to other peers in the same community. The second term is the income from exporting electricity to other communities, and the last term shows the income from exporting electricity to the grid. The amount of electricity peer n exports to peer m in community k at time t () is denoted by $P^{Ex}_{n_k,m_k,t}$ (). The amount of electricity peer n in community k exports to the community i at time t (h) is denoted by $P^{ExC}_{n_k,i,t}$ (kW). Finally, the amount of electricity peer n in community k exports to the grid at time t (h) is denoted by $P^{ExG}_{n_k,t}$ (kW). $\lambda_{n_k,m_k,t}$ (£/kWh) represents cleared trading price between peer n and peer m in community k at time t. $\lambda^{C}_{k,i,t}$ (£/kWh) shows cleared trading price between community k and community i at time t. $\lambda^{CG}_{k,t}$ (£/kWh) is the smart export guarantee (SEG) tariff rate [30]. The SEG is a UK program where energy suppliers pay small-scale generators for excess electricity fed back into the grid, with rates varying based on suppliers and time [30]. N_k is the set of seller peers and M_k is the set of buyer peers in community k. Total electricity that community k exports to community i equals to sum of electricity that all peers in community k export to the community i at time t as (2). The surplus electricity for a seller peer and the deficit of electricity for a buyer peer is specified by (3) and (4), respectively.

$$G_{n_k,t} = \sum_{m_k=1}^{M_k} P^{Ex}_{n_k,m_k,t} + \sum_{\substack{i=1 \\ i \neq k}}^{K} P^{ExC}_{n_k,i,t} + P^{ExG}_{n_k,t} \quad (3)$$

$$D_{m_k,t} = \sum_{n_k=1}^{N_k} P^{Im}_{m_k,n_k,t} + \sum_{\substack{i=1 \\ i \neq k}}^{K} P^{ImC}_{m_k,i,t} + P^{Dch}_{m_k,t} - P^{Ch}_{m_k,t} + P^{ImG}_{m_k,t} - FL_{m_k,t} \quad (4)$$

$G_{n_k,t}$ in (3) represents the surplus electricity of peer n in community k at hour t. As evident from (3), a portion of this electricity can be sold to other peers within the same community. Another portion can be sold to other communities, while the remaining portion can be sold to the grid. $D_{m_k,t}$ represents the electricity required by peer m in community k at hour t. As indicated by (4), this electricity, along with the electricity needed for flexible load (FL) and battery charging, can be supplied through other peers within the same community, other communities, the grid or battery discharge.

The amount of electricity peer m imports from peer n in community k at time t (h) is denoted by $P^{Im}_{m_k,n_k,t}$ (kW). The amount of electricity peer m in community k imports from community i at time t (h) is denoted by $P^{ImC}_{m_k,i,t}$ (kW), and finally, the amount of electricity peer m in community k imports from the grid at time t (h) is denoted by $P^{ImG}_{m_k,t}$ (kW). $FL_{m_k,t}$ represents peer m's FL consumption in community k at time t. $P^{Ch}_{m_k,t}$ (kW) and $P^{Dch}_{m_k,t}$ (kW) show charge and discharge of peer's m ESS in community k at time t, respectively. The classification of peers, particularly those equipped with flexible loads or batteries, into the categories of sellers or buyers, depends on the net power they contribute to the system.

2.2.1 | Flexible load

In this study, FLs are assumed to be electric heaters whose purpose is to maintain the air temperature in the buildings in the comfort range and enable prosumers to provide flexibility and exchange electricity with suppliers or other prosumers in response to P2P electricity trading prices. 1R1C model has been used to describe the building thermal inertia in a multi-community system based on (5)–(7) [31], where the dynamics of the indoor temperature of a household are described as (5). Equation (6) shows the temperature boundaries to maintain a peer's comfort, and (7) states the heater's minimum and maximum power consumption limitations.

$$Te_{m_k,t} = e^{\left(\frac{-\Delta t.u_{m_k}}{c_{m_k}}\right)} Te_{m_k,t-1} + \left[1 - e^{\left(\frac{-\Delta t.u_{m_k}}{c_{m_k}}\right)}\right] \cdot Te_t^a + \frac{1}{u_{m_k}}\left[1 - e^{\left(\frac{-\Delta t.u_{m_k}}{c_{m_k}}\right)}\right] \mathrm{FL}_{m_k,t}, \forall k \in K, \forall t \in T, m \in M \quad (5)$$

$$Te_{m_k,t}^{\mathrm{Min}} \le Te_{m_k,t} \le Te_{m_k,t}^{\mathrm{Max}}, \forall k \epsilon K, \forall t \epsilon T, m \epsilon M \quad (6)$$

$$FL_{m_k,t}^{\mathrm{Min}} \le FL_{m_k,t} \le FL_{m_k,t}^{\mathrm{Max}}, \forall k \epsilon K, \forall t \epsilon T, m \epsilon M \quad (7)$$

$Te_{m_k,t}$ (K) stands for the indoor temperature of the household with the mth peer's heater in the kth community at time t. Δt shows the time steps. u_{m_k} (W/K) shows the thermal transmittance of the mth peer's heater in the kth community, c_{m_k} (J/kg K) stands for the thermal capacitance of the mth peer's heater in the kth community, Te_t^a (K) shows the temperature of the ambient air at time t, and $Te_{m_k,t}^{\mathrm{Min}}$ (K) and $Te_{m_k,t}^{\mathrm{Max}}$ (K) are the minimum and maximum temperature boundaries to maintain the comfort of the mth peer in the kth community at time t. Finally, $FL_{m_k,t}^{\mathrm{Min}}$ and $FL_{m_k,t}^{\mathrm{Max}}$ show the minimum and maximum power consumption of peer m's FL in community k at time t, respectively.

2.2.2 | Energy storage system

ESSs could also play a crucial role in providing flexibility for the system. Features of ESSs are described as (8)–(12).

$$E_{m_k,t} = (1-\mu)\ E_{m_k,t-1} + \Delta t \left(\eta P_{m_k,t}^{Ch} - \frac{1}{\eta} P_{m_k,t}^{Dch}\right), \forall k \epsilon K, \forall t \epsilon T, m \epsilon M \quad (8)$$

$$P_{m_k,t}^{Ch} \le P_{m_k,t}^{Ch^{\mathrm{Max}}} \vartheta_{m_k,t}, \forall k \epsilon K, \forall t \epsilon T, m \epsilon M \quad (9)$$

$$P_{m_k,t}^{Dch} \le P_{m_k,t}^{Dch^{\mathrm{Max}}} \tau_{m_k,t}, \forall k \epsilon K, \forall t \epsilon T, m \epsilon M \quad (10)$$

$$E_{m_k,t}^{\mathrm{Min}} \le E_{m_k,t} \le E_{m_k,t}^{\mathrm{Max}}, \forall k \epsilon K, \forall t \epsilon T, m \epsilon M \quad (11)$$

$$\vartheta_{m_k,t} + \tau_{m_k,t} \le 1, \forall k \epsilon K, \forall t \epsilon T, m \epsilon M \quad (12)$$

Equation (8) shows the state of charge of peer m's ESS in community k at time t. In other words, (8) represents the energy balance equation. It outlines how the energy stored in the ESS evolves from one-time step to the next. Both the charging and discharging processes incorporate efficiency losses, which are considered through η. $P_{m_k,t}^{Ch}$ (kW) and $P_{m_k,t}^{Dch}$ (kW) are positive variables and denoted the charging and discharging power of the mth peer's ESS in the community k at time t. The charge and discharge limits of the ESS are modelled according to (9) and (10). Equation (11) shows the ESS's minimum and maximum state of charge. Equation (12) indicates that charging and discharging does not coincide [32]. $\vartheta_{m_k,t}$ and $\tau_{m_k,t}$ are the binary variables and show the charging and discharging states of the peer m's ESS in community k at time t, respectively.

2.3 | A buyer's perspective

As (13) indicates, the cost of peer m in community k at time t is denoted by $C_{m_k,t}$ [£], which should be minimized. Total electricity that community i imports from community k equals to sum of electricity that all peers in community i import from community k at time t as (14).

$$Min\ C_{m_k,t} = \sum_{n_k=1}^{N_k} P_{m_k,n_k,t}^{Im} \Delta t \lambda_{n_k,m_k,t} + \sum_{\substack{i=1 \\ i \ne k}}^{K} P_{m_k,i,t}^{ImC} \Delta t \lambda_{k,i,t}^{\mathrm{C}} + P_{m_k,t}^{ImG} \Delta t \lambda_{k,t}^{GC} \quad (13)$$

$$P_{i,k,t}^{ImCC} = \sum_{m_i=1}^{M_i} P_{m_i,k,t}^{ImC} \quad (14)$$

The first term in (13) indicates the cost of importing electricity from other peers in the same community. The second term is the cost of importing electricity from other communities, and the last term shows the cost of importing electricity from the grid. In this equation, $\lambda_{n_k,m_k,t}$ (£/kWh), as mentioned before, represents cleared trading price between peer n and peer m in community k at time t. $\lambda_{k,t}^{GC}$ (£/kWh) is the price of buying from the grid for community k at time t.

2.4 | Proposed fully decentralized ADMM-based multi-community market clearing mechanism

The proposed P2P electricity trading mechanism aims to optimize the objective function for all sellers and buyers across all communities in an iterative process. This objective function is represented by (15). In the multi-community P2P problem, there exist two coupled constraints, as depicted in (16) and (17).

$$\mathrm{Max} \sum_{k=1}^{K}\left(\sum_{n_k=1}^{N_k}\left(\sum_{m_k=1}^{M_k} P_{n_k,m_k,t}^{Ex} \Delta t \lambda_{n_k,m_k,t} + \sum_{\substack{i=1 \\ i \ne k}}^{K} P_{n_k,i,t}^{ExC} \Delta t \lambda_{k,i,t}^{\mathrm{C}} + P_{n_k,t}^{ExG} \Delta t \lambda_{k,t}^{CG}\right) - \sum_{m_k=1}^{M_k}\left(\sum_{n_k=1}^{N_k} P_{m_k,n_k,t}^{Im} \Delta t \lambda_{n_k,m_k,t} - \sum_{\substack{i=1 \\ i \ne k}}^{K} P_{m_k,i,t}^{ImC} \Delta t \lambda_{k,i,t}^{\mathrm{C}} - P_{m_k,t}^{ImG} \Delta t \lambda_{k,t}^{GC}\right)\right) \quad (15)$$

$$P^{Ex}_{n_k,m_k,t} = P^{Im}_{m_k,n_k,t} \ : \lambda_{n_k,m_k,t} \quad (16)$$

$$P^{ExCC}_{k,i,t} = P^{ImCC}_{i,k,t} \ : \lambda^{C}_{k,i,t} \quad (17)$$

$$(2) - (12)\text{, and } (14) \quad (18)$$

Equation (16) illustrates that the electricity exported by peer n to peer m in community k at hour t is equal to the electricity imported by peer m from peer n within the same community and hour. The dual variable of this equation is denoted as $\lambda_{n_k,m_k,t}$ (£/kWh), which represents the cleared price between these peers. The subsequent equilibrium constraint pertains to the amount of electricity community k exports to community i. This electricity is equivalent to the amount of electricity that community i imports from community k. The dual variable associated with this equation is $\lambda^{C}_{k,i,t}$ (£/kWh), indicating the cleared price for between-community exchanges.

The optimization problem presented in (15)–(18) can be effectively addressed through a centralized approach. However, this approach necessitates the presence of a supervisory node serving as a central controller for all communities. Entrusting the supervisory node with the operational and commercial information of the participating peers introduces potential risks, including breaches of privacy and unauthorized disclosure of sensitive data. In order to circumvent these concerns, this study proposes a decentralized ADMM-based mechanism that eliminates the need for a supervisory node by enabling a fully decentralized solution to the problem at hand. It should be noted that a sequential update of local ADMM variables at each peer is required. Within the framework of the decentralized ADMM, each peer independently solves their optimization problem while receiving minimal and non-sensitive information from other prosumers. The optimization problem is decomposed into multiple secondary sub-problems based on the principles of dual decomposition [33]. This decomposition entails relaxing the interconnected constraint (16) and (17) and their dual variables are considered as between-peers and between-communities prices. Consequently, each participant addresses their optimization problem as a secondary problem in a decentralized manner.

Upon formulating the augmented Lagrangian corresponding to the optimization problem delineated in (15)–(18), this function can be derived as follows:

$$\begin{aligned} L_t = &\left(\sum_{k=1}^{K}\left(\sum_{n_k=1}^{N_k} R_{n_k,t} - \sum_{m_k=1}^{M_k} C_{m_k,t}\right)\right) \\ &+ \lambda_{n_k,m_k,t}\left(P^{Ex}_{n_k,m_k,t} - P^{Im}_{m_k,n_k,t}\right)\Delta t \\ &+ \lambda^{C}_{k,i,t}\left(P^{ExCC}_{k,i,t} - P^{ImCC}_{i,k,t}\right)\Delta t \\ &- \delta\left\|P^{Ex}_{n_k,m_k,t} - P^{Im}_{m_k,n_k,t}\right\|_2^2 - \delta'\left\|P^{ExCC}_{k,i,t} - P^{ImCC}_{i,k,t}\right\|_2^2 \end{aligned} \quad (19)$$

The dual variables $\lambda_{n_k,m_k,t}[£/kWh]$ and $\lambda^{C}_{k,i,t}[£/kWh]$ correspond to the coupled constraints in both the buyer and seller problems. The conventional Lagrangian framework is applicable in the case of fully convex problems devoid of abrupt fluctuations. However, in order to address these limitations, an augmented Lagrangian, as expressed in (19), is employed, incorporating the terms $\delta\|P^{Ex}_{n_k,m_k,t} - P^{Im}_{m_k,n_k,t}\|_2^2$ and $\delta'\|P^{ExCC}_{k,i,t} - P^{ImCC}_{i,k,t}\|_2^2$. This augmented formulation ensures convergence and robustness of the problem by introducing the penalty parameters δ and δ', which are positive scalars [33]. By formulating the original buyer and seller problems using the augmented Lagrangian approach, the following expressions can be obtained:

$$\begin{aligned} Max\ R_t = &\left(\sum_{\substack{k=1\\k\neq i}}^{K}\left(\sum_{n_k=1}^{N_k}\left(\sum_{m_k=1}^{M_k} P^{Ex}_{n_k,m_k,t}\Delta t\lambda_{n_k,m_k,t} + \sum_{\substack{i=1\\i\neq k}}^{K} P^{ExC}_{n_k,i,t}\Delta t\lambda^{C}_{k,i,t}\right.\right.\right. \\ &+ P^{ExG}_{n_k,t}\Delta t\lambda^{C_kG}_{t} - 0.5\delta\left\|P^{Ex}_{n_k,m_k,t} - P^{Im}_{m_k,n_k,t}\right\|_2^2 - 0.5\delta'\left\|P^{ExCC}_{k,i,t}\right. \\ &\left.\left.\left.\left. - P^{ImCC}_{i,k,t}\right\|_2^2\right)\right)\right) \end{aligned} \quad (20)$$

In (20), $P^{Im}_{m_k,n_k,t}$ (kW) and $P^{ImCC}_{i,k,t}$ (kW) are taken as predetermined parameters. In (21), $P^{Ex}_{n_k,m_k,t}$ (kW) and $P^{ExCC}_{k,i,t}$ (kW) are taken as predetermined parameters.

$$\begin{aligned} \text{Min } C_t = &\left(\sum_{\substack{k=1\\k\neq i}}^{K}\left(\sum_{m_k=1}^{M_k}\left(\sum_{n_k=1}^{N_k} P^{Im}_{m_k,n_k,t}\Delta t\lambda_{n_k,m_k,t} + \sum_{\substack{i=1\\i\neq k}}^{K} P^{ImC}_{m_k,i,t}\Delta t\lambda^{C}_{k,i,t}\right.\right.\right. \\ &+ P^{ImG}_{m_k,t}\Delta t\lambda^{GC}_{k,t} + 0.5\delta\left\|P^{Ex}_{n_k,m_k,t} - P^{Im}_{m_k,n_k,t}\right\|_2^2 + 0.5\delta'\left\|{}^{ExCC}_{k,i,t}\right. \\ &\left.\left.\left.\left. - P^{ImCC}_{i,k,t}\right\|_2^2\right)\right)\right) \end{aligned} \quad (21)$$

The iterative method as shown in Figure 2 is employed to update all dual variables of the problem, following (25)–(28).

The convergence criteria are expressed as (22)–(24). If these convergence criteria are satisfied within the predetermined maximum number of iterations, the iteration process will be terminated. Otherwise, the procedure will continue from (20).

$$err1_t^{l+1} = \sum_{\substack{k=1\\k\neq i}}^{K}\left(\sum_{m_k=1}^{M_k}\left(\sum_{n_k=1}^{N_k}\lambda^{l+1}_{n_k,m_k,t} - \lambda^{l}_{n_k,m_k,t}\right)\right) \quad (22)$$

$$err2_t^{l+1} = \sum_{\substack{k,i=1\\k\neq i}}^{K}\left(\lambda^{C^{l+1}}_{k,i,t} - \lambda^{C^{l}}_{k,i,t}\right) \quad (23)$$

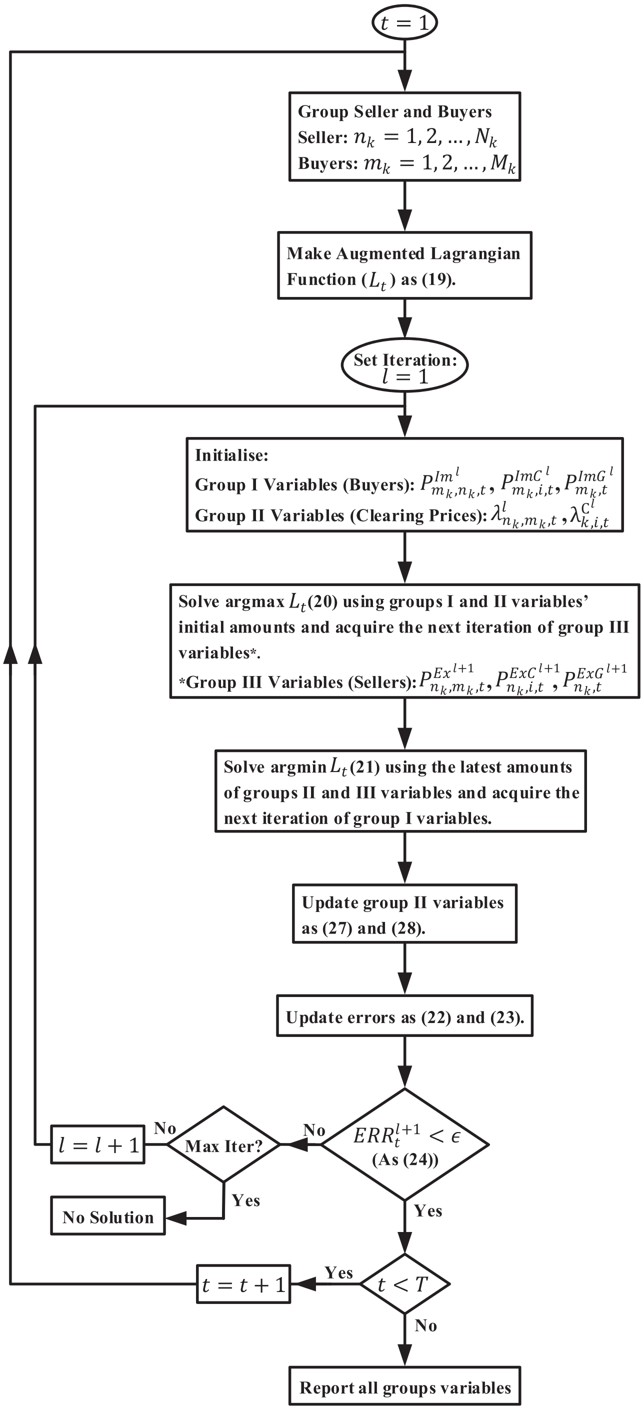

FIGURE 2 Flowchart of the proposed method.

$$ERR_t^{l+1} = \max\left(err1_t^{l+1}, err2_t^{l+1}\right) < \epsilon \tag{24}$$

3 | CASE STUDY

The proposed method has been implemented on an electricity system comprising two energy communities. Energy community α comprises 15 peers, while community β comprises 18 peers.

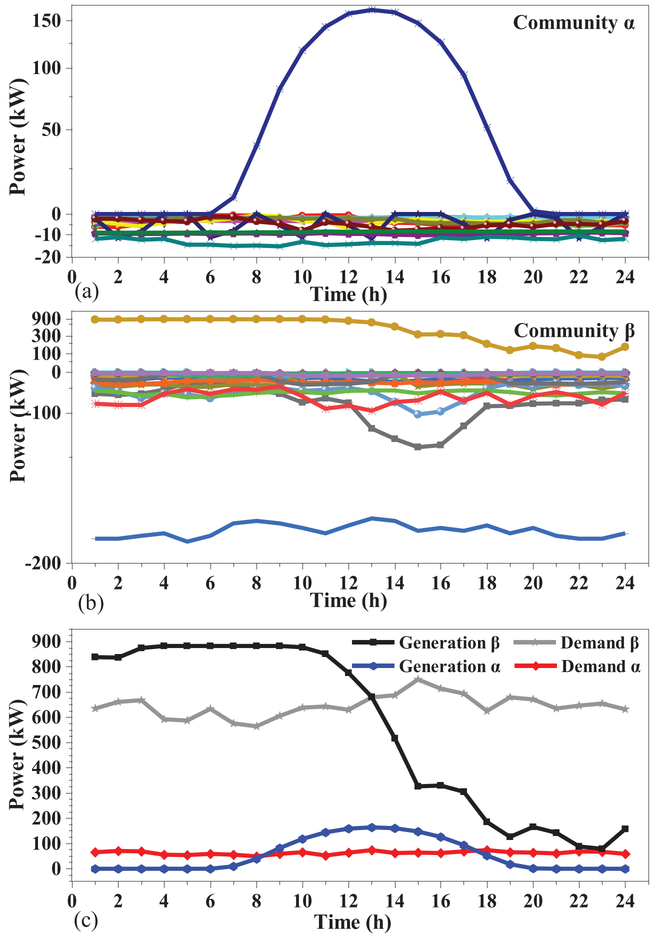

FIGURE 3 (a) Net power of all peers in community α. (b) Net power of all peers in community β. (c) Net generation and demand of both communities.

$$P^{Ex^{l+1}}_{n_k,m_k,t}, P^{ExC^{l+1}}_{n_k,i,t}, P^{ExG^{l+1}}_{n_k,t} := \underset{P^{Ex}_{n_k,m_k,t}, P^{ExC}_{n_k,i,t}, P^{ExG}_{n_k,t}}{\operatorname{argmax}} \times L\left(P^{Ex}_{n_k,m_k,t}, P^{ExC}_{n_k,i,t}, P^{ExG}_{n_k,t}, \lambda^{l}_{n_k,m_k,t}, \lambda^{C^l}_{k,i,t}, P^{Im^l}_{m_k,n_k,t}, P^{ImC^l}_{m_k,i,t}, P^{ImG^l}_{m_k,t}\right) \tag{25}$$

$$P^{Im^{l+1}}_{m_k,n_k,t}, P^{ImC^{l+1}}_{m_k,i,t}, P^{ImG^{l+1}}_{m_k,t} := \underset{P^{Im}_{m_k,n_k,t}, P^{ImC}_{m_k,i,t}, P^{ImG}_{m_k,t}}{\operatorname{argmax}} \times L\left(P^{Ex^{l+1}}_{n_k,m_k,t}, P^{ExC^{l+1}}_{n_k,i,t}, P^{ExG^{l+1}}_{n_k,t}, \lambda^{l}_{n_k,m_k,t}, \lambda^{C^l}_{k,i,t}, P^{Im}_{m_k,n_k,t}, P^{ImC}_{m_k,i,t}, P^{ImG}_{m_k,t}\right) \tag{26}$$

$$\lambda^{l+1}_{n_k,m_k,t} = \lambda^{l}_{n_k,m_k,t} - \delta\left(P^{Ex^{l+1}}_{n_k,m_k,t} - P^{Im^{l+1}}_{m_k,n_k,t}\right) \tag{27}$$

$$\lambda^{C^{l+1}}_{k,i,t} = \lambda^{C^l}_{k,i,t} - \delta\left(P^{ExCC^{\,l+1}}_{k,i,t} - P^{ImCC^{\,l+1}}_{i,k,t}\right) \tag{28}$$

Figure 3a,b depicts the net power of all peers within both energy communities, where positive values represent the power

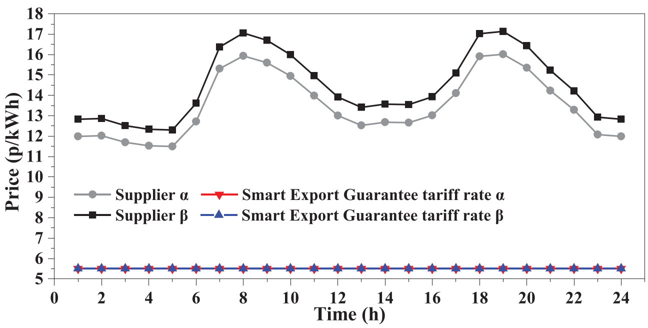

FIGURE 4 Suppliers' prices and smart export guarantee tariff rates in both communities.

TABLE 2 Parameters of the heater and the energy storage systems (ESS) [27].

Parameter	Value	Parameter	Value
u_{m_k}	409.09 W/K	η	97%
c_{m_k}	1.75E6 J/Kg K	$E_{m_k,0}$	31 kWh
$Te^{\text{Min}}_{m_k,t}$	290 K	$P^{Dch^{\text{Max}}}_{m_k,t}$	50 kW
$Te^{\text{Max}}_{m_k,t}$	296 K	$P^{Ch^{\text{Max}}}_{m_k,t}$	50 kW
$Te_{m_k,0}$	293.1 K	$E^{\text{Max}}_{m_k,t}$	100 kWh

of seller peers and negative values indicate the power of buyer peers [34]. Figure 3c represents both communities' net generation and demand. As shown in Figure 3c, there is an excess of electricity in community β during the first 12 h, while community α experiences this excess from 9:00 to 17:00.

The suppliers' prices and SEG tariff rates in both communities are depicted in Figure 4. The SEG tariff rate in the system is set at 5.5 p/kWh [30].

One peer in the electricity community α has been equipped with an ESS with a capacity of 100 kWh/50 kW and an electric heater acting as the FL per the specifications outlined in Table 2. The optimization problem is solved using the CPLEX solver within the GAMS software. The ADMM algorithm's stopping criterion and step sizes (δ and δ') are set at 0.0005 and 0.05, respectively.

A fully decentralized multi-community P2P electricity trading mechanism is applied in two case studies with and without between-communities trading capability.

3.1 | Case I: Fully decentralized multi-community P2P electricity trading mechanism with between-communities trading capability

In this case, all communities can exchange electricity with each other. Therefore, the electricity shortage of each community can be supplied from other communities in addition to the supplier. On the other hand, the extra electricity of each community is exported to other communities in addition to the grid. To solve this model, assuming zero initial values for group I and II variables according to the flowchart presented in Figure 2.

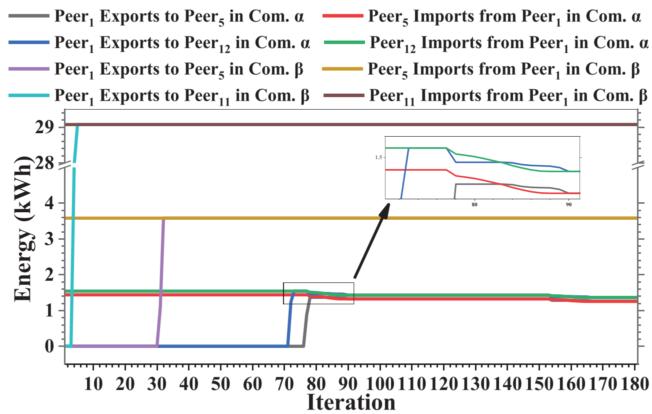

FIGURE 5 Traded electricity between some peers at hour 7:00.

Figure 5 shows the electricity exchanged between some sellers and buyers within each community at hour 7:00. As shown in Figure 3c, peer 1 in communities α and β has excess electricity. Therefore, they play the role of the seller at different hours. Peer 1 in community α has 8.667 kWh of extra electricity at this hour. On the other hand, peer 5 has got 1.44 kWh shortage of electricity, of which 1.26 kWh is supplied by peer 1, and the rest is compensated by importing electricity from the community, β. As Figure 5 shows, after approximately 165 iterations, these two peers have matched and converged. A similar process happened between peer 1 and peer 12 in this community. Peer 12 needs 1.545 kWh of electricity at this hour, of which 1.365 kWh was supplied by peer 1 and the rest from community β. In the community β, at the same hour, peer 1, which has excess electricity (883.2 kWh), gives part of its electricity to the consumer peers in the same community. For example, Figure 5 shows the process of exporting electricity from peer 1 to peers 5 and 11 in the community β. The electricity exchange between peers 1 and 5 after 32 iterations and peers 1 and 11 after 4 has converged. In this exchange, the total electricity required by peer 5, which is 3.584 kWh and the total electricity needed by peer 11, which is 29.072 kWh, is compensated by peer 1.

Figure 6 shows the cleared prices between some buyers and sellers in both communities at hours 7:00 and 15:00. As it is clear from this figure, the prices have converged in less than 80 iterations. For instance, peers 1 and 5 in community α have converged at the price of 5.5 p/kWh at hour 7:00 and the price of 12.66 p/kWh at hour 15:00. The same thing happened in the community β between peers 1 and 5, with the difference that the cleared price was 5.5 p/kWh at hour 7:00 and 13.55 p/kWh at hour 15:00. At hour 7:00, community α has 56 kWh of electricity shortage and community β has 307.63 kWh of excess electricity, so that community α can meet its needs from community β.

The low cleared price at hour 7:00 in Figure 6 is due to the fact that, at this time, the whole system does not need to import electricity from the grid due to the increase in electricity, so the cleared prices are close to the selling price to the grid. Still,

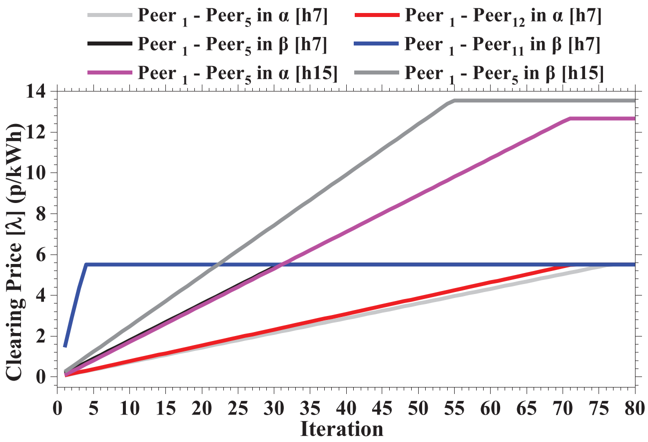

FIGURE 6 Cleared prices between some peers at hours 7:00 and 15:00.

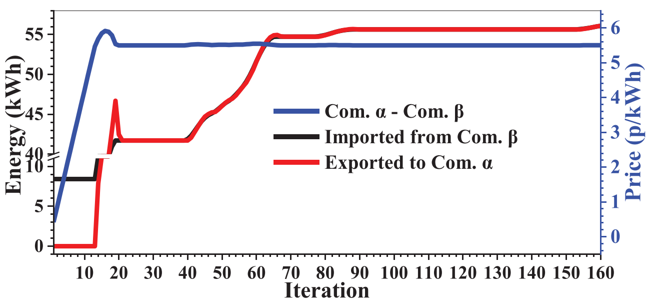

FIGURE 7 Electricity trading between communities α and β.

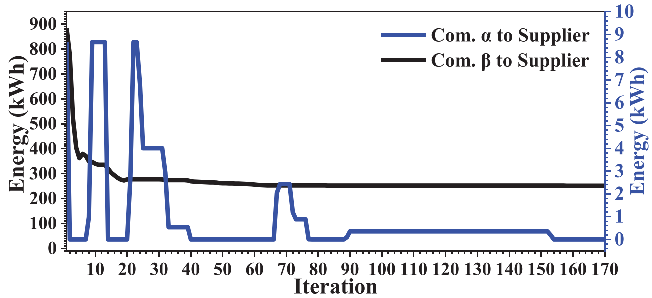

FIGURE 8 Traded electricity of communities with suppliers.

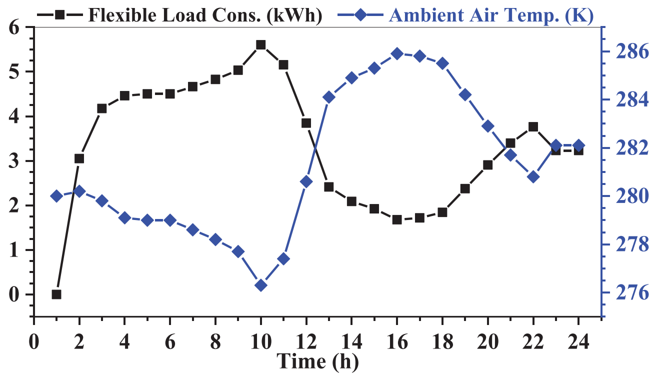

FIGURE 9 Flexible load's consumption and the ambient air temperature.

at hour 15:00, the system has an electricity shortage (community β 423.634 kWh of electricity shortage and community α 80.224 kWh of excess electricity). The system has to buy part of its electricity from the grid. For this reason, the cleared prices at this hour are closer to the purchasing prices from the grid.

Figure 7 shows the iterative process of electricity exchanged between communities and also the cleared price of exchanges between communities at hour 7:00. As it is clear from Figure 3a, at this hour, community α has a shortage of electricity, and community β has excess electricity. Therefore, community β will export part of its electricity to community α. As it is clear from Figure 7, the electricity community β exports to α and the electricity community α imports from β have fluctuated a lot. Finally, it has reached a constant value of 56 kWh in the 157th iteration. The cleared price of between-communities exchanges has reached a fixed value after 66 iterations during an iterative process at this hour.

Figure 8 shows the electricity exchanged by each community with its supplier. As mentioned, community β had 883.2 kWh of excess electricity at 7:00, of which 56 kWh was exported to community α, and 251 kWh was sold to the grid. The rest, 576 kWh, was sold to consumer peers in this community. The electricity exported by the community α to the grid is zero because this community lacks electricity at this hour and imports electricity itself.

The ambient air temperature and power consumption of the FL are presented in Figure 9. Because the objective of the consumers is to minimize the total cost, the less power the FL consumes, the lower the cost. Therefore, at all hours, FL is at its lowest consumption to maintain the temperature in the comfort range. As the temperature decreases, the amount of electricity consumed to maintain the inside temperature of houses within a comfortable range increases. As stated in Table 2, the comfort range is between 290 and 296 K. As stated earlier, the house's air temperature in the first hour is assumed to be 293.1 K. For this reason, the power consumption of the FL is zero at this hour despite the low outside air temperature.

3.2 | Case II: Fully decentralized multi-community P2P electricity trading without between-communities trading capability

In this case, the communities cannot exchange electricity with each other and can only exchange electricity with the grid. Therefore, the lack of electricity in each community can only be compensated through the supplier of the same community, and the excess electricity can only be sold to the grid. It is expected that the total cost, in this case, will be higher than the previous case.

Figure 10 shows the electricity exchanged between some buyers and sellers in both communities at hour 7:00. Exchanges in community α converge in a higher number of iterations because, unlike community β, there is an ESS and a FL in this community, which makes this issue a little more complicated.

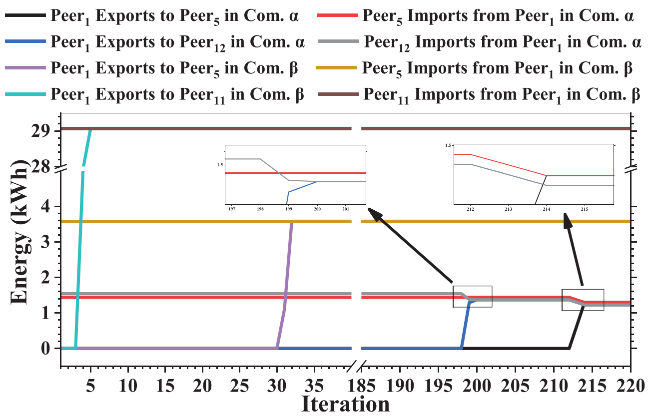

FIGURE 10 Traded electricity between some peers at hour 7:00.

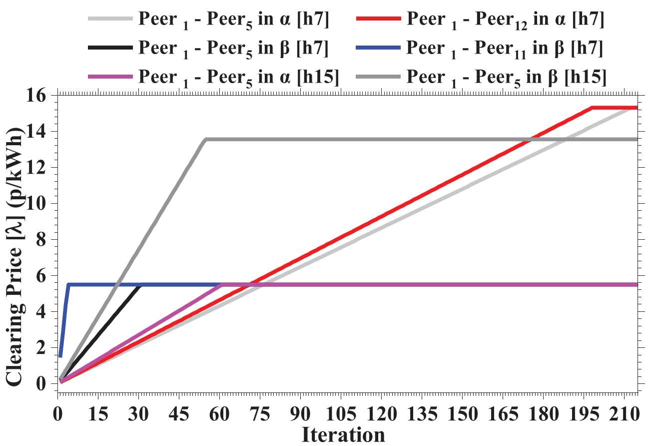

FIGURE 11 Cleared prices between some peers at hours 7:00 and 15:00.

Exchanges between peers 1 and 5 in community α reach convergence after 214 iterations, in which 1.296 kWh of electricity is exported from peer 1 to peer 5. This process is performed for peers 1 and 12 in the same community in 216 iterations, which exports 1.229 kWh of electricity from peers 1 to 12. The rest of the electricity required for peers 5 and 12 in community α is provided by the supplier. In community β, peer 1 converges with peer 5 in 4 iterations and with peer 11 in 32 iterations and exports 3.584 and 29.072 kWh of electricity to them, respectively. It should be noted that this is the total need of these peers, which is provided by peer 1.

Figure 11 shows the cleared prices between some buyers and sellers in both communities at hours 7:00 and 15:00. As it is clear from this figure, the exchanges in community β have converged in less than 50 iterations, but this happened for community α in nearly 200 iterations, which is because community α is more complex due to its FL and ESS. For instance, peers 1 and 5 converged in community α at hour 7:00 for 15.3 p/kWh and at hour 15:00 for 5.5 p/kWh. The same thing happened in community β between peers 1 and 5, with the difference that the cleared price was 5.5 p/kWh at hour 7:00 and 13.55 p/kWh at hour 15:00. These prices are directly related to electricity exchange with the grid. If a community has excess electricity, its internal

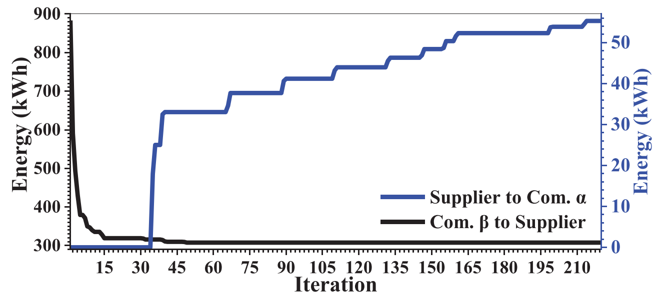

FIGURE 12 Traded electricity of communities with suppliers.

TABLE 3 Cost of the whole system.

	Cost (£)
Case I	604.38
Case II	662.48
Conventional market	1646.68

exchange price will be close to the price of selling to the grid. If a community has a deficit of electricity, its internal exchange price will be close to the price of buying from the supplier. For example, at hour 7:00, community α lacks electricity and has to import the electricity it needs from the supplier. Because of this, the exchange price of peer 1 and peers 5 and 12 has become 15.3 p/kWh. At hour 15:00, community α has excess electricity, and the price of internal exchanges has decreased significantly.

Figure 12 shows that, unlike the previous case, community α has supplied its electricity shortage from the supplier at hour 7:00. At the same hour, community β has sold all of its excess electricity to the grid. In the previous case, community α had supplied all 56 kWh of electricity needed for hour 7:00 through community β, but in this case, it has supplied all of it from the supplier. Community β also sold only 251 kWh of electricity to the grid in the previous case, but it sold 307 kWh in this case. The same as the previous case because the objective of the consumers is to minimize the total cost; the less power the FL consumes, the lower the cost. Therefore, in this case, FL is at its lowest consumption at all hours to maintain the temperature in the comfort range as well.

The cost of communities in both cases is shown in Table 3. The cost in cases I and II is £604.38 and £662.48, respectively. The cost in Case II increased by more than 9.6% compared to the first case, the main reason of which was the impossibility of between-communities exchanges. In this case, the excess electricity of each community is sold only to the grid at the lowest possible price. The lack of electricity in every community is provided only through the supplier at the highest possible price, which increases the cost of peers. As is apparent in Table 3, the cost of the studied system has also been investigated in the form of a conventional market, and the results show a 172% increase in the cost of communities in this model compared to the full P2P model. This increase can be attributed to the structure of the conventional market, where each consumer acquires the required electricity directly from the supplier at the highest

TABLE 4 Execution time of the model with different number of communities.

Number of communities	Execution time (s)
2	273
3	257
4	275
10	311

price, while each producer sells their surplus electricity to the grid at the lowest price. Consequently, the producer's revenue is minimized, and the consumer's expenses are maximized.

A thorough analysis of the execution time is conducted across varying numbers of communities. Table 4 indicates that the execution time remains within the acceptable time frame, even as the number of communities increases significantly. The characteristics of the communities and the data of individual peers significantly impact the execution time of the problem. For instance, in a scenario involving three communities, two communities were assumed to have identical specifications, resulting in a faster clearing process compared to a two-community system. In the case of four communities, it was assumed that the communities were grouped into two pairs, with each pair consisting of items that have the same specifications. Consequently, the execution time was slightly longer than that of the two-community system.

4 | CONCLUSION

This research introduced a fully decentralized multi-community peer-to-peer electricity trading mechanism that integrated iterative auction and pricing methods within local electricity markets. The mechanism classified peers in all communities on an hourly basis, based on their electricity surplus or deficit, distinguishing them as sellers and buyers. Furthermore, communities engaged in energy exchange not only among themselves but also with the grid. To address privacy concerns, a fully decentralized method known as the ADMM was used and developed.

Moreover, the model incorporated the flexibility provided by residential heating systems into the energy scheduling of certain prosumers. The prosumers aimed to minimize the total cost, and thus, they ensured that the FL consumed as little power as possible to keep the building's temperature within the comfort range at all hours. The results demonstrated that the proposed model exhibited exceptional economic efficiency compared to the conventional market. Additionally, between-communities exchanges were found to significantly increase communities' economic efficiency. The proposed mechanism reduced average daily electricity costs by 63% compared to the reference case without peer-to-peer electricity trading, while between-communities trading reduced the total cost by 8.8% compared to the case without between-communities trading capability.

Regulatory challenges and infrastructure requirements could be potential limitations for implementing decentralized multi-community P2P electricity trading framework. We advocate for a deeper exploration of the interplay among diverse energy vectors, an area presently under intense scrutiny. Our research specifically integrates electric heaters into the framework of heat demand. Consequently, it becomes imperative to assess the feasibility of P2P heat trading alongside electricity trading among prosumers. This necessitates the formulation of a robust methodology to facilitate comprehensive investigation in this domain.

AUTHOR CONTRIBUTIONS

Morteza Shafiekhani: Methodology; software; visualization; writing—original draft. **Meysam Qadrdan**: Funding acquisition; project administration; resources; supervision; writing—review and editing. **Yue Zhou**: Conceptualization; methodology; validation; writing—review and editing. **Jianzhong Wu**: Funding acquisition; project administration; resources; writing—review and editing.

ACKNOWLEDGEMENTS

The authors wish to acknowledge that this work has been conducted within the framework of the European Union's Horizon 2020 Research and Innovation Program under grant agreement No. 957852, titled "Virtual Power Plant for Interoperable and Smart isLANDS" (VPP4ISLANDS).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be available upon request.

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How to cite this article: Shafiekhani, M., Qadrdan, M., Zhou, Y., Wu, J.: Designing a decentralized multi-community peer-to-peer electricity trading framework. IET Gener. Transm. Distrib. 1–12 (2024). https://doi.org/10.1049/gtd2.13257