IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 12, 2021, accepted November 15, 2021, date of publication November 17, 2021,
date of current version December 2, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3129050

Peer-to-Peer Electricity Market Based on Local Supervision

HOSNA KHAJEH[1], **(Graduate Student Member, IEEE),**
AMIN SHOKRI GAZAFROUDI[2], **HANNU LAAKSONEN**[1], **(Member, IEEE),**
MIADREZA SHAFIE-KHAH[1], **(Senior Member, IEEE),**
PIERLUIGI SIANO[3], **(Senior Member, IEEE),**
AND JOÃO P. S. CATALÃO[4], **(Senior Member, IEEE)**
[1]School of Technology and Innovations, Flexible Energy Resources, University of Vaasa, 65200 Vaasa, Finland
[2]Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany
[3]Department of Management and Innovation Systems, University of Salerno, 84084 Fisciano, Italy
[4]Faculty of Engineering, University of Porto and INESC TEC, 4200-465 Porto, Portugal

Corresponding author: Miadreza Shafie-Khah (mshafiek@uwasa.fi)

This work was supported in part by the FLEXIMAR Project (novel marketplace for energy flexibility) through Business Finland under Grant 6988/31/2018, and in part by the Finnish companies. The work of Amin Shokri Gazafroudi was supported by the Collective Nonlinear Dynamics Complex Electricity Networks (CoNDyNet2) Project funded by German Federal Ministry of Education and Research under Grant 03EK3055E.

ABSTRACT The active participation of small-scale prosumers and consumers with demand-response capability and renewable resources can be a potential solution to the environmental issues and flexibility-related challenges. Local energy markets based on peer-to-peer trading is defined as one of solutions to exploit the maximum flexibility potential of prosumers. However, the existing literature that proposed peer-to-peer based local energy markets did not lead to respecting the peers' energy trading preferences simultaneously in the profitable market settlement. To solve this issue, a new local energy market model is presented in which network users can trade with their preferred trading partners within the local market as well as the grid. The proposed trading model includes two levels to consider both the democracy and the profitability of energy trading. At the first level, the model considers the trading preferences of each player to respect the peers' choices. The second level matches the rest of the bids and offers of the local buyers and sellers aiming to maximize the social welfare of all of the players participating in the local market. Our proposed local market is implemented for a test system consisting of fifteen residential players, and the results are compared to other trading models through different comparison criteria such as social-welfare of all players and the net cost of each individual player from consuming electricity. According to the results, the proposed model stands in the second rank compared to the other models that do not simultaneously consider preferences and social welfare of the peers, in terms of social welfare, total profits of the players, and the sustainability and liquidity-based criteria. The proposed model achieves 1416-Cent as the total net energy costs of all peers and the total accepted blocks equaling 76. This means that the proposed local market model can still be profitable and liquid while respecting the players' trading preferences and choices.

INDEX TERMS Electricity market, local market, offering strategy, peer-to-peer trading, social welfare.

NOMENCLATURE

Indexes

j, i	Trading partner.
l1,l2	The proposed local-market levels.
m	Block.
t	Time slot (h).
ω, ω'	Scenario (varying from 1 to the number of scenarios).

Variables for building offering/bidding strategies

EC_j	Expected cost for trading partner *j* (Cent) (1 Cent = €0.01).
$L^{f,up}_{j,t,\omega}$	The upward flexibility for trading partner *j* (kW).
$L^{f,dn}_{j,t,\omega}$	The downward flexibility for trading partner *j* (kW).

The associate editor coordinating the review of this manuscript and approving it for publication was Arash Asrari.

$P_{j,t,\omega}^{b,p2p}$	The scheduled power bought in P2P trading for trading partner j (kW).
$P_{j,t,\omega}^{s,p2p}$	The scheduled power sold in P2P trading for trading partner j (kW).
$P_{j,t,\omega}^{b,lm}$	The scheduled power bought in the LM for trading partner j (kW).
$P_{j,t,\omega}^{s,lm}$	The scheduled power sold in the LM for trading partner j (kW).
$P_{j,t,\omega}^{b,T}$	The total scheduled power bought for trading partner j (kW).
$P_{j,t,\omega}^{s,T}$	The total scheduled power sold for trading partner j (kW).
$v_{j,t,\omega}$	A binary variable for expressing selling/buying energy status of trading partner j.
$x_{j,t,\omega}$	A binary variable for expressing upward/ downward flexibility status of trading partner j.

Variables for clearing the proposed two-level LM

$p_{j,i,t}^{pos}$	Power sold by trading partner j to trading partner i in the proposed LM (kW).
$p_{j,i,t}^{neg}$	Power bought by trading partner j from trading partner i in the proposed LM (kW).
$p_{j,i,t,m}^{pos,bl}$	The quantity of offering block m for trading partner j accepted to be sold to trading partner i (kW).
$p_{j,i,t,m}^{neg,bl}$	The quantity of bidding block m for trading partner j accepted to be supplied by trading partner i (kW).
$P_{j,t}^{buy}$	Power bought from the grid by trading partner j at time t (kW).
$P_{j,t}^{sell}$	Power sold to the grid by trading partner j (kW).
$u_{j,i,t,m}$	A binary variable for showing the acceptance of offering block m offered by trading partner j to be sold to trading partner i.

Parameters for building offering/bidding strategies

τ_{ω}	Probability of scenario ω.
$\pi_{t,\omega}^{da}$	Day-ahead market price at time t and scenario ω (Cent /kW).
γ_j	Flexibility coefficient for trading partner j.

Parameters for clearing the proposed two-level LM

$L_{j,t}$	Power scheduled to be consumed by trading partner j (kW).
$L_{j,t,m}^{bl}$	Quantity of bidding block m for trading partner j (kW).
$P_{j,t,m}^{bl}$	The quantity of offering block m for trading partner j (kW).
$P_{j,t}$	Power scheduled to be produced by trading partner j (kW).
$\pi_{j,t,m}^{l}$	Price of bidding block m offered by trading partner j (cent/kWh).
$\pi_{j,t,m}^{p}$	Price of offering block m offered by trading partner j (cent/kWh).
π_t^{buy}	Retail buying price at time t (cent/kWh).
π_t^{sell}	Retail selling price at time t (cent/kWh).
$\alpha_{j,i}$	A binary parameter showing the preference of trading partners j and i for trading energy with each other.

I. INTRODUCTION

A. MOTIVATION

Recently, the roles of electricity consumers are undergoing a considerable change. These consumers who were previously regarded as ‘‘submissive rate-payers’’ can manage their consumption, produce electricity and make profits through the use of their distributed energy resources (DER) [1]. Also, the high ratio of active prosumers with efficient energy storage, scheduling, and trading possibility can be the most promising ways of balancing energy demand and supply [2].

The high utilization of the DERs along with the technological development in the energy area such as the advent of smart meters and home energy management systems empower consumers and encourage them to change their roles from consumers to pro-active consumers or so-called ‘‘prosumers’’. Prosumers need to be incentivized and be constantly flexible to the changes happening in the power system to exploit the maximum potential of the DERs. However, the existing feed-in-tariff [3], [4] receiving from selling surplus generation to the grid has not provided the prosumers with enough motivation [5].

In addition to these problems, approximately 11% of the world populations still do not have access to electricity [6]. Therefore, they must be equipped with the local resources and trade with each other to meet their own and even their neighbors' demand [7].

Along with technological development, new business models are required to engage prosumers and consumers in producing electricity and react to the system changes by managing their production and consumption [8]. In this way, the concepts of LMs (local market) and P2P (peer-to-peer) energy trading have attracted much attention aiming to put small-scale prosumers and consumers at the heart of energy markets.

B. LITERATURE REVIEW

The concept of P2P trading was introduced for different scale of energy trading to increase democracy and exploit peers' maximum resource potential for producing energy and flexibility [9]. In this regard, a local market can provide peers with the environment so that they can trade energy with each other bilaterally, or in an aggregated manner.

1) DIFFERENT TYPES OF LM DESIGN AND P2P TRADING

LM designs can fit into three categories. The first category is called a full P2P trading model in which two peers may agree on a transaction, leading to the multi-bilateral economic dispatch [10]. The research included in this category respects the preferences of players to choose their trading partners. Ref. [12] is an example of these studies.

The second category is called community-based P2P trading in which prosumers join a community to trade energy with other communities through trading models. For instance, in [12], microgrids can trade with each other. In this research, small-scale prosumers and consumers are not considered as individual players. Ref. [13] also proposed a three-level hierarchical energy sharing and transactions for residential microgrids, which can belong to the community-based trading.

Finally, the hybrid model is a combination of the two previous models in which both small-scale prosumers and communities can trade energy with each other [10]. For example, in a model proposed by [17], residential units and communities trade energy with each other aiming to assist the system with fulfilling the demand.

In another categorization, P2P trading and LMs can be designed for system-wide or local level purposes. In this way, system-wide trading models aim to trade energy or flexibility services in large scales and for system-wide requirements whereas local trading models trade energy or flexibility to satisfy local energy or flexibility needs [15].

2) SYSTEM-WIDE P2P TRADING MODELS

In terms of the system-wide trading models, [16] developed a P2P energy contract between individual customers and/or utilities. The authors of [17] put forward the idea of bilateral contracts between large-scale peers in a forward market. The direct interaction between suppliers and consumers of the electricity market was also proposed in [18]. Similarly, [11] presented a bottom-up approach for future decentralized electricity markets in which consumers can choose their products considering various energy product differentiation. According to [11], the product differentiation in energy trading allows consumers to set a dynamic value on the other important aspects of electricity than its energy content. For example, the source of energy can make product differentiation since it highly affects the environment.

The participation of small-scale players in the wholesale energy market and providing system-wide energy was suggested in [19]. The authors of [20] presented a method that encourages customers to perform P2P trading to provide system-wide flexibility services by alleviating the congestion at peak hours.

3) LOCAL P2P TRADING MODELS

In the context of local energy trading at customer (local) levels, there exist some research proposing LM structures with different objectives.

Game theory-based approaches were deployed in most of the studies with the objectives to model the P2P trading. For instance, a Stackelberg game was utilized in which sellers play the role of leaders, followed by the buyers in [20]. The authors of Ref. [21] inserted the output of participants' non-cooperative game as the input of the evolutionary game to update the strategy selection of the sellers. A method associated with game theory was also employed in [22] to reach the LM equilibrium of P2P trading and increase the social welfare of the players. In a full P2P model, authors of [24] proposed a model in which peers negotiate together to trade energy and flexibility. Similarly, [25] presented a full P2P structure, in which players can trade with their preferred trading partners. However, they need to follow multiple rules so that their bids and offers are accepted. A decentralized LM clearing mechanism was also suggested by [26], where each agent should communicate with its neighbors to achieve the optimal trading. In another game-based approach that was suggested by [27], the number of local transactions was maximized so that local production can be consumed locally. The work also tried to maximize the social welfare of the strategic participants. In the mentioned studies, LM participants play a key role in the LM clearing mechanism.

Ref. [18] designed a novel P2P trading model in which both energy and uncertainty can be traded. The authors of [19] present auction-based LM clearing rules that aim to increase seller profits while minimizing the total saving costs of the buyers. Authors of [30] suggested that each player participating in the P2P trading can have a reputation index and the proposed LM tries to maximize the traders' reputation indexes as well as their social welfare in its matching process. In [31], a P2P trading model was built based on social-welfare maximization formulation regardless of the preference of peers for choosing their trading partners. In other research conducted for [32], the distribution system operator was proposed to be responsible of marching bids and offers of local players in the LM. The authors of [33], proposed a slimemould-inspired optimization method to find best matches for offers and bids of peers in the LM.

In the work proposed by [34], the matching of small-scale players' bids and offers are based on the local network flexibility needs. However, it ignores the trading preferences of the peers. In [35], authors suggested a P2P market structure that seeks the maximum benefits for the local players. Considering this method, the LM players can maximize their profits compared to the way that they should trade their surplus with the retailer. However, the players do not have an option to select their trading partners freely. In addition, they are not allowed to submit their preferred buying/selling prices and the P2P transaction prices are determined based on the grid prices, not those offered by the peers. Finally, [36] used different trading functionalities such as bilateral contracts, trading with the retailer and Vickrey-Clarke-Groves mechanism. Although the introduced method considered the trading preference of the peers, one can argue that the matching process did not lead to the most profitable point for the participants. In this research, trading energy with the grid was the option that can be selected by the players, not an option that can lead to the maximum profits for the LM players.

Generally, the existing LM and P2P trading model structures mainly suffer from the following limitations:

1- The game theory-based approaches need the contribution and cooperation of rational participants in the process of matching bids with offers, which may not be a valid assumption. Moreover, as stated in [34], if the local players want to maximize their profits in a collaborative game-based clearing approach, they need to truthfully disclose their information and the LM requires their cooperation in solving the Nash equilibrium problem. However, LM clearing mechanisms should be able to match bids with offers regardless of the behavior and the cooperation of participants and with respect to their preferences.

2- A prosumer or consumer may set value on some aspects of energy other than economic aspect. Thus, in order to engage small-scale customers to participate in local energy trading, first, prosumers and consumers should be allowed to choose their trading partners freely. Second, the LM clearing mechanism needs to profit all players participating in the LM by maximizing the revenues of local sellers from selling electricity to both the LM and the upstream grid and minimizing the costs of buyers from buying electricity from both the grid and the LM. Thus, the research dealing with local energy trading at customer levels needs to guarantee these two factors i.e. profitability and the choice of peers. However, most of the existing literature (if not all) did not fully cover these two factors to maintain the balance between social welfare and the energy democracy in the LM environment.

C. PAPER CONTRIBUTION, ASSUMPTIONS, AND ORGANIZATION

This paper proposes a novel local P2P trading model for prosumers and consumers under the supervision of a local market operator (LMO). The proposed model aims to satisfy two factors. First, it respects the preference of peers to choose their trading partners and their buying/selling prices. Second, it seeks profitable energy trading in the LM because it aims to maximize the social welfare of the LM players.

The main contributions of the paper are as follows:

C1 (bidding/offering blocks): Local players can submit several blocks with different quantities and prices to the LMO at each time slot. The LM clearing mechanism matches bidding blocks with the offering blocks, according to different offered and bided prices.

C2 (price-based constraints): In the proposed LM, price-based constraints are imposed on the block matching process to respect players' offered prices. In other words, the peers' offered blocks are matched according to the prices. In this way, all of the LM players are satisfied with the LM clearing mechanism.

C3 (choice of peers): The proposed market structure not only can settle imbalances in the local community and maximize the social welfare of the players, but it also increases consumer choice and value. In other words, it has the benefits of both centralized and P2P markets by proposing a hybrid model.

C4 (maximizing/minimizing the revenues/costs of the sellers/buyers): After respecting the peers' trading preferences, the proposed LM tries to settle all of the transactions with the aim of maximizing the local sellers' revenues and minimizing the local buyers' costs. The proposed LM aims to fulfil this objective in trading within the LM as well as trading with the upstream grid. Hence, the local players would trade energy with the upstream grid whenever trading with the grid leads to the revenue maximization or the cost minimization. Thus, local sellers can sell their surplus energy in a way to ensure that they achieve maximum revenues while local buyers can buy their required energy ensuring that it minimizes their energy costs.

TABLE 1. A comparison between the existing similar literature and our paper.

Ref.	C1	C2	C3	C4
[11]		✓	✓	
[19]			✓	
[21]		✓		
[22]		✓		
[23]		✓	✓	
[24]			✓	
[25]		✓		
[26]				
[27]		✓		
[28]		✓	✓	
[29]		✓		
[30]		✓		
[31]		✓		
[32]		✓		
[33]				
[34]		✓		
[35]				✓
[36]		✓	✓	
Our paper	✓	✓	✓	✓

Table 1 compares the proposed P2P trading model with similar research presenting P2P and LM concepts at the distribution network level. As can be seen in the table, there is no previous research that has the features of both C3 and C4, meaning that they did not simultaneously consider choice of peers while trying to minimize the costs of local buyers from buying electricity and maximize the revenues of local sellers from selling electricity. In addition, the price-based market clearing mechanisms (C2) of the previous research were totally different as they proposed different clearing mechanisms. However, all of the papers that considered C2 tried to take into account prices offered by the local players in their proposed clearing mechanism.

The remainder of this paper is organized as follows. The bidding strategies of LM players are defined in section II. The architecture of the proposed market and market-related formulation are discussed in section III. The case study and numerical results are expressed and discussed in section IV. Finally, the paper is concluded in Section V.

II. HOUSEHOLD BIDDING AND OFFERING STRATEGIES

The energy management system of players should build their optimal offering and bidding strategies so that they will be able to participate in the LM. The local-market players are considered to build their bidding/offering strategies based on their net consumption and production in different scenarios using the method proposed in [37]. It should be highlighted that the paper's focus is on introducing a novel P2P local market clearing mechanism and the mechanism is independent of the players 'contribution and their cooperation in matching bids with offers.

Stochastic programming is deployed to capture uncertainties of prices, the consumption and production of each player. In this regard, a set of scenarios is generated for different market prices, production and consumption, using a scenario tree and the method introduced in [37]. By considering different scenarios, different offering and bidding blocks are obtained for each player through optimization problem that will be introduced in the following. Accordingly, a player schedules its flexible resources and simultaneously obtains its bidding/offering strategy according to its total costs. At each time slot, the player determines to either play the role of consumer and submit bids or to play the role of prosumer and submits offers to the LM based on each scenario's production and consumption.

Here, expected cost of player j (EC_j) is defined as an objective function for players which needs to be minimized.

$$EC_j = \sum\nolimits_{\omega=1}^{N_\omega} \tau_\omega [\underbrace{\sum\nolimits_{t=1}^{24} \pi_{t,\omega}^{da} (P_{j,t,\omega}^{b,p2p} - P_{j,t,\omega}^{s,p2p})}_{I} + \underbrace{\sum\nolimits_{t=1}^{24} \pi_t^{buy} P_{j,t,\omega}^{b,lm}}_{II} - \underbrace{\sum\nolimits_{t=1}^{24} \pi_t^{sell} P_{j,t,\omega}^{s,lm}}_{III}], \forall j. \quad (1)$$

Eq. (1) presents an objective function for player j consisting of three terms: I. expected cost/revenue of P2P trading, II. expected cost of electricity bought from the LM and III. expected revenue of electricity sold to the LM, respectively. The player should minimize (1) to obtain its optimal bidding/offering strategy. It should be noted that in the proposed bidding strategy, prices of different scenarios are parameters and the offered/bided quantities are the variables of the optimization problem.

Balancing is an indispensable equation in all energy systems represented in (2) for the proposed home energy management problem.

$$P_{j,t,\omega} + P_{j,t,\omega}^{b,T} = L_{j,t,\omega} - L_{j,t,\omega}^{f,up} + L_{j,t,\omega}^{f,dn} + P_{j,t,\omega}^{s,T}, \quad \forall j,\ \forall t,\ \forall \omega. \quad (2)$$

In Eq. (2), $L_{j,t,\omega}^{f,up}$ and $L_{j,t,\omega}^{f,dn}$ are defined as upward and downward flexibilities for player j. $P_{j,t,\omega}^{b,T}$ and $P_{j,t,\omega}^{s,T}$ represent total power bought and power sold of player j, respectively, to other players and the LM as seen in (3,4).

$$P_{j,t,\omega}^{b,T} = P_{j,t,\omega}^{b,p2p} + P_{j,t,\omega}^{b,lm}, \quad \forall j,\ \forall t,\ \forall \omega. \quad (3)$$

$$P_{j,t,\omega}^{s,T} = P_{j,t,\omega}^{s,p2p} + P_{j,t,\omega}^{s,lm}, \quad \forall j,\ \forall t,\ \forall \omega. \quad (4)$$

Besides, player j can act as either a seller or a buyer of energy at time slot t and scenario ω, which is denoted by (5) and (6). Besides, these constraints restrict the maximum generation and consumption of the player.

$$0 \le P_{j,t,\omega}^{b,T} \le L_{j,t} v_{j,t,\omega}, \quad \forall j,\ \forall t,\ \forall \omega. \quad (5)$$

$$0 \le P_{j,t,\omega}^{s,T} \le P_{j,t}(1 - v_{j,t,\omega}), \quad \forall j,\ \forall t,\ \forall \omega. \quad (6)$$

Eqs. (7,8) express upward and downward flexibility constraints for player j. Here, γ_j is a parameter between zero and one and represents potential flexibility provided from consumer-side (e.g. energy storage system, shiftable and interruptible loads) defined in [38].

According to (7,8), upward and downward flexibilities cannot be provided simultaneously at time slot t and scenario ω,

$$0 \le L_{j,t,\omega}^{f,up} \le \gamma_j L_{t,\omega} x_{j,t,\omega}, \quad \forall j,\ \forall t,\ \forall \omega. \quad (7)$$

$$0 \le L_{j,t,\omega}^{f,dn} \le \gamma_j L_{t,\omega}(1 - x_{j,t,\omega}), \quad \forall j,\ \forall t,\ \forall \omega. \quad (8)$$

Finally, Eqs. (9, 10) present the corresponding constraints of offering and bidding strategies for player j.

$$P_{j,t,\omega}^{s,p2p} \ge P_{j,t,\omega'}^{s,p2p}, \quad \forall \pi_{t,\omega}^{da} \ge \pi_{t,\omega'}^{da}\ \forall \omega \ge \omega', \forall j,\ \forall t. \quad (9)$$

$$P_{j,t,\omega}^{b,p2p} \le P_{j,t,\omega'}^{b,p2p}, \quad \forall \pi_{t,\omega}^{da} \ge \pi_{t,\omega'}^{da}\ \forall \omega \ge \omega',\ \forall j,\ \forall t. \quad (10)$$

According to (9,10), the prices of different scenarios are compared to each other and accordingly optimal offering and bidding curves are obtained in ascending and descending stepwise functions, respectively [37]. In this regard, the non-equality constraint, $\forall \omega \ge \omega'$, tries to avoid the repetition in the process of comparing scenarios.

In the optimal offer curves, the quantity of offered P2P to be sold in scenario ω is higher (or equal) than offered P2P to be sold in ω', if its offered price in scenario ω is higher (or equal) than its offered price at scenario ω'. On the other hand, in their optimal bidding curves, the quantity of P2P bid to be purchased in scenario ω is lower (or equal) than P2P bid to be purchased in ω', if the bid's price in scenario ω is higher (or equal) than the price of scenario ω'.

In this way, the sellers and buyers submit their "offers" and "bids" to the LM based on offering and bidding blocks, respectively. However, in addition to the cost minimization objective, the consumers and prosumers may have other generic preferences for choosing their trading partners. Hence, the LM players should also be given an option to choose the peer(s) with whom they are willing to trade.

These generic preferences of local consumers and prosumers can be as follows:

- A player chooses to trade with the peers in its neighborhood intending to empower its neighboring local community.
- A player decides to trade with the peers who are more likely to fulfil their promises related to selling energy, called high-rated peers in this paper.

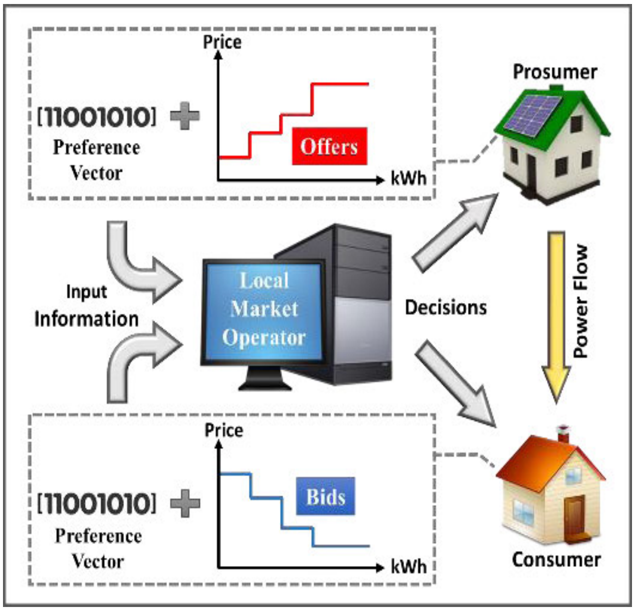


FIGURE 1. Architecture for offers, bids and LM clearing.

- A consumer may choose its peers based on their utilized energy resources. For instance, environmentally aware consumers prefer to select peers with renewable resources.

Binary parameters model the generic preferences of players. For example, the preference of player i for trading with player j is denoted by a binary parameter $\alpha'_{i,j}$. In other words, player i associates $\alpha'_{i,j} = 1$ to peer j with whom she/he is willing to trade. In this way, the smart system that facilitates the bidirectional communication between local market participants and the operator is in charge of determining these binary parameters. It needs to determine the binary parameters based on the generic preferences of the local market players. For example, if buyer i prefers to buy electricity from those with a battery as the energy resource, the system sets $\alpha'_{i,j} = 1$ for all j sellers who sell electricity from their batteries. The player may also select a combination of preferences. Thus, the system needs to find the available peers according to the selected preferences and define their associated binary parameters to equal one.

Having determined the binary variables for the preferred trading partners, the player should submit these binary parameters along with its optimal offering and bidding curves to the LM. Fig. 1 illustrates an example of players submitting bidding curves and preference parameters to the LM.

III. PROPOSED P2P LOCAL MARKET

In this paper, residential consumers and prosumers can trade energy through a platform provided by the local market operator (LMO) as shown in Fig. 2.

Households as players of the LM submit their bidding and offering curves. The LMO also receives their preference parameters. Note that an LMO is a non-profit agent responsible for clearing energy transactions according to the households' offers and bids and their corresponding preferences. The LMO supplies the local demand and trades the local power imbalances with the upstream grid. These imbalances can be the result of local day-ahead generation/demand mismatching or generation/demand uncertainties in real-time.

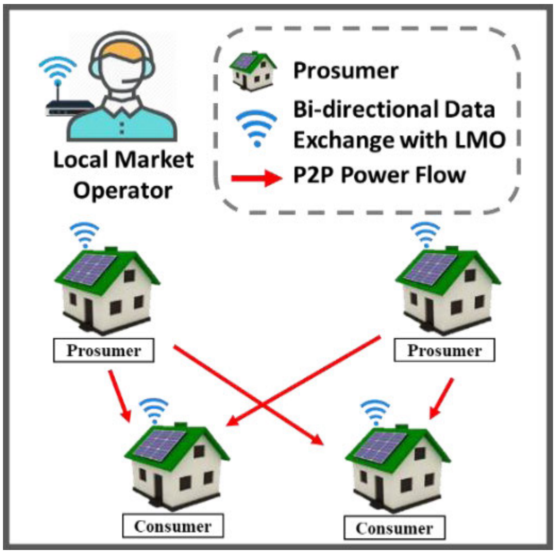


FIGURE 2. Structure of the proposed P2P LM.

After receiving the bids and offers, the LMO forms a P2P local market seeking to maximize revenues and minimize the costs of all of the players within the LM. It also respects the preferences of peers for choosing their trading partners as the priority of the LM clearing mechanism. To this end, the proposed model follows two sequential levels:

In each time slot, the LMO receives a list of the peer(s) (binary parameters) that a player prefers to trade with and its hourly bidding/offer curves. After choosing the preferred peer(s), at the first level, the LMO matches offers and bids submitted by the players who both preferred to trade with each other. In other words, it matches the bidding blocks with offering blocks of peers if $\alpha_{ij} = \alpha'_{i,j}\alpha'_{j,i} = 1$. In addition to binary parameters, the matched bids and offers need to respect a price constraint introduced in the next section. At the first level of the LM, the LMO aims to maximize the matched offering and bidding blocks based on players' preferences. In this regard, the trading priority is given to those players leading to the greater overall bids' and offers' matching based on the participants' preferences. After matching bids and offers based on preference parameters and price constraints, the surplus of net demand and net production that were not matched at the first level are transferred to the second level.

At the second level, the blocks of offers are matched with the bidding blocks aiming to maximize the social welfare of all LM participants. In other words, a bidding block would be matched with an offering block providing that the

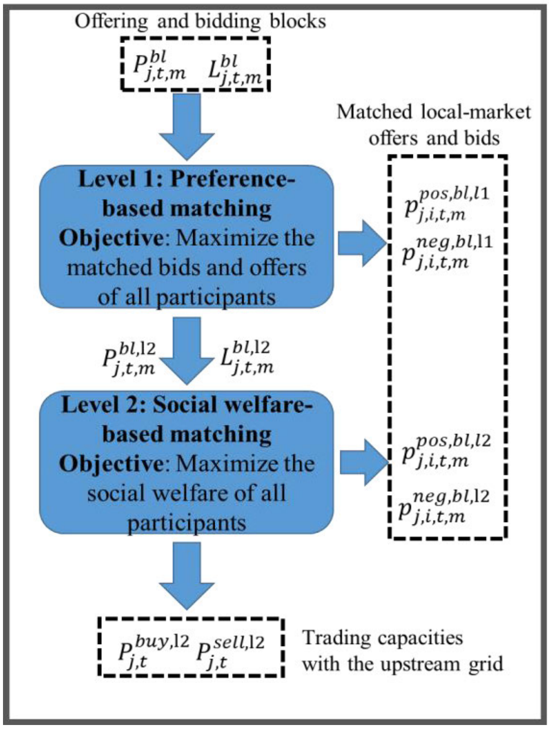


FIGURE 3. **An overview of the matching process applied by the LMO.**

transaction can maximize the social welfare of all LM participants. Finally, the local market surplus (both in net production and net consumption) is settled through the upstream grid. Fig. 3 provides a comprehensive overview on the matching process performed by the LMO based on the formulation presented in the next section.

A. FIRST LEVEL: PREFERENCE-BASED P2P TRADING

Firstly, it is assumed that each player i has a binary preference-based vector with N_j elements ($\alpha'_{i,j}$) introducing the peer(s) it chose to trade with, where N_j denotes the number of players participating in the LM. The players also submit several blocks illustrating their offers and bids for each time slot as illustrated in Fig. 1.

After the local-market gate closure, the LMO matches the bids and offers. The main objective of the LMO is to maximize the quantities offered in the proposed LM to highly consider the trading preference of the peers as represented in (11).

$$\max_{p^{pos,l1}_{j,i,t}} \sum\nolimits_{t=1}^{24} \sum\nolimits_{j=1}^{N_j} \sum\nolimits_{i=1 i\neq j}^{N_j} p^{pos,l1}_{j,i,t} \tag{11}$$

According to the first-level objective function, the priority of trading is given to those trading partners who help achieve the maximum matching capacities based on players' preference. The introduced optimization problem is restricted to some constraints which are presented in the following equations.

Eq. (12) represents a balance-related constraint explaining that the demand of user j at each time slot should be met by the power bought from other peers at the first level of the LM and the remaining demand is transferred to the second level of the trading.

Similarly, (13) expresses that the net generation of the player j at each time is traded with the preferred peers' demand and the remaining net generation is transferred to the second level. This paper assumes that the player is either a seller or a buyer and submits either the offer or the bid at each time slot.

$$L_{j,t} = \sum\nolimits_{i=1 i\neq j}^{N_j} p^{neg,l1}_{j,i,t} + L^{l2}_{j,t}, \quad \forall t, \ \forall j. \tag{12}$$

$$P_{j,t} = \sum\nolimits_{i=1 i\neq j}^{N_j} p^{pos,l1}_{j,i,t} + P^{l2}_{j,t}, \quad \forall t, \ \forall j. \tag{13}$$

Moreover, each bidding block would be matched with one or several offering blocks or vice versa, considering the objective of the LM. Eqs. (14,15) state that the total amount of the quantities for offering and bidding blocks should not exceed the offered blocks' capacity.

$$\sum\nolimits_{i=1 i\neq j}^{N_j} p^{pos,bl,l1}_{j,i,t,m} \leq P^{bl}_{j,t,m}, \quad \forall t, \ \forall j, \ \forall m. \tag{14}$$

$$\sum\nolimits_{i=1 i\neq j}^{N_j} p^{neg,bl,l1}_{j,i,t,m} \leq L^{bl}_{j,t,m}, \quad \forall t, \ \forall j, \ \forall m. \tag{15}$$

The total power traded between players i and j is obtained from the summation of all the blocks matched for these two peers as represented in (16,17).

$$p^{pos,l1}_{j,i,t} = \sum\nolimits_{m=1}^{N_m} p^{pos,bl,l1}_{j,i,t,m}, \quad \forall t, \ \forall j, \ \forall i. \tag{16}$$

$$p^{neg,l1}_{j,i,t} = \sum\nolimits_{m=1}^{N_m} p^{neg,bl,l1}_{j,i,t,m}, \quad \forall t, \ \forall j, \ \forall i. \tag{17}$$

The constraints taking into accounts the preference of the peers are represented in (18,19). According to these constraints, the power cannot be traded between two players if they did not choose each other as their preferred trading partners. Here, $\alpha_{i,j}$ represents a binary parameter indicating the preference of players j and i for trading energy with each other. It obtains from multiplying $\alpha'_{i,j}$ by $\alpha'_{j,i}$. If the binary parameter representing the preference of player j trading with i equals zero, $p^{pos,l1}_{j,i,t}$, $p^{neg,l1}_{j,i,t}$ are equal to zero, accordingly. It means that these players' offers and bids cannot be matched at the first level of the LM. Besides, Eqs. (18,19) indicate the upper limits for the trading capacities between players j and i.

$$p^{pos,l1}_{j,i,t} \leq \alpha_{i,j} P_{j,t}, \quad \forall t, \ \forall j, \ \forall i. \tag{18}$$

$$p^{neg,l1}_{j,i,t} \leq \alpha_{i,j} L_{j,t}, \quad \forall t, \ \forall j, \ \forall i. \tag{19}$$

It is noticeable that the network constraints are not taken into account in this level. This assumption could be valid for a system with a limited number of players [21]. Thus, the amount traded between two players should be the same, meaning that the power that player i sells to player j at time t is equal to the power that player j buys from player i at t as

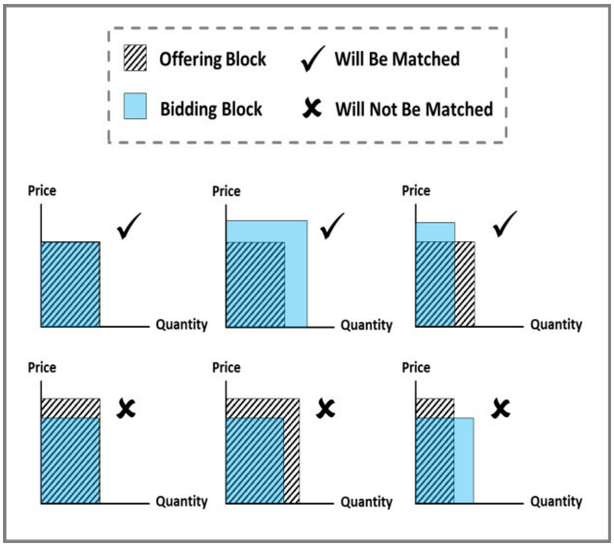


FIGURE 4. Demonstration of applying constraints related to the offered prices.

illustrated in (20).

$$p^{pos,l1}_{j,i,t} = p^{neg,l1}_{i,j,t}, \quad \forall t,\ \forall j,\ \forall i. \tag{20}$$

The offering quantity of player *j,* which is sold in the LM should not exceed its maximum offered capacity. Further, the bidding quantity of player *j,* which is supplied from other peers should not exceed the player's demand as represented in (21,22).

$$\sum\nolimits_{i=1 i\neq j}^{N_j} p^{pos,l1}_{j,i,t} \le P_{j,t}, \quad \forall t,\ \forall j. \tag{21}$$

$$\sum\nolimits_{i=1 i\neq j}^{N_j} p^{neg,l1}_{j,i,t} \le L_{j,t}, \quad \forall t,\ \forall j. \tag{22}$$

A peer can choose several trading partners and has several transactions with different peers at one trading time slot. However, two offering and bidding blocks are matched whenever buyers' offered prices are equal or higher than the prices of sellers as represented in (23).

$$\pi^{l}_{i,t,m} \ge u^{l1}_{j,i,t,m}\pi^{p}_{j,t,m}, \quad \forall t,\ \forall j,\ \forall i, \forall m. \tag{23}$$

Fig. 4. shows all the possible situations that can happen concerning the prices of offers and bids. As seen in Fig. 4, the offered price of a buyer peer should be higher than that of the seller peer. Accordingly, the first row offers and bids can match while those of the second row are not allowed to be matched with each other. As a result of a zero value for $u^{l1}_{j,i,t,m}$, the matched blocks between players *i* and *j* should also equal zero. Thus, Eq. (24) restricts the traded amount according to the binary variable determined by (23). Finally, the traded amount of power should be a positive value, as in (25).

$$p^{pos,bl,l1}_{j,i,t,m} \le u^{l1}_{j,i,t,m}P^{bl}_{j,t,m}, \ \forall t, \forall j, \forall i, \forall m. \tag{24}$$

$$p^{neg,l1}_{j,i,t}, p^{pos,l1}_{j,i,t}, p^{neg,bl,l1}_{j,i,t,m}, p^{neg,bl,l1}_{j,i,t,m} \ge 0, \quad \forall t,\ \forall j,\ \forall i,\ \forall m. \tag{25}$$

B. SECOND LEVEL: SOCIAL-WELFARE-BASED TRADING

The second level of the trading model aims at maximizing the social welfare of all of the players participating in the LM. For this purpose, the LMO matches the bidding by offering blocks of the players considering the social welfare of all of the participants in the LM.

Furthermore, suppose more than one option exist for matching offering with bidding blocks. In this case, the priority is given to the trading couple who are benefiting all of the LM players through maximizing the social welfare of the LM. The accepted first-level offering and bidding quantities should be subtracted from the total offering and bidding capacities of players to obtain the second-level bidding and offering quantities. The remaining offering and bidding capacities should be traded at the second level of the proposed LM.

$$P^{l2}_{j,t} = P_{j,t} - \sum\nolimits_{i=1 i\neq j}^{N_j} p^{pos,l1}_{j,i,t}, \quad \forall t,\ \forall j. \tag{26}$$

$$L^{l2}_{j,t} = L_{j,t} - \sum\nolimits_{i=1 i\neq j}^{N_j} p^{neg,l1}_{j,i,t}, \quad \forall t,\ \forall j. \tag{27}$$

$$P^{bl,l2}_{j,t,m} = P^{bl}_{j,t,m} - \sum\nolimits_{i=1 i\neq j}^{N_j} p^{pos.bl,l1}_{j,i,t,m}, \quad \forall t,\ \forall j,\ \forall m. \tag{28}$$

$$L^{bl,l2}_{j,t,m} = L^{bl}_{j,t,m} \sum\nolimits_{i=1 i\neq j}^{N_j} L^{neg.bl,l1}_{j,i,t,m}, \quad \forall t,\ \forall j,\ \forall m. \tag{29}$$

Eqs. (26,27) determine the total remaining supply and demand of player *j*, respectively. The remaining capacities for each block offered by player *j,* which is ready to be traded at the second level are determined in (28,29). In these equations, $\sum\nolimits_{i=1 i\neq j}^{N_j} p^{pos.bl,l1}_{j,i,t}$ is the obtained amount of selling capacity submitted by block *m* of *j* which was sold in the first-level of LM.

Similarly, $\sum\nolimits_{i=1 i\neq j}^{N_j} p^{neg,bl,l1}_{j,i,t,m}$ is the obtained amount of buying capacity submitted by block m of player j which was bought from the peers in the first-level of LM. As two trading peers may offer different prices for their blocks, the trading price is considered an average of buying and selling prices to benefit both parties as given in (30) [29].

$$\pi^{l2}_{i,j,t,m} = \frac{\pi^{p}_{j,t,m} + \pi^{l}_{i,t,m}}{2} \quad \forall t,\ \forall j,\ \forall i,\ \forall m. \tag{30}$$

In this way, the social welfare of the LM is defined as the revenues of all players from selling electricity to the LM (I) and/or the grid (IV) minus the total costs of buying electricity from the LM (II) and/or the grid (III). Thus, the social welfare of the proposed LM is obtained from (31).

$$\begin{aligned} SW^{p2p,l2} = &\sum\nolimits_{t=1}^{24} \sum\nolimits_{j=1}^{N_j} \sum\nolimits_{i=1 i\neq j}^{N_j} \sum\nolimits_{m=1}^{N_m} \underbrace{\pi^{l2}_{i,j,t,m}p^{pos,bl,l2}_{j,i,t,m}}_{I} \\ &- \underbrace{\pi^{s2}_{i,j,t,m}p^{neg,bl,l2}_{j,i,t,m}}_{II} - \underbrace{\pi^{buy,l2}_{t} P^{buy,l2}_{j,t}}_{III} + \underbrace{\pi^{sell,l2}_{t} P^{sell,l2}_{j,t}}_{IV} \end{aligned} \tag{31}$$

Accordingly, the second-level objective of the LMO is to match the bids and the offers to maximize the social welfare of the whole players participating in the LM.

$$\max_{p^{pos,bl,l2}_{j,i,t}, p^{neg,bl,l2}_{j,i,t}, p^{buy,l2}_{j,t}, p^{sell,l2}_{j,t}} SW^{p2p,l2} \tag{32}$$

Constraints associated with the balance of the demand and supply are considered in (33,34), explaining that each player's net generation should be consumed in the P2P local market and/or be sold to the grid. Likewise, each player's demand should be met by the local net generation and/or be supplied from the grid.

$$L^{l2}_{j,t} = \sum_{i=1 i\neq j}^{N_j} p^{neg,l2}_{j,i,t} + P^{buy,l2}_{j,t}, \quad \forall t,\ \forall j. \tag{33}$$

$$P^{l2}_{j,t} = \sum_{i=1 i\neq j}^{N_j} p^{pos,l2}_{j,i,t} + P^{sell,l2}_{j,t}, \quad \forall t,\ \forall j. \tag{34}$$

Besides, the offering and bidding blocks traded with different peers should not exceed their maximum capacity as represented in (35,36).

$$\sum_{i=1 i\neq j}^{N_j} p^{pos,bl,l2}_{j,i,t,m} \leq P^{bl,l2}_{j,t,m}, \quad \forall t,\ \forall j,\ \forall m. \tag{35}$$

$$\sum_{i=1 i\neq j}^{N_j} p^{neg,bl,l2}_{j,i,t,m} \leq L^{bl,l2}_{j,t,m}, \quad \forall t,\ \forall j,\ \forall m. \tag{36}$$

Furthermore, other constraints restrict the capacities of offering and bidding blocks and the total trading quantities between two peers. Eqs. (37, 38) present that the total trading power between players i and j are equal to the summation of their corresponding traded block quantities. Eq. (39) states that the traded power between players i and j should be the same since the power loss is negligible. Eqs. (40,41) present the maximum limits for trading at the second level.

$$p^{pos,l2}_{j,i,t} = \sum_{m=1}^{N_m} p^{pos,bl,l2}_{j,i,t,m}, \quad \forall t,\ \forall j,\ \forall i. \tag{37}$$

$$p^{neg,l2}_{j,i,t} = \sum_{m=1}^{N_m} p^{neg,bl,l2}_{j,i,t,m}, \quad \forall t,\ \forall j,\ \forall i. \tag{38}$$

$$p^{pos,l2}_{j,i,t} = p^{neg,l2}_{i,j,t}, \quad \forall t,\ \forall j,\ \forall i. \tag{39}$$

$$\sum_{i=1 i\neq j}^{N_j} p^{pos,l2}_{j,i,t} \leq P^{l2}_{j,t}, \quad \forall t,\ \forall j. \tag{40}$$

$$\sum_{i=1 i\neq j}^{N_j} p^{neg,l2}_{j,i,t} \leq L^{l2}_{j,t}, \quad \forall t,\ \forall j. \tag{41}$$

Also, only the bidding blocks with higher or equal prices can be matched with the offering blocks at the second level of trading. The related constraints are denoted with (42) and (43). Finally, the trading power at the second level should also be a positive value, as represented in (44).

$$\pi^{l}_{i,t,m} \geq u^{l2}_{j,i,t,m} \pi^{p}_{j,t,m} \forall t, \forall j, \forall i, \forall m. \tag{42}$$

$$p^{pos,bl,l1}_{j,i,t} \leq u^{l2}_{j,i,t,m} P^{bl}_{j,t,m} \forall t, \forall j, \forall i, \forall m. \tag{43}$$

$$\begin{gathered} P^{sell,l2}_{j,t}, P^{sell,l2}_{j,t}, p^{neg,l2}_{j,i,t}, p^{pos,l2}_{j,i,t}, p^{neg,bl,l2}_{j,i,t,m}, \\ p^{neg,bl,l2}_{j,i,t,m} \geq 0, \forall t, \forall j, \forall i, \forall m. \end{gathered} \tag{44}$$

As a third level of the LM, the LMO can also run a power flow optimization to ensure that the matched offers and bids do not jeopardize the security of the local network. As an example, [15] utilized a linearized power flow to check whether the network constraints are satisfied. It should be noted that P2P energy trading in an LM environment can decrease losses as it avoids power flows through different voltage levels and networks [21]. However, there would be still other types of loss caused by other factors including serious harmonic loss resulted from the high penetration of renewable resources, the increasingly use of electric equipment, the dielectric loss of the capacitor, as well as reactor loss such as conductor, hysteresis, and eddy current losses [39].

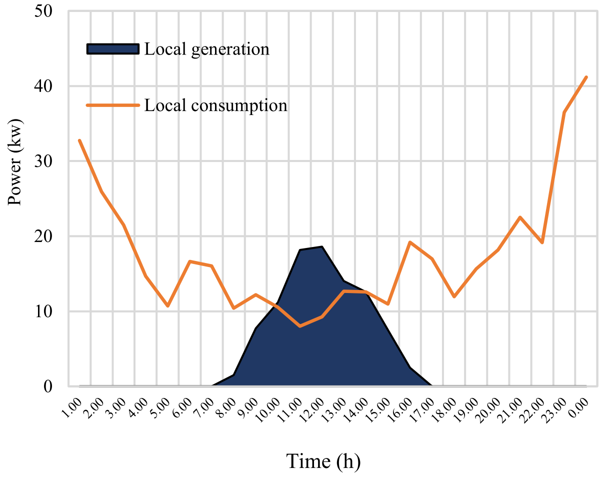


FIGURE 5. Local net generation and consumption of the case study.

The proposed optimization problem was coded and solved in GAMS software using CPLEX solver performed in a PC with a 2 GHz processor and 8 GB memory.

IV. CASE STUDY AND NUMERICAL RESULTS

A. PROPOSED MODEL IMPLEMENTATION

A case study includes ten residential consumers and prosumers h1-h10 who are willing to participate in the LM. In addition, there are five local PV producers p1-p5 who are willing to sell their production in the LM.

Players h1,...,h10 submit their bidding/offering blocks for their net demand/generation. In this regard, h1-h4 can be 'prosumers' in some time slots, meaning that their net generation can be positive during these time slots while h5-h10 are denoted as 'consumers' in all time slots. In comparison, p1,...,p5 are small-scale utility that installed PV panels to sell electricity and make profits. Hence, they can only play the role of sellers in the LM.

The information about the maximum local net generation capacities and the daily net consumption obtained from their optimal bidding strategy is illustrated in Fig. 5. The prosumers and consumers submit their hourly net consumption and generation to the LMO. Producers p1,...,p5 also submit their offers to the LM.

The amount of offered hourly net production for each prosumer of the LM is shown in Fig. 6 [37]. The amounts are the net generation of the seller obtained from its offering strategy. It is assumed that h2 is selected as the only preferred

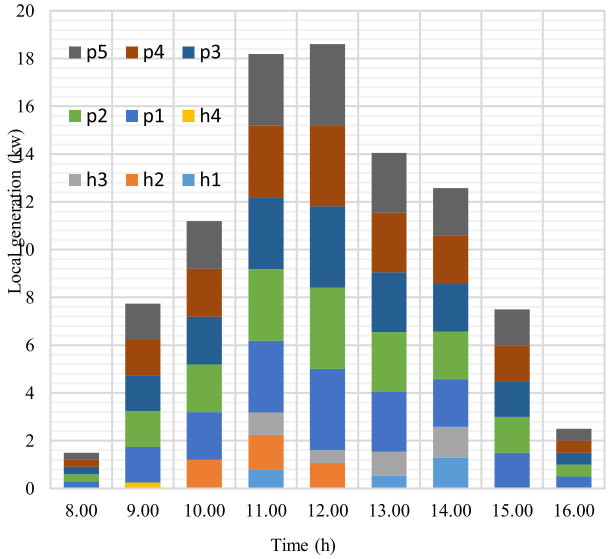


FIGURE 6. The hourly amount of net production for each prosumer.

TABLE 2. Objective and constraints of the introduced trading models.

Model	Objective Function	Constraints	Computing Time (second)
Community-empowering	(11)	(12)-(17) , (20)-(25)	0.35
Tariff-based	(32)	(33), (34), (45), (46)	0.24
Unsupervised P2P	(11)	(12)-(25)	0.43
SW-based	(32)	(33)-(44)	0.39
Proposed model	(11),(32)	(12)-(25),(33)-(44)	0.78

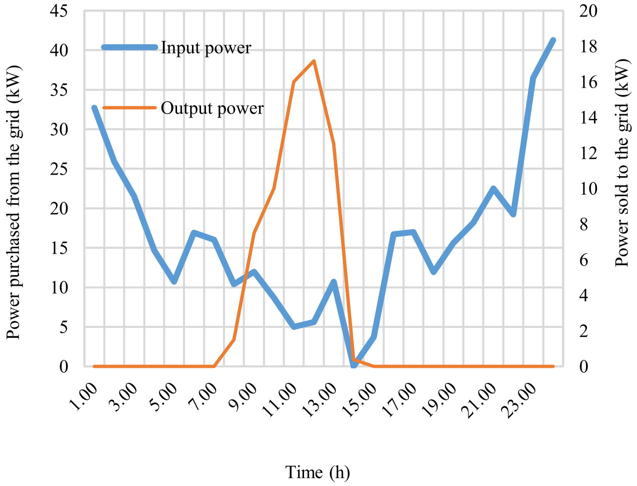


FIGURE 7. The power traded between the local market and the upstream grid.

seller for users h5, h7, h8, and h10, regarding transactions at the first level. The other players did not identify their trading priorities at the first level of the LM. The retail prices for buying power from the grid are equal to 5.27 cent/kWh for t=1-7, 6.24 cent/kWh for t=8-22, and 5.27 cent/kWh for t=23-24 based on the data extracted from [40], where 1 Cent is equal to €0.01.

This way, the proposed P2P local market is simulated for the case study. Fig. 7 shows the total output and input power from/to the grid obtained from solving the proposed model's optimization problem. As seen in Fig. 7, the LM sold power to the upstream grid during timeslots in which it had local net production, i.e. 8-16. The input and output power obtained from the proposed method leads to the LM social welfare maximization.

Our proposed P2P local market model results are compared with four different models in the following sections, as described in table 2.

The first model is called "community-empowering" whose main objective is to maximize trading power within the local community, e.g. [28]. In the second model, there exists no LM. Thus, the households are trading with the grid considering the retail prices for selling and buying power. This model is named "tariff-based". In the third model called "unsupervised P2P", after matching the offers with bids of players at the first level, the remaining power will be traded with the grid. Finally, the fourth model, named "social-welfare-based" (SW-based), is the proposed model with eliminating the first level, meaning that players' trading preferences are not regarded in this model.

The proposed model and the first, third, and fourth models have local markets, whereas there is no local market in the tariff-based model. In other words, players' needs are supplied from the grid in the tariff-based model. The problem formulations related to these trading models selected for comparison are presented in Table 2. Also, the computing time associated with solving the model's optimization problem(s) is shown in the table. As previously mentioned, the problems were solved using CPLEX solver.

Since the tariff-based model does not have local trade, the following equations should be considered as constraints:

$$p^{neg}_{j,i,t} = 0, \quad \forall t,\ \forall j,\ \forall i. \tag{45}$$

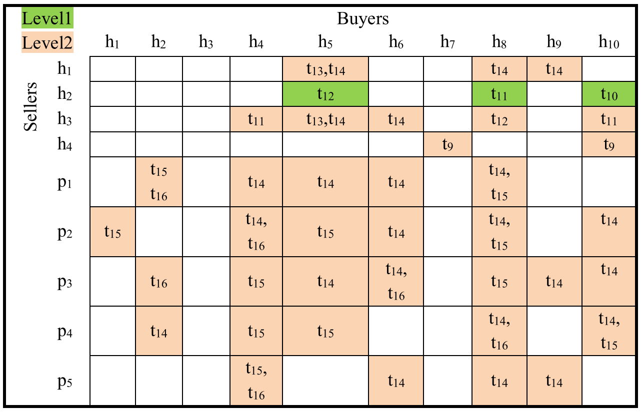
$$p^{pos}_{j,i,t} = 0, \quad \forall t\ ,\forall j,\ \forall i. \tag{46}$$

Fig. 8 indicates the trading time slots in which local sellers and local buyers trade with each other. For example, seller h1 and buyer h8 trade energy at t14 at the second level of the LM. Fig. 9 depicts examples of bidding and offering curves of two trading couples and their matched quantities and trading prices.

B. MODEL COMPARISON

This paper uses different criteria in order to evaluate the performance of the introduced models from various viewpoints:

- Social welfare (SW) criterion is deployed to demonstrate the effectiveness of the model in benefiting all local players.
- The higher total amount of total local (energy) trading (TLT) criterion demonstrates the local community's



Level1 Level2	Buyers h1	h2	h3	h4	h5	h6	h7	h8	h9	h10
Sellers h1					t_{13},t_{14}			t_{14}	t_{14}	
h2					t_{12}			t_{11}		t_{10}
h3				t_{11}	t_{13},t_{14}	t_{14}		t_{12}		t_{11}
h4							t_9			t_9
p1		t_{15} t_{16}		t_{14}	t_{14}	t_{14}		t_{14}, t_{15}		
p2	t_{15}			t_{14}, t_{16}	t_{15}	t_{14}		t_{14}, t_{15}		t_{14}
p3		t_{16}		t_{15}	t_{14}	t_{14}, t_{16}		t_{15}	t_{14}	t_{14}
p4		t_{14}		t_{15}	t_{15}			t_{14}, t_{16}		t_{14}, t_{15}
p5				t_{15}, t_{16}		t_{14}		t_{14}	t_{14}	

FIGURE 8. Trading timeslot for peers participating in the proposed P2P local market.

TABLE 3. LM-based indicators for different trading models.

High 🟧 🟧 🟧 🟧 ⬜ Low

Indicator	Proposed model	Community-empowering	Tariff-based	Unsupervised p2p	SW-based
SW(CENT)	-1430	-1686	-1478	-1473	-1416
TLT(KW)	28.8	62	0	3.76	28.4
AB	76	100	0	13	75

self-sufficiency as it needs less electricity to be met from the upstream grid.

- The higher number of blocks matched in the LM (AB) evaluates the liquidity of the LM.
- The lower number of total net costs (TNC) indicates the higher profitability for individual players.

1) FROM THE VIEWPOINT OF THE LM

The models described above are simulated for the same test case, and the results will be compared together. The daily and the presented hourly criteria are calculated for the introduced models, and the results are shown in table 3 and Figs. 10-14.

It is noticeable that the producers (p1,…,p10) has net production only during 8:00-16:00 and the households mostly play the role of consumers. Hence, the total SW of the LM is obtained as a negative value. In other words, the SW's absolute value can be regarded as the outgoing of the LM. From the perspective of the community, the SW-based model is more beneficial for the LM. A lower SW index for the proposed model was obtained by considering peers' preferences compared to the SW-based one. The unsupervised P2P model and tariff-based trading had high outgoing from the local community, meaning that they were less beneficial for the LM as presented in table 3.

Finally, the lowest SW index is obtained for the community-empowering model in which self-sufficiency of the LM comes at the cost of decreasing the SW of the LM.

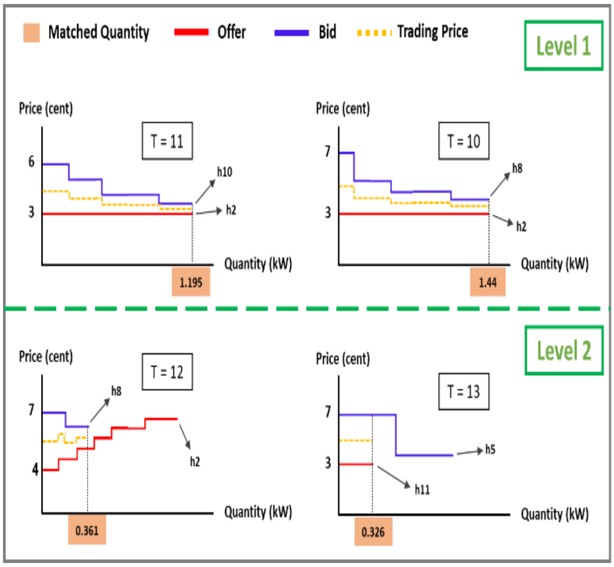


FIGURE 9. Examples of matching of prosumers' offers with consumers' bids considering the proposed model.

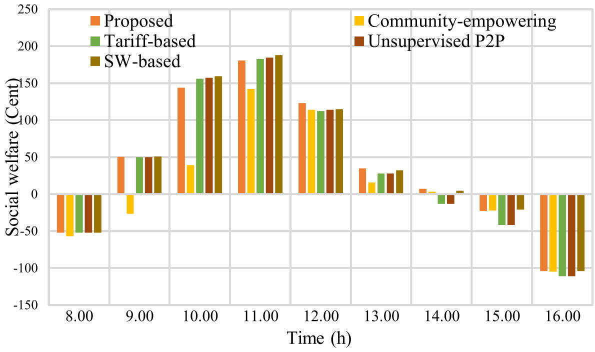


FIGURE 10. Hourly SW index of the households.

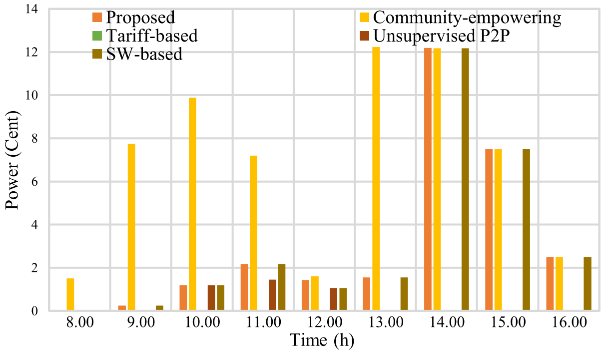


FIGURE 11. Hourly TLT index of households.

As seen in table 3, the proposed model obtained acceptable values for AB and TLT indicators. To maximize the total amount of local energy trading, the community-empowering model that seeks to maximize the matched bidding and offering blocks had the highest TLT and AB. The social-welfare based model can constitute approximately liquid and

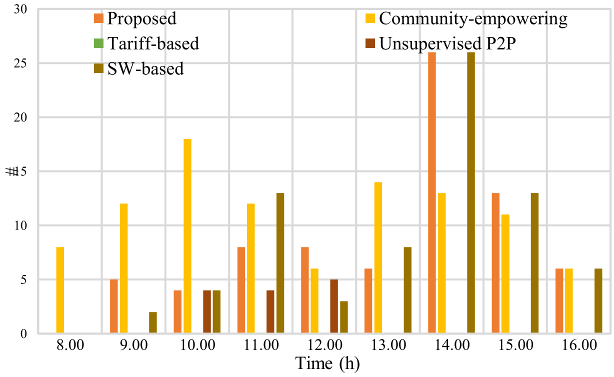


FIGURE 12. Hourly AB index for households.

self-sufficient LM as whose TLT and AB indexes are slightly lower than those of the proposed model. In comparison, the unsupervised P2P models did not have a good performance to bring self-sufficiency and liquidity-related benefits for the local community. The TLT and AB indicators for the tariff-based model equal zero as long as this model does not consider the concept of LM.

2) FROM THE VIEWPOINT OF INDIVIDUAL PLAYERS

As stated before, households (h1,…,h10) play the role of consumers rather than prosumers in most time slots. As a result, considering the daily scheduling, the households total profit is a minus value. This paper defines a criterion named the total net costs (TNC) for each household obtained as represented in (45).

$$TNC_j = \sum\nolimits_{t=1}^{24} \sum\nolimits_{i=1 i\neq j}^{N_j} \sum\nolimits_{m=1}^{N_m} \pi^{s2}_{i,j,t,m} p^{neg,bl,s2}_{j,i,t,m} - \pi^{s2}_{i,j,t,m} p^{pos,bl,s2}_{j,i,t,m} + \pi^{buy,s3}_{t} P^{buy,s3}_{j,t} - \pi^{sell,s3}_{t} P^{sell,s3}_{j,t}. \quad (47)$$

In other words, the TNC for player j is the total monetary amount paid to the local suppliers or/and the grid for meeting the player's demand minus the total amount that receives from selling electricity to the LM as well as the grid. Accordingly, from the viewpoints of players, a profitable model should incur less TNC for the player. This criterion was calculated for the households, and Fig. 13 depicts the distribution of this indicator for different households. The data points are the TNC of households (h1,…,h10) participating in different trading models while the box plots denote the maximum, minimum and the mean values of the TNCs. Besides, Fig. 15 demonstrates the hourly results for a selected household, h1, as an example.

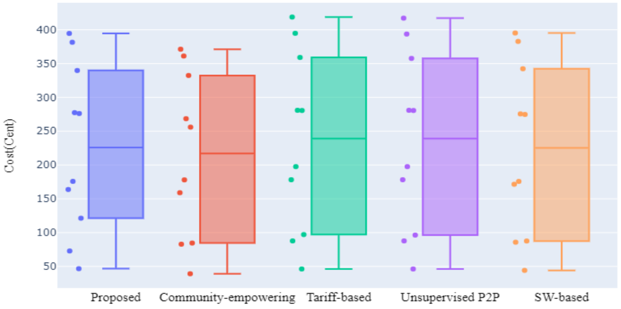


FIGURE 13. A box plot regarding the total net costs (TNC) criterion for the households (h1,…,h10) participating in different trading models.

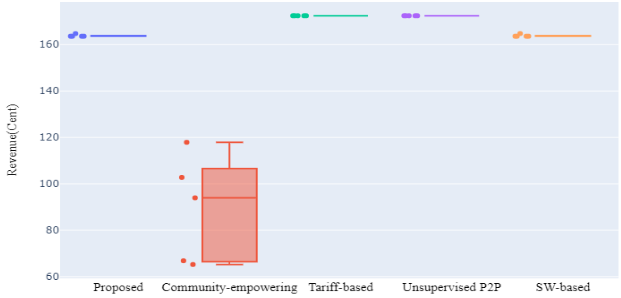


FIGURE 14. A box plot indicating the distribution of the total revenues for the producers (p1,…,p5) participating in different trading models.

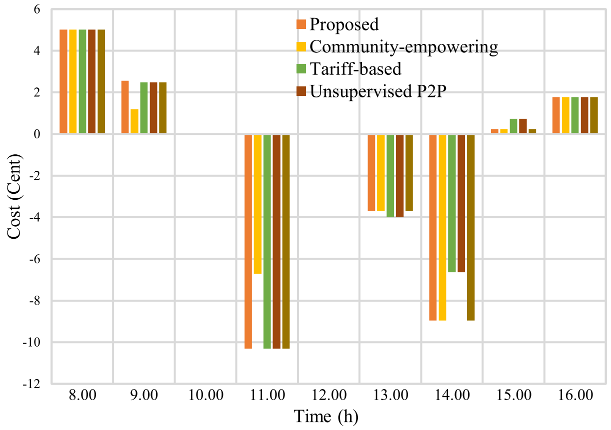


FIGURE 15. Hourly TNC index for h1 of the case system.

Additionally, the revenues of producers (p1,…,p5) were estimated for the introduced models and the distribution of revenues for different producers is illustrated in Fig. 14. Again, the data points show the revenues of producers considering different trading models while the box plots indicate the maximum, minimum, and the mean values of producers' revenues. The producers' revenues are very close to each other for the SW-based, unsupervised, tariff-based, and the proposed trading models. Accordingly, the box plots of these models depict lines. Fig. 16 indicates the hourly revenues of a selected producer (p5) that has participated in different trading models.

As shown in Fig. 13 and Fig. 14, the proposed model and the SW-based model can be beneficial for both households and producers. This is due to the fact that these two models aim to benefit all of the players participating in the LM. Thus, the consumers' costs are minimized while the producers' revenues are maximized in these two models. Considering TNC criterion, the proposed model had less cost after the community-empowering model. However, the

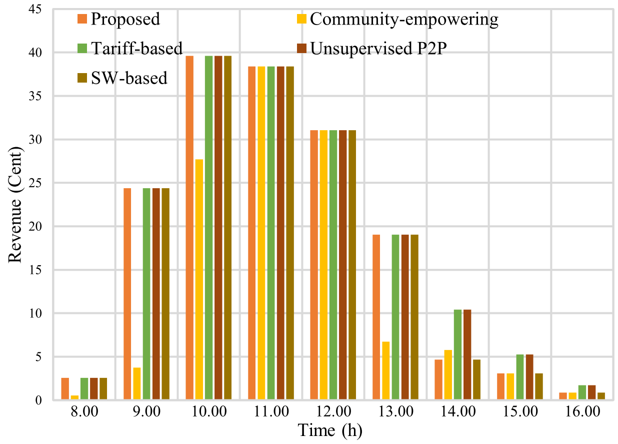


FIGURE 16. Hourly revenue for p5 of the case system.

community-empowering model was unable to benefit producers. As Fig. 14 states, the producers gain less revenues in the community-empowering trading model compared to the other models.

Fig. 15 depicts the TNC index for household h1. According to this figure, the player achieves more revenue when it participates in the community-empowering and the proposed trading model. SW-based model also offers low costs for this player. The figure also states that the household played the role of prosumers at 11:00, 13:00, and 14:00 whereas it was consumers at 8:00, 9:00, 15:00, and 16:00. Unlike h1, the community-empowering trading model was the least profitable trading model for p5, as illustrated in Fig. 16. It can be concluded that in this case, trading with the upstream grid was more profitable for local producers. However, the proposed model and SW-based model can still provide acceptable revenues for p5.

C. DISCUSSION

Considering peers' preferences can be regarded as the only advantage of the unsupervised P2P model. The other indicators state that this model is not profitable for both the community and individuals. On the other hand, the SW-based model and the proposed supervised model offer considerable advantages from the viewpoints of the LM and individual players. Although the SW-based may perform better in terms of the individuals' profitability, its main drawback is its weakness in considering peers' trading preferences. It would be better to give players the option to find their best partners and consider their choices as the priority so that they understand that the LM fully appreciates their decisions which can incentivize all the players.

When it comes to the community-empowering trading model, its only benefit is its effort to make the LM more self-sufficient. However, in this case, it was less profitable than other trading models. According to table 2, this model seeks to maximize the local trades. However, if the players do not achieve enough revenues from the LM, they may decide to quit participating in the local energy trading, which may harm the LM self-sufficiency in long-term. As a result, considering long-term trading, the community-empowering model would not be a good option compared to our proposed supervised and SW-based models which seek to maximize the social-welfare of the participants rather than their trades. Thus, it is necessary that the LM model includes the second-level formulations to ensure the profitability of the market for local players and incentivize them to persist with their active participation in the LM.

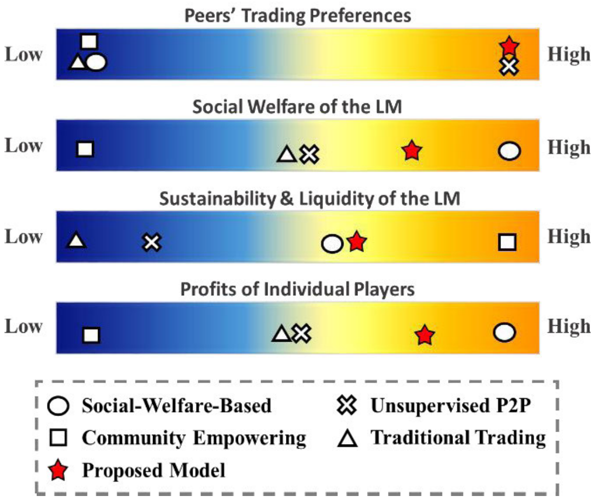


FIGURE 17. Demonstration of situations of five trading models for the case study considering various criteria.

Finally, the indicators express that most of the models with the permission of local energy trading perform better than the tariff-based trading. According to Fig. 17, SW-based and proposed models lead to the highest social welfare compared to the tariff-based model. In these two models, if trading with the grid is more beneficial for the players, they will trade with the upstream grid. As a result, the benefits of local players participating in SW-based and proposed model are always equal or higher than those of the tariff-based model. Not only can the tariff-based manner of selling and buying electricity to/from the grid increase the costs of individual players, but also it fails to benefit the whole community of households locating in the neighboring areas. Accordingly, the importance of forming the local market can be more evident from the simulation results of this paper.

The proposed model tries to consider different factors to obtain a model which is profitable and simultaneously respect the peers' trading preferences. However, depending on the choice of the local players, the results of our model may be more close to the unsupervised P2P model or close to those of the SW-based model. In the case that the local players prefer to choose their trading partners freely, it results in less benefit for the players. The results may be also more close to the SW-based model in the case where players prefer the market operator to choose their trading partners which lead to their revenue maximization.

Thus, the proposed model can be different for different combinations of prosumers and consumers. However, all of the participants are given the option to choose between their principles, preferences and their economic benefits. To this end, with the proposed model, each participant knows that the market mechanism is highly flexible according to its choice and preference.

V. CONCLUSION

This paper proposed a new local market structure for peer-to-peer trading that incentivizes small-scale prosumers and consumers to play a more active role in energy markets. The proposed model consists of two levels. At the first level, the local market operator matches bids and offers to consider the preferred peers for each player and the prices offered by consumers and prosumers. In this regard, the offers are matched with bids so that the sellers' prices should be lower or equal than the buyers' prices. The remaining demand and generation, which has not been matched during the first level, is transferred to the second level where the trading is based on social welfare maximization. Additionally, imbalances of the local market are settled through the upstream grid.

The proposed two-level local market model has been implemented for a case study. The results have been assessed and compared to three different local market-based models and a tariff-based trading model in which there is no local electricity market. The results are as follows:

First, the proposed local market can be profitable for all participants because it increases the social welfare of all of the local players. It respects the generic preferences of participants for choosing their trading partners since at the first level, the local market operator aims to maximize accepted capacities based on players' preferences.

Second, the proposed local market can reach sufficient liquidity and self-sufficiency by incentivizing local and small-scale prosumers and consumers to play active roles in the local market. Considering the players' preferences can also lead to the liquid market on the long-term horizon. Finally, future works can be conducted in the following directions:

a) Analyzing the optimal sizing of local markets to obtain tractable optimization problems.
b) Considering the situations in which local markets as a player can trade energy with other local markets as well as trading with the upstream grid.
c) Considering the strategic behavior of a local market that can participate in the wholesale markets as an individual player. Note that in this paper, the local market could trade with the grid in a tariff-based format.

REFERENCES

[1] E. Espe, V. Potdar, and E. Chang, "Prosumer communities and relationships in smart grids: A literature review, evolution and future directions," *Energies*, vol. 11, no. 10, p. 2528, Sep. 2018.

[2] M. Ul Hassan, M. Husain Rehmani, and J. Chen, "Optimizing blockchain based smart grid auctions: A green revolution," 2021, *arXiv:2102.02583*.

[3] W. Tushar, B. Chai, C. Yuen, and D. B. Smith, "Three-party energy management with distributed energy resources in smart grid," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2487–2498, Apr. 2015.

[4] L.-C. Ye, J. F. D. Rodrigues, and H. X. Lin, "Analysis of feed-in tariff policies for solar photovoltaic in China 2011–2016," *Appl. Energy*, vol. 203, pp. 496–505, Oct. 2017.

[5] W. Tushar, T. K. Saha, C. Yuen, P. Liddell, R. Bean, and H. V. Poor, "Peer-to-peer energy trading with sustainable user participation: A game theoretic approach," *IEEE Access*, vol. 6, pp. 62932–62943, 2018.

[6] The World Bank Data. *Access to Electricity*. Accessed: Apr. 1, 2020. [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

[7] A. Shrestha, R. Bishwokarma, A. Chapagain, S. Banjara, S. Aryal, B. Mali, R. Thapa, D. Bista, B. P. Hayes, A. Papadakis, and P. Korba, "Peer-to-peer energy trading in micro/mini-grids for local energy communities: A review and case study of Nepal," *IEEE Access*, vol. 7, pp. 131911–131928, 2019.

[8] H. Laaksonen, H. Khajeh, C. Parthasarathy, M. Shafie-khah, and N. Hatziargyriou, "Towards flexible distribution systems: Future adaptive management schemes," *Appl. Sci.*, vol. 11, no. 8, p. 3709, Apr. 2021.

[9] H. Khajeh, H. Laaksonen, A. S. Gazafroud, and M. Shafie-Khah, "Towards flexibility trading at TSO-DSO-customer levels: A review," *Energies*, vol. 13, no. 1, p. 165, 2019.

[10] T. Sousa, T. Soares, P. Pinson, F. Moret, T. Baroche, and E. Sorin, "Peer-to-peer and community-based markets: A comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 104, pp. 367–378, Apr. 2019.

[11] E. Sorin, L. Bobo, and P. Pinson, "Consensus-based approach to peer-to-peer electricity markets with product differentiation," *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 994–1004, Mar. 2018.

[12] M. Daneshvar, B. Mohammadi-Ivatloo, K. Zare, S. Asadi, and A. Anvari-Moghaddam, "A novel operational model for interconnected microgrids participation in transactive energy market: A hybrid IGDT/stochastic approach," *IEEE Trans. Ind. Informat.*, vol. 17, no. 6, pp. 4025–4035, Jun. 2020.

[13] M. N. Akter, M. A. Mahmud, and A. M. T. Oo, "A hierarchical transactive energy management system for microgrids," in *Proc. IEEE Power Energy SoC. Gen. Meeting (PESGM)*, Jun. 2016, pp. 1–5.

[14] W. Tushar, B. Chai, C. Yuen, S. Huang, D. B. Smith, H. V. Poor, and Z. Yang, "Energy storage sharing in smart grid: A modified auction-based approach," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1462–1475, May 2016.

[15] H. Khajeh, H. Firoozi, M. R. Hesamzadeh, H. Laaksonen, and M. Shafie-Khah, "A local capacity market providing local and system-wide flexibility services," *IEEE Access*, vol. 9, pp. 52336–52351, 2021.

[16] S. Wang, A. F. Taha, J. Wang, K. Kvaternik, and A. Hahn, "Energy crowdsourcing and peer-to-peer energy trading in blockchain-enabled smart grids," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 49, no. 8, pp. 1612–1623, Aug. 2019.

[17] T. Morstyn, A. Teytelboym, and M. D. McCulloch, "Bilateral contract networks for peer-to-peer energy trading," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2026–2035, Mar. 2019.

[18] M. Khorasany, Y. Mishra, and G. Ledwich, "A decentralized bilateral energy trading system for peer-to-peer electricity markets," *IEEE Trans. Ind. Electron.*, vol. 67, no. 6, pp. 4646–4657, Jun. 2020.

[19] T. Morstyn and M. D. McCulloch, "Multiclass energy management for peer-to-peer energy trading driven by prosumer preferences," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 4005–4014, Sep. 2018.

[20] W. Tushar, T. K. Saha, C. Yuen, T. Morstyn, H. V. Poor, and R. Bean, "Grid influenced peer-to-peer energy trading," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1407–1418, Mar. 2020.

[21] K. Anoh, S. Maharjan, A. Ikpehai, Y. Zhang, and B. Adebisi, "Energy peer-to-peer trading in virtual microgrids in smart grids: A game-theoretic approach," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1264–1275, Mar. 2020.

[22] A. Paudel, K. Chaudhari, C. Long, and H. B. Gooi, "Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model," *IEEE Trans. Ind. Electron.*, vol. 66, no. 8, pp. 6087–6097, Aug. 2018.

[23] Z. Zhang, H. Tang, P. Wang, Q. Huang, and W.-J. Lee, "Two-stage bidding strategy for peer-to-peer energy trading of nanogrid," *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 1000–1009, Mar. 2020.

[24] Z. Guo, P. Pinson, S. Chen, Q. Yang, and Z. Yang, "Chance-constrained peer-to-peer joint energy and reserve market considering renewable generation uncertainty," *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 798–809, Jan. 2021.

[25] Z. Li and T. Ma, "Peer-to-peer electricity trading in grid-connected residential communities with household distributed photovoltaic," *Appl. Energy*, vol. 278, Nov. 2020, Art. no. 115670.

[26] A. Paudel, M. Khorasany, and H. B. Gooi, "Decentralized local energy trading in microgrids with voltage management," *IEEE Trans. Ind. Informat.*, vol. 17, no. 2, pp. 1111–1121, Feb. 2021.

[27] Z. Zhang, H. Tang, J. Ren, Q. Huang, and W.-J. Lee, "Strategic prosumers-based peer-to-peer energy market design for community microgrids," *IEEE Trans. Ind. Appl.*, vol. 57, no. 3, pp. 2048–2057, Jun. 2021.

[28] Z. Zhang, R. Li, and F. Li, "A novel peer-to-peer local electricity market for joint trading of energy and uncertainty," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1205–1215, Mar. 2020.

[29] M. Khorasany, Y. Mishra, and G. Ledwich, "Design of auction-based approach for market clearing in peer-to-peer market platform," *J. Eng.*, vol. 2019, no. 18, pp. 4813–4818, Jul. 2019.

[30] M. H. Ullah and J.-D. Park, "Peer-to-peer energy trading in transactive markets considering physical network constraints," *IEEE Trans. Smart Grid*, vol. 12, no. 4, pp. 3390–3403, Jul. 2021.

[31] A. Paudel, L. P. M. I. Sampath, J. Yang, and H. B. Gooi, "Peer-to-peer energy trading in smart grid considering power losses and network fees," *IEEE Trans. Smart Grid*, vol. 11, no. 6, pp. 4727–4737, Nov. 2020.

[32] K. Zhang, S. Troitzsch, S. Hanif, and T. Hamacher, "Coordinated market design for peer-to-peer energy trade and ancillary services in distribution grids," *IEEE Trans. Smart Grid*, vol. 11, no. 4, pp. 2929–2941, Jul. 2020.

[33] O. Jogunola, W. Wang, and B. Adebisi, "Prosumers matching and least-cost energy path optimisation for peer-to-peer energy trading," *IEEE Access*, vol. 8, pp. 95266–95277, 2020.

[34] W. Zhong, S. Xie, K. Xie, Q. Yang, and L. Xie, "Cooperative P2P energy trading in active distribution networks: An MILP-based Nash bargaining solution," *IEEE Trans. Smart Grid*, vol. 12, no. 2, pp. 1264–1276, Mar. 2021.

[35] R. Faia, J. Soares, T. Pinto, F. Lezama, Z. Vale, and J. M. Corchado, "Optimal model for local energy community scheduling considering peer to peer electricity transactions," *IEEE Access*, vol. 9, pp. 12420–12430, 2021.

[36] M. K. Alashery, Z. Yi, D. Shi, X. Lu, C. Xu, Z. Wang, and W. Qiao, "A blockchain-enabled multi-settlement quasi-ideal peer-to-peer trading framework," *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 885–896, Jan. 2021.

[37] A. Shokri Gazafroudi, J. Soares, M. A. Fotouhi Ghazvini, T. Pinto, Z. Vale, and J. M. Corchado, "Stochastic interval-based optimal offering model for residential energy management systems by household owners," *Int. J. Electr. Power Energy Syst.*, vol. 105, pp. 201–219, Feb. 2019.

[38] A. S. Gazafroudi, M. Shafie-Khah, F. Prieto-Castrillo, J. M. Corchado, and J. P. S. Catalao, "Monopolistic and game-based approaches to transact energy flexibility," *IEEE Trans. Power Syst.*, vol. 35, no. 2, pp. 1075–1084, Mar. 2020.

[39] J. Zhang, C. Hu, C. Zheng, T. Rui, W. Shen, and B. Wang, "Distributed peer-to-peer electricity trading considering network loss in a distribution system," *Energies*, vol. 12, no. 22, p. 4318, Nov. 2019.

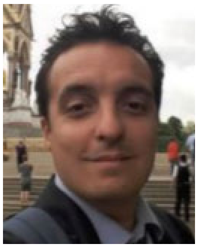
[40] V. S. Oy. *Prices for Electricity Products*. Accessed: Apr. 1, 2020. [Online]. Available: http://www.vaasansahko.fien/prices-for-electricity-products-2/

HOSNA KHAJEH (Graduate Student Member, IEEE) received the M.Sc. (Tech.) degree in electrical engineering (power systems) from Semnan University, Semnan, Iran, in 2016. She is currently pursuing the Ph.D. degree with the University of Vaasa, Vaasa, Finland. Her research interests include future electricity market concepts, energy-flexibility management, forecast, and trading structures.

AMIN SHOKRI GAZAFROUDI received the B.Sc. and M.Sc. degrees in power electrical engineering, and the Ph.D. degree in computer science from the University of Salamanca, Salamanca, Spain, in 2019. He is currently a Postdoctoral Researcher with the Energy System Modeling Research Group, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany. His research interests include power system and electricity market modeling, power flow and contingency analysis, local energy and flexibility markets design, peer-to-peer energy trading in smart grids, market-based coordination mechanisms, decentralized energy management systems, bidding strategies for autonomous home energy management systems, planning and operation of integrated energy systems, and application of machine learning algorithms on price and demand forecasting.

HANNU LAAKSONEN (Member, IEEE) received the M.Sc. (Tech.) degree in electrical power engineering from the Tampere University of Technology, Tampere, Finland, in 2004, and the Ph.D. (Tech.) degree in electrical engineering from the University of Vaasa, Vaasa, Finland, in 2011. His employment experience includes working as a Research Scientist at the VTT Technical Research Centre of Finland and at the University of Vaasa. He worked as a Principal Engineer at ABB Ltd., Vaasa. He is currently a Professor of electrical engineering at the University of Vaasa. He is also the Manager of the Smart Energy Master's Program. His research interests include protection of low-inertia power systems (including microgrids), and active management of distributed and flexible energy resources in future smart energy systems as well as future-proof technology and market concepts for smart grids.

MIADREZA SHAFIE-KHAH (Senior Member, IEEE) received the first Ph.D. degree in electrical engineering from Tarbiat Modares University, Tehran, Iran, and the second Ph.D. degree in electromechanical engineering from the University of Beira Interior (UBI), Covilha, Portugal. He held the first postdoctoral position at the University of Beira Interior (UBI), and the second postdoctoral position at the University of Salerno, Salerno, Italy. He is currently an Associate Professor at the University of Vaasa, Vaasa, Finland. He has coauthored more than 440 articles that received more than 8400 citations with an H-index equal to 51. His research interests include power market simulation, market power monitoring, power system optimization, demand response, electric vehicles, price and renewable forecasting, and smart grids. He is an Editor of the IEEE Transactions on Sustainable Energy, an Associate Editor of the IEEE Systems Journal, an Associate Editor of IEEE Access, an Editor of the IEEE Open Access Journal of Power and Energy (OAJPE), an Associate Editor of *IET-RPG*, the Guest Editor-in-Chief of the IEEE Open Access Journal of Power and Energy, the Guest Editor of the IEEE Transactions on Cloud Computing, and the guest editor of more than 14 special issues. He was considered one of the Outstanding Reviewers of the IEEE Transactions on Sustainable Energy, in 2014 and 2017, one of the Best Reviewers of the IEEE Transactions on Smart Grid, in 2016 and 2017, and one of the Outstanding Reviewers of the IEEE Transactions on Power Systems, in 2017 and 2018, and one of the Outstanding Reviewers of the IEEE Open Access Journal of Power and Energy, in 2020. He is also the Volume Editor of the book *Blockchain-Based Smart Grids* (Elsevier, 2020). He is a Top Scientist in the Guide2Research Ranking in computer science and electronics, and he has won five best paper awards at IEEE conferences.



PIERLUIGI SIANO (Senior Member, IEEE) received the M.Sc. degree in electronic engineering and the Ph.D. degree in information and electrical engineering from the University of Salerno, Salerno, Italy, in 2001 and 2006, respectively.

He is currently a Professor and a Scientific Director of the Smart Grids and Smart Cities Laboratory, Department of Management & Innovation Systems, University of Salerno. Since 2021, he has been a Distinguished Visiting Professor with the Department of Electrical and Electronic Engineering Science, University of Johannesburg. His research interests include demand response, on energy management, on the integration of distributed energy resources in smart grids, on electricity markets and on planning and management of power systems. In these research fields, he has coauthored more than 650 articles, including more than 370 international journal papers that received in Scopus more than 12700 citations with an H-index equal to 55. In 2019, 2020, and 2021, he has been awarded as a Highly Cited Researcher in Engineering by Web of Science Group. He has been the Chair of the IES TC on Smart Grids. He is the Editor of the Power & Energy Society Section of IEEE Access, the IEEE Transactions on Power Systems, the IEEE Transactions on Industrial Informatics, the IEEE Transactions on Industrial Electronics, the IEEE Systems Journal, the IEEE Open Journal of the Industrial Electronics Society, *IET Smart Grid*, and *IET Renewable Power Generation*.

JOÃO P. S. CATALÃO (Senior Member, IEEE) received the M.Sc. degree from the Instituto Superior Técnico (IST), Lisbon, Portugal, in 2003, and the Ph.D. degree and Habilitation for Full Professor (''Agregação'') from the University of Beira Interior (UBI), Covilha, Portugal, in 2007 and 2013, respectively. He is currently a Professor with the Faculty of Engineering, University of Porto (FEUP), Porto, Portugal, and the Research Coordinator with INESC TEC. He was also appointed as a Visiting Professor by North China Electric Power University (NCEPU), Beijing, China. He was the Primary Coordinator of the EU-funded FP7 project Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration (SiNGULAR), a 5.2-million-euro project involving 11 industry partners. He was also the Principal Investigator of three funded projects by the Portuguese National Funding Agency for Science, Research and Technology (FCT) and the European Regional Development Fund (FEDER). Moreover, he has authored or coauthored more than 940 publications, including 455 international journal articless (more than 150 IEEE Transactions/Journal articles, 200 Elsevier, and 20 IET journal articles), 440 international conference proceedings papers (vast majority co-sponsored by IEEE), four books and 41 book chapters, with an H-index of 71, an i10-index of 374, and more than 20,400 citations (according to Google Scholar), having supervised more than 95 postdoctorals, Ph.D., and M.Sc. students. He was the Inaugural Technical Chair of SEST 2018-first International Conference on Smart Energy Systems and Technologies (technically co-sponsored by IEEE IES), the General Chair of SEST 2019 (technically co-sponsored by IEEE PES and IEEE IES), the General Co-Chair of SEST 2020 (technically co-sponsored by IEEE PES, IEEE IES, and IEEE IAS), and the Honorary Chair of SEST 2021 (technically co-sponsored by IEEE PES, IEEE IES, IEEE IAS, and IEEE PELS). He was also the Editor of the books *Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling* and *Smart and Sustainable Power Systems: Operations, Planning and Economics of Insular Electricity Grids* (Boca Raton, FL, USA: CRC Press, 2012 and 2015, respectively). He is also the Senior Editor of the IEEE Transactions on Smart Grid, the Promotion and Outreach (Senior) Editor of the IEEE Open Access Journal of Power and Energy, an Associate Editor of the IEEE Transactions on Power Systems, the IEEE Power Engineering Letters, the IEEE Transactions on Systems, Man, and Cybernetics: Systems, the IEEE Transactions on Neural Networks and Learning Systems, the IEEE Transactions on Industrial Informatics, the IEEE Transactions on Intelligent Transportation Systems, the IEEE Transactions on Vehicular Technology, the IEEE Transactions on Cloud Computing, the IEEE Transactions on Industry Applications, the IEEE Systems Journal, the IEEE Access, the IEEE Transactions on Sustainable Energy, 2011–2018, and the IEEE Transactions on Smart Grid, 2013–2020. He was the Guest Editor-in-Chief for the Special Section on ''Real-Time Demand Response'' of the IEEE Transactions on Smart Grid, published in December 2012, the Guest Editor-in-Chief for the Special Section on ''Reserve and Flexibility for Handling Variability and Uncertainty of Renewable Generation'' of the IEEE Transactions on Sustainable Energy, published in April 2016, the Corresponding/Lead Guest Editor (Guest Editor-in-Chief) for the Special Section on ''Industrial and Commercial Demand Response'' of the IEEE Transactions on Industrial Informatics, published in November 2018, the Guest Co-Lead Editor for the Special Section on ''Invited Papers on Emerging Topics in the Power and Energy Society'' of the IEEE Open Access Journal of Power and Energy, published in October 2020, the Guest Co-Lead Editor for the Special Section on ''Invited Papers in 2021 on Emerging Topics in the Power and Energy Society'' of the IEEE Open access Journal of Power and Energy, published in November 2021, and the Guest Editor-in-Chief for the Special Section on ''Demand Response Applications of Cloud Computing Technologies'' of the IEEE Transactions on Cloud Computing, to be published in January 2022. He is also the Guest Lead Editor (Guest Editor-in-Chief) for the Special Section on ''Real-World Challenges of TSO-DSO Coordination'' of the IEEE Transactions on Power Systems. He was the recipient of the 2011 Scientific Merit Award UBI-FE/Santander Universities, the 2012 Scientific Award UTL/Santander Totta, the 2016–2019 (four years in a row) FEUP Diplomas of Scientific Recognition, the 2017 Best INESC-ID Researcher Award, and the 2018 Scientific Award ULisboa/Santander Universities. He was recognized as one of the Outstanding Associate Editors and Reviewers 2020 of the IEEE Transactions on Smart Grid. He is a Top Scientist in the Guide2Research Ranking, which lists only scientists having H-index equal or greater than 40. He is also among the 0.5% Top Scientists, according to a study published by a team at Stanford University. Furthermore, he has won five Best Paper Awards at IEEE Conferences and the MPCE Best Paper Award 2019. Moreover, former M.Sc. and Ph.D. students have won the National Engineering Award 2011, the first Prize in REN (Portuguese TSO) Award 2019, and the first Prize in 2020 Young Engineer Innovation Award.

His research interests include power system operations and planning, power system economics and electricity markets, distributed renewable generation, demand response and smart grid, and multi-energy carriers.

• • •