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Hierarchical Approach for Coordinating Energy and Flexibility Trading in Local Energy Markets

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Abstract

Prosumers play a central role in current distribution networks. Local markets provide an environment for prosumers to interact with each other, either directly through peer-to-peer (P2P) markets, or indirectly via community-based markets. In this paper, we propose a hierarchical approach for local energy and flexibility trading among prosumers in distribution networks, in which prosumers are able to trade energy via P2P manner and transact flexibility in the local energy market to maintain distribution network constraints. The proposed method enables prosumers to manage their resources and participate in a P2P market by submitting their optimal bidding and offering curves. A local market operator runs the P2P market for energy trading among prosumers, and cooperates with the distribution system operator to dispatch the flexibility provided by prosumers. Moreover, a real-world distribution network consisting of ten prosumers is considered to assess the performance of the proposed model for local energy market based on flexible behavior of prosumers in the bottom layer of the distribution network.

Keywords: Bidding strategy, distribution network, energy community, flexibility, local energy market, peer-to-peer, prosumer.

Nomenclature

Abbreviations

CS	Cost-saving
DSO	Distribution System Operator
LEM	Local enegy market
LMO	Local Market Operator
MG	Micro-grid
P2P	Peer-to-peer
PV	Photovoltaics
SC	Self-consumption
SS	Self-sufficiency
ToU	Time of Use

Indices and sets

$\omega, \omega^{'}$	Scenarios
j, i	Prosumers
$j, j^{'}$	Buses
m	Offer and bid blocks for prosumers
n	Linear partitions for linearization
t	Time slots

Parameters in the first stage

β_{jt}	Portion of interruptible loads for prosumer j at time slot t which is between 0 and 1
$\lambda^{lm}_{jt\omega}$	Predicted energy trading price in the LEM for prosumer j at time slot t and scenario ω
λ^{+}_{t}	ToU selling price to the grid at time slot t
λ^{-}_{t}	ToU buying price from the grid at time slot t
$\overline{L}_j$	Maximum energy consumption for prosumer j
$\overline{P}_j$	Maximum energy generation (PV capacity) for prosumer j
ρ_ω	Probability of scenario ω
$L_{jt\omega}$	Energy consumption for prosumer j at time slot t and scenario ω

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$P_{jt\omega}$	Energy generation for prosumer j at time slot t and scenario ω
Variables in the first stage	
λ^{p2p}_{jit}	The price of P2P energy trading between prosumers j and i at time slot t
λ^{b}_{jtm}	Bidding price of prosumer j in block m and time t
λ^{o}_{jtm}	Offering price of prosumer j in block m and time t
$\mathcal{B}_{jt}$	Bid vector for prosumer j at time t
$\mathcal{O}_{jt}$	Offer vector for prosumer j at time t
B_{jtm}	Bidding quantity of prosumer j in block m and time t
EC^{p}_{j}	Expected cost for prosumer j
EP^{p}_{j}	Expected profit for prosumer j
$L^{f,i}_{jt\omega}$	The amount of interruptible load for prosumer j at time t and scenario ω
$L^{f,s}_{jt\omega}$	The amount of shiftable load for prosumer j at time t and scenario ω
$L^{f}_{jt\omega}$	The amount of flexible load for prosumer j at time t and scenario ω
O_{jtm}	Offering quantity of prosumer j in block m and time t
OF^{p}_{j}	Objective function for prosumer j
$P^{p2p,+,bl}_{jitm}$	The quantity of offering for P2P trading among prosumers j and i at time slot t and block m
$P^{p2p,+}_{jit}$	Energy that prosumer j sells to prosumer i at time slot t
$P^{p2p,-,bl}_{jitm}$	The quantity of bidding for P2P trading among prosumers j and i at time slot t and block m
$P^{p2p,-}_{jit}$	Energy that prosumer j buys from prosumer i at time slot t
$P^{+}_{jt\omega}$	Total energy sold of prosumer j at time slot t and scenario ω
$P^{-}_{jt\omega}$	Total energy purchased of prosumer j at time slot t and scenario ω
$P^{g,+}_{jt\omega}$	Energy sold to the grid at ToU price by prosumer j at time slot t and scenario ω
$P^{g,-}_{jt\omega}$	Energy purchased from the grid at ToU price to prosumer j at time slot t and scenario ω
$P^{lm,+}_{jt\omega}$	Energy quantities of offering for prosumer j at time slot t and scenario ω
$P^{lm,-}_{jt\omega}$	Energy quantities of bidding for prosumer j at time slot t and scenario ω
u_{jit}	A binary variable representing P2P trading status between prosumers j and i at time slot t
$v_{jt\omega}$	A binary variable for expressing status of buying/selling in the LEM of prosumer j at time slot t and scenario ω
Parameters in the second stage	
γ_{jt}	Flexibility factor for prosumer j at time slot t which is between 0 and 1
$\mathcal{P}^{net}_{jt}$	Net energy provided by prosumer j at time slot t
$\mathcal{Q}_{jt}$	Potential reactive power provided at bus j and time slot t
$\overline{V}$	Maximum voltage range for all buses
$\underline{V}$	Minimum voltage range for all buses
$R_{jj'}$	Resistance between buses j and j' in the distribution network
$X_{jj'}$	Reactance between buses j and j' in the distribution network
Variables in the second stage	
$\Delta\mathcal{P}_{jj'nt}$	Discretized active power flowing between nodes j and j' at n linear partition and time slot t
$\Delta\mathcal{Q}_{jj'nt}$	Discretized reactive power flowing between nodes j and j' at n linear partition and time slot t
$\mathcal{F}_{jt}$	Flexibility service provided by prosumers j at time slot t.
$\mathcal{I}_{jj't}$	An auxiliary variable linearly stating the squared current flow $I^2_{jj't}$ in a distribution line connected between buses j and j' at time slot t
$\mathcal{P}^{d}_{jj't}$	Active power flows of the distribution line connected between j and j' in the downstream flow at time slot t
$\mathcal{P}^{g}_{jt}$	Traded energy of prosumer j with the grid at time slot t
$\mathcal{P}^{u}_{jj't}$	Active power flows of the distribution line connected between j and j' in the upstream flow at time slot t
$\mathcal{Q}^{d}_{jj't}$	Reactive power flows of the distribution line connected between j and j' in the downstream flow at time slot t
$\mathcal{Q}^{u}_{jj't}$	Reactive power flows of the distribution line connected between j and j' in the upstream flow at time slot t
$\mathcal{V}_{jt}$	An auxiliary variable for representing the squared voltage V^2_{jt} of bus j at time slot t
OF^{d}	The objective function for the DSO in the second stage

1. Introduction

1.1. Motivation

Proactive consumers act as the main decision-makers in the bottom layer of distribution networks. Not only are some of prosumers in the power system able to supply their electrical demand, but also they can sell their extra energy generated via distributed energy resources to the distribution grid. Moreover, prosumers can be equipped with flexible resources such as batteries, electric vehicles, shiftable devices and interruptible loads, which enable them to provide flexibility services by modifying their net energy in response to the distribution network requests. This flexible behavior provided by prosumers decreases dependency of the distribution network to the upstream grid. In this way, local energy markets (LEMs) provide a competitive environment for prosumers to trade electricity services such as energy and flexibility in distribution networks [1]. To this end, there is a need to design innovative approaches to coordinate energy and flexibility trading of prosumers in LEMs, considering distribution network constraints and autonomous decisions which are made by prosumers for local energy tradings.

1.2. Literature Review

In the literature, there exist several researches to address design of market structures and approaches for local energy trading and electricity services, e.g. energy and flexibility, in the LEMs. Existing works fall into two categories. The first category studies LEM designs for energy trading in distribution systems. In [2], a hybrid LEM has been designed, which combines community-based and Peer-to-Peer (P2P) trading schemes for the active participation of prosumers in the market . Zhang *et al.* [3] proposed a hierarchical structure for the real-time energy trading in distribution networks. In addition, researchers discussed different approaches for energy trading in distribution networks. The decentralized optimization methods are used in [4] and [5] to model energy trading in LEM. A decentralized optimization is proposed in [4] to model the operation of a local energy community in which Alternative Direction Method of Multipliers (ADMM) is employed to keep the preferences and cost structures of prosumers private. In [5], a decentralized optimization-based algorithm for energy trading in LEM is presented considering welfare maximization and network voltage management through local information exchange among prosumers in the LEM. In [6], a coalition formation game is proposed that enables prosumers to participate in the P2P trading based on social coalition groups of prosumers. On the other hand, the P2P trading scheme has been presented based on cooperative Stackelberg game among the centralized power system and prosumers in [7]. A two-stage mechanism design for energy sharing of prosumers in local energy communities is presented in [8], in which prosumers as strategic agents can bid in the day-ahead and real-time markets to trade energy within the community and with the grid. Morstyn *et al.* [9] presented a P2P energy market platform of a multi-class energy management system defined based on the generation technology and location of prosumers in the distribution network. Moreover, the P2P trading has been utilized in [10] for multi-energy resource management for interconnected Micro-grids (MGs). A distributed mechanism has been proposed for trading energy among MGs in [11]. Additionally, Ref. [12] introduced contribution-based energy transaction between MGs. In [13], a methodology has been proposed to evaluate the impact of P2P trading considering network constraints. Zhang *et al.* [14] proposed a P2P energy trading considering bidding strategy based on the value-at-risk. The P2P energy trading based on congestion control in distribution networks has been studied in [15]. In [16], a P2P trading structure is proposed, in which aggregators operate a two-sided local market platform to match consumer and producer peers. In [17], a P2P trading framework for energy exchange in active distribution networks is developed which employs multi-round double auction with average pricing mechanism for market settlement. The auction mechanism is also used in [18] to model P2P trading in a community microgrid, where an iterative uniform-price auction mechanism is presented to determine a uniform trading price and an efficient energy allocation.

The second category of works defines flexibility as an electricity service that can be traded in the local market or with the upstream grid [19]. The key concepts related to local flexibility markets have been reviewed in [20], where a survey on the definitions, key elements, technologies and participants of local flexibility markets is presented. A real-life demonstration of local flexibility markets is presented in [21], in which the flexibility market includes 800 participating customers and runs in parallel with the wholesale markets. In [22], an optimization problem for an aggregator of flexible resources is introduced that allows the aggregator to response to the distribution system operator (DSO) requests on flexibility. This aggregator operates a LEM and schedules flexible energy resources of market participants. In [23], a decentralized market has been designed in which the DSO manages local flexibility provided by prosumers based on the DSO-to-aggregators and aggregators-to-prosumers interactions. A two-stage stochastic optimization model is presented in [24] which models the decision making of an aggregator in procuring prosumers' flexibility with the objective of minimizing the net cost of buying and selling energy and secondary reserve in both day-ahead and real-time market stages. The participation of an aggregator in the day-ahead energy and local flexibility markets is modeled in [25], where the aggregator can provide flexibility bids on a local market as well as local constraint support for the DSO. The study in [26] presents a transactive-based market to utilize flexibility of small-scale residential consumers in a local flexibility market to prevent transformer overloading. This work develops a two-stage optimization-based scheduling model to optimize transactive bidding of consumers in the flexibility market. In [27], a P2P LEM has been presented for overcoming uncertainty in distribution networks through trading energy and flexibility of prosumers simultaneously. A combined P2P and flexibility market has been presented in [28], in which prosumers participate in a flexibility market to assist the network operator in managing transformer loading. Authors in [29] proposed an iterative algorithm for local flexibility trading among consumers-aggregators-DSO in distribution networks.

1.3. Contribution

Although there exist various researches to study LEMs, the P2P energy trading and flexibility management models, a comprehensive model has not been proposed to cover local energy and flexibility tradings considering distribution network constraints, and different strategies for P2P trading. In this paper, we propose a novel hierarchical approach for P2P energy trading based on coordinating by the local market operator (LMO) and flexibility committed for prosumers considering distribution network limitations. According to our proposed model, prosumers make autonomous optimal energy management decisions considering offering-bidding strategy in the local market. Considering decisions made by prosumers, the LMO and the DSO operate flexibility provided by prosumers. In this way, three main contributions of this paper can be summarized as follows:

- Designing a 2-stage model for flexibility and P2P energy trading in LEMs based on a hierarchical approach.
- Proposing two P2P energy coordinating strategies, and studying the performance of prosumers in each stage of the proposed LEM.
- Defining flexibility scenarios and analyzing the behavior of the distribution network and prosumers based on P2P coordinating strategies and flexibility scenarios.

The rest of this paper is organized as follows. In Section 2, different stages of our proposed LEM are modeled. Section 3 discusses the simulation results of a Finnish distribution test network. Finally, our findings are concluded in Section 4.

2. Proposed Local Energy Market Model

In this section, we propose a 2-stage model for trading energy and flexibility among prosumers in the LEM as shown in Fig.1. Here, flexibility is defined as an electricity commodity which is provided by flexible power system players based on changing their desired energy production/consumption due to reaction to price or other incentive signals [30]. According to our proposed LEM structure, in the first stage, prosumers are able to trade with each other in a P2P energy market, where the LMO is in charge of coordinating P2P tradings among them. In the second stage, the LMO in cooperation with the DSO dispatches the flexibility provided by prosumers considering distribution network constraints. In our proposed model, we assume that:

- Prosumers have access to grid and can always trade with the grid at time of use (ToU) selling/buying prices,
- Prosumers have their own autonomous energy management systems that act on behalf of them in the local market and generate bids and offers,
- Prosumers and the LMO can communicate with each other through a communication platform.

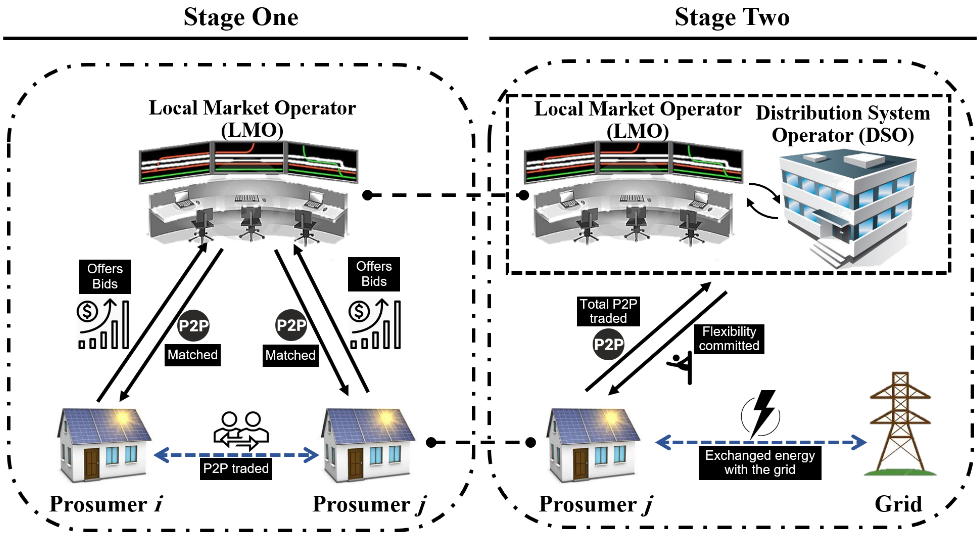


Figure 1: Players and our proposed framework for energy and flexibility trading in the LEM.

2.1. First Stage: P2P Energy Market

In the first stage, prosumers manage their own energy production and consumption independently and submit their optimal offering and bidding to the local market, where the LMO coordinates P2P energy tradings between prosumers based on their submitted offers and bids. Although the LMO is in charge of coordinating P2P matches in the local market, each P2P energy trading has its corresponding matching price which does not depend on the rest of P2P transactions in the LEM. Our proposed P2P energy market is described in the following.

2.1.1. Bidding Strategy for Prosumers

In this paper, each prosumer is defined as a strategic player which is able to find its optimal offers and bids autonomously based on its energy production/consumption and potential flexibility. Here, we propose optimal offering/biding strategy for prosumers through a stochastic programming based on probabilistic scenarios of the electricity price, generation and consumption. Besides, it is noted that this section does not propose a home (building) energy management system. According to our proposed model, each prosumer has their energy generation/consumption profile, and they make their optimal decisions to trade with other prosumers in the LEM based on their bidding strategies. In this way, the objective function for prosumer j, OF^p_j, presents the difference between its expected cost and expected profit as given in Eq. (1):

$$OF^p_j = EC^p_j - EP^p_j, \forall j \tag{1}$$

where EC^p_j and EP^p_j represent expected cost and profit for prosumer j, respectively. Moreover, Eqs. (2) and (3) express expected cost and profit for prosumer j, respectively.

$$EC^p_j = \sum_{t\omega} \rho_\omega (\lambda^{lm}_{jt\omega} P^{lm,-}_{jt\omega} + \lambda^-_t P^{g,-}_{jt\omega}), \forall j \tag{2}$$

$$EP^p_j = \sum_{t\omega} \rho_\omega (\lambda^{lm}_{jt\omega} P^{lm,+}_{jt\omega} + \lambda^+_t P^{g,+}_{jt\omega}), \forall j \tag{3}$$

According to Eq. (2), the expected cost for player j includes two terms. The first term, $\lambda^{lm}_{jt\omega} P^{lm,-}_{jt\omega}$, represents the expected cost of energy trading with other prosumers in LEM in scenario ω and time t.

The expected cost of energy bought from the grid is represented in the second term, $\lambda_t^- P_{jt\omega}^{g,-}$. Moreover, Eq. (3) consist of two terms. The first term, $\lambda_{jt\omega}^{lm} P_{jt\omega}^{lm,+}$, states the expected profit of energy trading in the LEM, and the second term, $\lambda_t^+ P_{jt\omega}^{g,+}$, states the expected profit of energy sold to the grid. Here, $\lambda_{jt\omega}^{lm}$ is a parameter (input) of the proposed decision making problem for prosumer j representing energy trading price in the LEM which are obtained based on prediction by prosumer j. Moreover, λ_t^- and λ_t^+ are parameters expressing ToU buying and selling prices to the grid. Here, ρ_ω present the probability of scenario ω. Moreover, $P_{jt\omega}^{lm,+}$ and $P_{jt\omega}^{lm,-}$ represent energy quantities of offering and bidding for prosumer j at time slot t and scenario ω, respectively, where each scenario presents an energy block. Also, $P_{jt\omega}^{g,+}$ and $P_{jt\omega}^{g,-}$ state energy sold to/purchased from the grid at ToU price. Thus, the total purchased/sold energy of prosumer j at time slot t and scenario ω can be defined which is splitted to the local energy traded with other prosumers and the energy exchanged with the grid as seen in Eqs. (4) and (5):

$$P_{jt\omega}^- = P_{jt\omega}^{lm,-} + P_{jt\omega}^{g,-}, \forall j, \forall t, \forall \omega \tag{4}$$

$$P_{jt\omega}^+ = P_{jt\omega}^{lm,+} + P_{jt\omega}^{g,+}, \forall j, \forall t, \forall \omega \tag{5}$$

where $P_{jt\omega}^-$ and $P_{jt\omega}^+$ represent total energy purchased and sold of prosumer j, respectively. Moreover, each prosumer is able to participate only as a seller or a buyer of energy at time slot t and scenario ω as represented in (6) and (7):

$$0 \leq P_{jt\omega}^- \leq L_{jt\omega} v_{jt\omega}, \forall j, \forall t, \forall \omega \tag{6}$$

$$0 \leq P_{jt\omega}^+ \leq P_{jt\omega}(1 - v_{jt\omega}), \forall j, \forall t, \forall \omega \tag{7}$$

where $L_{jt\omega}$ and $P_{jt\omega}$ represent energy consumption and generation of prosumer j at time t and scenario ω, and $v_{jt\omega}$ is a binary variable for expressing status of buying/selling in the LEM. Additionally, the proposed offering-bidding strategy is limited to several physical constraints which are presented in the following. Eq. (8) represents the power balancing equation for prosumers:

$$P_{jt\omega} + P_{jt\omega}^- = L_{jt\omega} - L_{jt\omega}^f + P_{jt\omega}^+, \forall j, \forall t, \forall \omega \tag{8}$$

where $L_{jt\omega}^f$ represents the amount of flexible load for prosumer j at time t and scenario ω based on increment and reduction in potential load of prosumers which is presented in (9):

$$|L_{jt\omega}^f| \leq L_{jt\omega}, \forall j, \forall t, \forall \omega. \tag{9}$$

In this paper, it is considered that the flexible load can be provided by shiftable and interruptible loads as expressed in (10):

$$L_{jt\omega}^f = \beta_{jt} L_{jt\omega}^{f,i} + (1 - \beta_{jt}) L_{jt\omega}^{f,s}, \forall j, \forall t, \forall \omega \tag{10}$$

where $L_{jt\omega}^{f,i}$ and $L_{jt\omega}^{f,s}$ present the amount of interruptible and shiftable loads of prosumer j at time slot t and scenario ω, respectively. Also, $0 \leq \beta_{jt} \leq 1$ denotes the portion of interruptible loads, such that all flexible loads are interruptible if $\beta_{jt} = 1$, whereas $\beta_{jt} = 0$ indicates that all flexible loads are shiftable. In this way, Eq. (11) presents shiftable load constraints in which its total energy reduction must be equal to energy increment to ensure satisfaction of prosumers demand [31]:

$$\sum_t \sum_\omega \rho_\omega L_{jt\omega}^{f,s} = 0, \forall j. \tag{11}$$

Finally, prosumers must submit their ascending offering and descending bidding curves for energy tradings to the LMO. Thus, optimal offering and bidding blocks are given by Eqs. (12) and (13) based on [31], respectively:

$$P^{lm,+}_{jt\omega} \geq P^{lm,+}_{jt\omega'}, \forall \lambda^{lm}_{jt\omega} \geq \lambda^{lm}_{jt\omega'}, \forall \omega \geq \omega', \forall j, \forall t \tag{12}$$

$$P^{lm,-}_{jt\omega} \leq P^{lm,-}_{jt\omega'}, \forall \lambda^{lm}_{jt\omega} \geq \lambda^{lm}_{jt\omega'}, \forall \omega \geq \omega', \forall j, \forall t \tag{13}$$

where both ω and ω' represent scenarios (offering/bidding blocks). In other words, Eqs. (12) and (13) guarantees that optimal offering and bidding curves are ascending and descending, respectively. Thus, the decision making problem of prosumer j in the bottom layer of the distribution network is given as:

$$\min OF^p_j$$
$$s.t. : (4) - (13)$$

In this way, prosumer j is able to make optimal decisions based on bidding strategy independently, and submits its offers or bids in each time slot. Thus, optimal offering and bidding blocks are ordered according to Eqs. (12) and (13) as seen in Eqs. (14) and (15):

$$\mathcal{O}_{jt} = \{[O_{jt1}, ..., O_{jtm}], [\lambda^o_{jt1}, ..., \lambda^o_{jtm}]\}, \forall j, \forall t \tag{14}$$

$$\mathcal{B}_{jt} = \{[B_{jt1}, ..., B_{jtm}], [\lambda^b_{jt1}, ..., \lambda^b_{jtm}]\}, \forall j, \forall t \tag{15}$$

where $\mathcal{O}_{jt}$ and $\mathcal{B}_{jt}$ represent offer and bid vectors for prosumers j at time t. Besides, O_{jtm} and λ^o_{jtm} state offering quantity and price of prosumer j in block m and time t, and B_{jtm} and λ^b_{jtm} express bidding quantity and price of prosumer j in block m and time t. Moreover, it is noted that each prosumer cannot act as a seller and a buyer in one time slot simultaneously.

2.1.2. P2P Coordinating Problem

In the P2P energy market, prosumers are able to buy/sell energy from/to other prosumers. In this way, total P2P traded energy by prosumer j with prosumer i is split into P2P sold energy and P2P purchased as represented in Eq. (16):

$$P^{p2p}_{jit} = P^{p2p,+}_{jit} - P^{p2p,-}_{jit}, \forall j, j \neq i, \forall t \tag{16}$$

where $P^{p2p,+}_{jit}(P^{p2p,-}_{jit})$ presents energy that prosumer j sells (buys) to (from) prosumer i at time t. Moreover, prosumer j can only buy or sell energy from prosumer i at time t as stated in Eqs. (17) and (18):

$$0 \leq P^{p2p,+}_{jit} \leq \overline{P}_j u_{jit}, \forall j, j \neq i, \forall t \tag{17}$$

$$0 \leq P^{p2p,-}_{jit} \leq \overline{L}_j(1 - u_{jit}), \forall j, j \neq i, \forall t \tag{18}$$

where $\overline{P}_j$ and $\overline{L}_j$ represent maximum energy generation (PV capacity) and consumption for prosumer j. Besides, u_{jit} is a binary variable representing P2P trading status between prosumers j and i at time t, such that $u_{jit} = 1$ if prosumer j sold energy to prosumer i. The demand supply balance constraint in each trade is modeled in Eq. (19), which implies that the amount of energy sold by prosumer j to i should be equal to the energy that prosumer i purchases from prosumer j:

$$P^{p2p,+}_{jit} - P^{p2p,-}_{ijt} = 0, \ \forall j, j \neq i, \forall t. \tag{19}$$

Eqs. (20) and (21) represent maximum and minimum constraints of P2P energy blocks:

$$0 \le P^{p2p,+,bl}_{jitm} \le O_{jtm}, \forall j, j \neq i, \forall m, \forall t \tag{20}$$

$$0 \le P^{p2p,-,bl}_{jitm} \le B_{jtm}, \forall j, j \neq i, \forall m, \forall t \tag{21}$$

where $P^{p2p,+,bl}_{jitm}$ and $P^{p2p,-,bl}_{jit,}$ express the quantity of offering and bidding for P2P trading among prosumers j and i at time t and block m. Besides, the relation between total P2P energy traded among prosumers j and i and the P2P energy blocks are represented in Eq. (22) and (23):

$$P^{p2p,+}_{jit} = \sum_{m} P^{p2p,+,bl}_{jitm}, \forall j, j \neq i, \forall t. \tag{22}$$

$$P^{p2p,-}_{jit} = \sum_{m} P^{p2p,-,bl}_{jitm}, \forall j, j \neq i, \forall t. \tag{23}$$

In this paper, we propose two coordinating strategies for P2P energy trading in the LEM. In strategy one, Υ^1, the LMO coordinates the P2P energy transactions locally to maximize matching the offering and bidding blocks submitted by prosumers as presented in (24):

$$OF^1 = \sum_{jtm} \sum_{i(i \neq j)} (\lambda^o_{jtm} P^{p2p,+,bl}_{jitm} - \lambda^b_{itm} P^{p2p,-,bl}_{ijtm}), \tag{24}$$

where λ^o_{jtm} and λ^b_{itm} present offering and bidding prices for P2P trading between prosumers j and i at time t and block m which are outputs of bidding strategy problem for prosumer j. Moreover, it is noted that λ^o_{jtm} (λ^b_{jtm}) are different with $\lambda^{lm}_{jt\omega}$ which is an input of bidding strategy problem for prosumer j. In this way, the decision-making problem of the LMO for coordinating P2P energy trading based on strategy one is given:

$$\begin{gathered} \min \ OF^1 \\ s.t.: (16) - (23). \end{gathered}$$

On the other hand, in strategy two, the LMO maximizes P2P energy transactions in the LEM to maximize self-sufficiency of the community. Eq. (25) represents objective function of the LMO in strategy two:

$$OF^2 = \sum_{j} \sum_{i(i \neq j)t} P^{p2p,+}_{jit}, \tag{25}$$

here, the P2P coordinating problem for strategy two is given:

$$\begin{gathered} \max \ OF^2 \\ s.t.: (16) - (23). \end{gathered}$$

Thus, in both strategies, the LMO coordinates P2P matching among offers and bids which are submitted by prosumers. In this way, after the LMO matches P2P energy trading between prosumers i and j, their P2P trading price is obtained in Eq. (26):

$$\lambda^{p2p}_{jit} = \frac{\lambda^o_{jt} + \lambda^b_{it}}{2}, \forall j, j \neq i, \forall t. \tag{26}$$

where λ^{p2p}_{jit} represents the price of P2P energy trading between prosumers j and i.

2.2. Second Stage: Flexibility Trading in Cooperation with the DSO

In the second stage, the LMO, in cooperation with the DSO, commits flexibility provided by local prosumers considering distribution network constraints based on P2P energy trades as outputs of the first stage. In the first stage, the LMO coordinates P2P trades between prosumers. This way, in each P2P trading, one prosumer acts as a seller and one prosumer acts as a buyer. Each seller injects the determined amount of power to the network, and each buyer withdraws the required amount of power from the network. In this paper, the linear power flow problem based on Ref. [32] is utilized to calculate the required flexibility[1], where the related power flow constraints in the distribution network are described in Appendix A Section. This way, minimizing power losses of distribution lines is defined as the objective function, OF^d, as presented in Eq. (27):

$$OF^d = \sum_{j} \sum_{j'(j' \neq j)t} (R_{jj'} \mathcal{I}_{jj't}), \tag{27}$$

where $\mathcal{I}_{jj't}$ is an auxiliary variable linearly stating the squared current flow $I^2_{jj't}$ in a distribution line connected between buses j and j' at time t. Moreover, $R_{jj'}$ represents resistance between buses j and j' in the distribution network. As highlighted before, not only is prosumer[2] able to trade energy with other prosumers as P2P transactions (which are outputs of the first stage), but also it can exchange energy and flexibility with the DSO as represented by Eq. (28):

$$\mathcal{P}^{net}_{jt} + \mathcal{F}_{jt} = \mathcal{P}^{g}_{jt} + \sum_{i(i \neq j)} P^{p2p}_{jit}, \forall j, \forall t \tag{28}$$

where $\mathcal{P}^{g}_{jt}$ is defined as traded energy of prosumer j with the grid at time slot t. In this case, if $\mathcal{P}^{g}_{jt} > 0$, prosumer j sells energy to the grid. Besides, $\mathcal{F}_{jt}$ represents flexibility service provided by prosumers j at time t. Moreover, $\mathcal{P}^{net}_{jt}$ represent net energy provided by prosumer j at time t as defined in Eq. (29):

$$\mathcal{P}^{net}_{jt} = \mathcal{P}_{jt} - \mathcal{L}_{jt}, \forall j, \forall t. \tag{29}$$

Moreover, flexibility service provided by prosumer j is constrained to flexible loads and energy traded with the grid as presented in Eqs. (30) and (31), respectively:

$$-\gamma_{jt}\mathcal{L}_{jt} \leq \mathcal{F}_{jt} \leq \gamma_{jt}\mathcal{L}_{jt}, \forall j, \forall t \tag{30}$$

$$\mathcal{F}_{jt} \leq \begin{cases} \mathcal{P}^{g}_{jt}, & \text{if } \mathcal{P}^{g}_{jt} > 0, \\ -\mathcal{P}^{g}_{jt}, & \text{otherwise,} \end{cases} \tag{31}$$

where γ_{jt} is a parameter constrained 0 and 1 which is defined as the flexibility factor in Ref. [29] representing potential flexibility provided by prosumer j at time slot t. This way, the decision-making problem for the second stage, where the LMO in cooperation with the DSO trades flexibility to maintain distribution network constraints (Eqs. (32)-(43) described in Appendix A section), is given as:

$$\begin{gathered} \min OF^d \\ s.t.: (28) - (31), (32) - (43). \end{gathered}$$

[1]It is noticeable that the studied power flow problem is not the DC one, and it is a linearized model of the AC problem.

[2]It is noticeable that only one prosumer is considered at each bus. In other words, prosumer j is located at bus j in the distribution network.

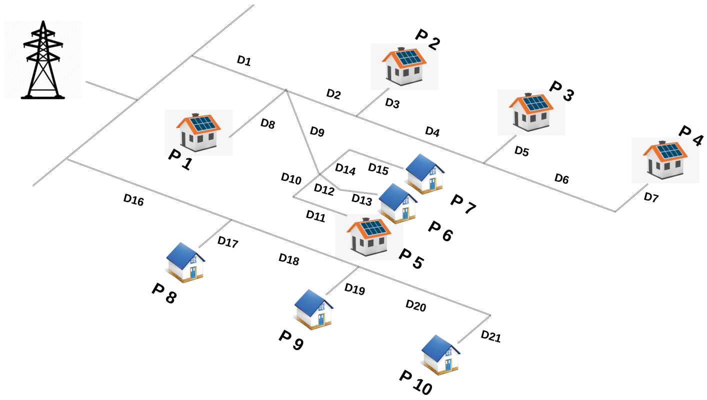


Figure 2: The considered real-world distribution network [33].

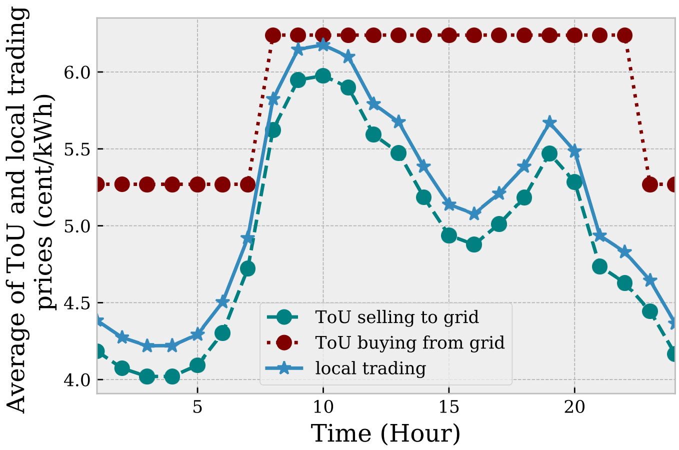


Figure 3: Average of ToU buying/selling from/to the grid and local trading prices [34].

3. Simulation Results

3.1. Case Study

In this paper, a real-world three-phase distribution network where the network voltage (phase-to-phase) is 400 V [33], and all prosumers are equipped with three-phase supply, is used to evaluate the performance of our proposed 2-stage local energy trading approach as shown in Fig. 2. The data of distribution lines are presented in Table Table 5 in Appendix B section. This way, ten local agents consisting of five prosumers equipped with PV panels (P1 to P5) and five consumers (P6 to P10) trade in the corresponding local market. Besides, average of ToU buying (selling) from (to) the grid and local trading prices are displayed in Fig. 3. Besides, twelve scenarios are used for energy production, consumption and electricity price with uniform probability of 0.083 for each scenario. Thus, scenarios came from auto-prediction of their corresponding time series. Fig. 4 illustrates average of net energy (difference between generation and consumption) for each prosumer. The flexibility factor and the PV capacity for prosumers are presented in Table 1. As shown in Table 1, flexibility factor for P5 is equal to zero representing that P5 is not willing to provide energy flexibility. Moreover, only P1 to P5 are equipped by PV panels.

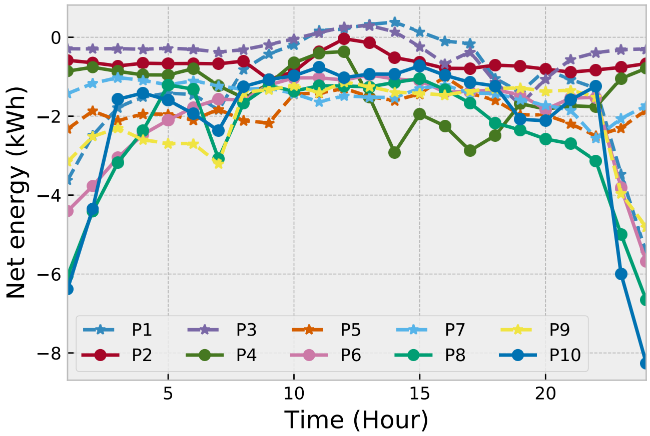


Figure 4: Average of net energy for all prosumers [35].

Table 1: Flexibility coefficient and PV capacity for prosumers.

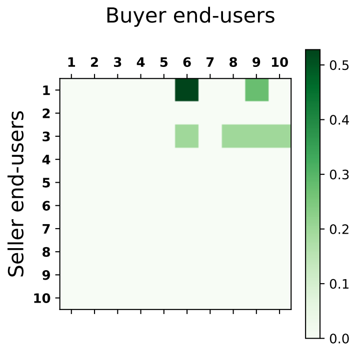
Prosumer #	γ_{jt}	$\overline{P}_j$ (kWh)	Prosumer #	γ_j
1	0.014	3	6	0.027
2	0.081	2.5	7	0.078
3	0.095	2.5	8	0.1
4	0.059	2	9	0.085
5	0	2.5	10	0.1

3.2. Evaluation of P2P Coordinating Strategies

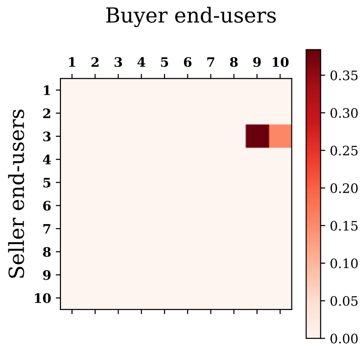
In this section, we study our two proposed strategies for the P2P coordinating described in Section 2.1.2. Prosumers make their own optimal decisions independently for finding offering and bidding curves calculated using Eqs. (4)-(13). Then, each prosumer submits its offering and bidding curves at each time interval to the LMO. In other words, each prosumer is able to play as a seller or a buyer at each time snapshot in the local market and submits either its corresponding offering or bidding curves to the LMO. After receiving offering and bidding curves, the P2P energy trading quantity will be calculated using either strategy one or two according to Eqs. (16)-(23). Fig. 5 displays the quantity of P2P energy traded among prosumers in strategy one. As shown in Fig. 5, in strategy one, energy is traded among peers only at $t = 11$ and $t = 12$. Thus, at $t = 11$, P1 sells energy to P6 and P9, and P3 sells energy to P6, P8, P9 and P10. However, at $t = 12$, there is only one seller, and P3 sells energy to P9 and P10.

In this way, for clarifying P2P coordinating between prosumers, Fig. 6 illustrates an example of P2P matching based on submitted offers and bids of prosumers in strategy one at $t = 12$. Figs. 6(a) and 6(b) show all offers and bids submitted by prosumers and consumers at $t = 12$. It is noticeable that all prosumers can only submit one of their offering and bidding curves to the LMO at each time snapshot. In this way, prosumers P2 and P3 act as producers and submit their offering curves to the LMO, whereas prosumers P4 and P5 play as consumers and submit their bidding curves. As mentioned before, the main purpose of strategy one is to minimize difference between offers and bids of prosumers. Hence, P2P trading between P3 and P9 is matched as shown in 6(a), where the quantity of their traded P2P is 0.384 kWh. Then, the rest of offered energy by P3, 0.157 kWh, is traded with P10.

Moreover, the quantity of P2P energy traded between prosumers in strategy two is illustrated in Fig. 7. According to Figs. 5 and 7, the number of P2P transactions in strategy two is more than strategy one. This is due to the fact that strategy two aims to maximize the P2P energy transactions. Besides, Table

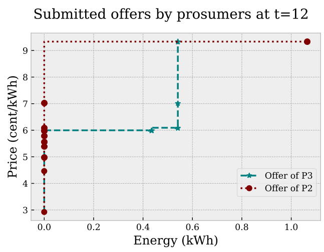


(a) P2P energy traded (kWh) at t=11

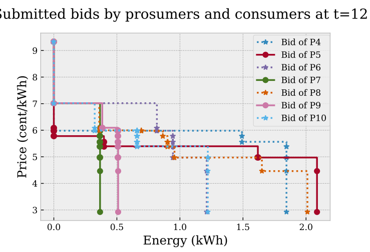


(b) P2P energy traded (kWh) at t=12

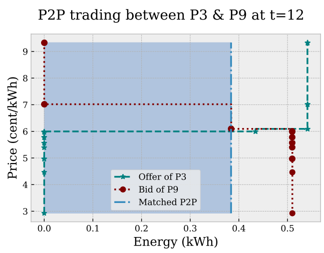
Figure 5: Matrix of P2P energy trading in strategy one at (a) t=11, (b) t=12.



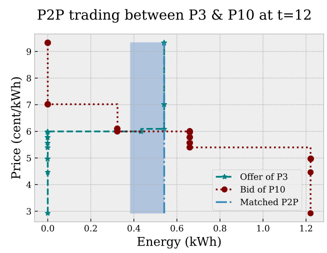
(a) Submitted offers by prosumers



(b) Submitted bids by prosumers and consumers



(c) P2P clearing between P3 and P9

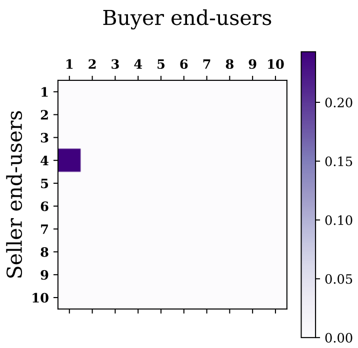


(d) P2P clearing between P3 and P10

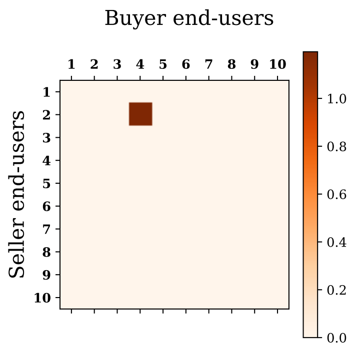
Figure 6: Coordinating between offers and bids for P2P trading based on strategy one at t=12.

Table 2: Cost/Profit of P2P trading for prosumers per time slots in our proposed P2P coordinating strategies (¢).

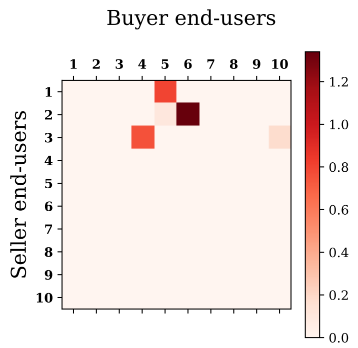
	Strategy 1		Strategy 2					
	t=11	t=12	t=9	t=10	t=11	t=12	t=13	t=14
P1	-5.03	-	2.729	-	-4.826	-	-6.815	-7.796
P2	-	-	-	-14.697	-11.843	-8.163	-	-
P3	-7.053	-3.497	-	-	-6.092	-4.423	-3.508	-8.924
P4	-	-	-2.729	14.697	6.092	-	10.324	8.924
P5	-	-	-	-	5.842	8.163	-	7.796
P6	4.554	-	-	-	10.827	4.423	-	-
P8	1.954	-	-	-	-	-	-	-
P9	3.625	2.482	-	-	-	-	-	-
P10	1.954	1.015	-	-	-	-	-	-



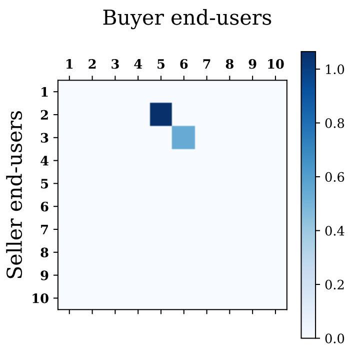
(a) P2P energy traded (kWh) at t=9



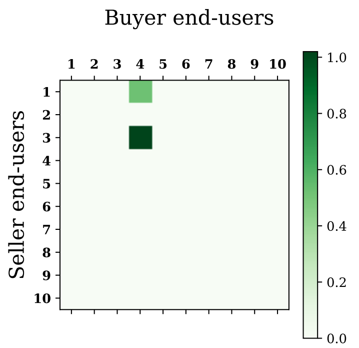
(b) P2P energy traded (kWh) at t=10



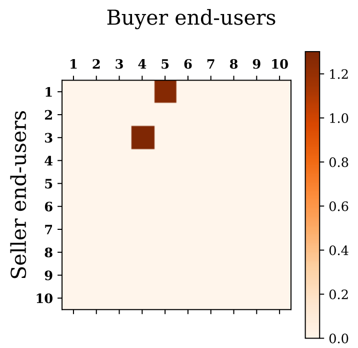
(c) P2P energy traded (kWh) at t=11



(d) P2P energy traded (kWh) at t=12



(e) P2P energy traded (kWh) at t=13



(f) P2P energy traded (kWh) at t=14

Figure 7: Matrix of P2P energy trading in strategy two at (a) t=9, (b) t=10, (c) t=11, (d) t=12, (e) t=13, (f) t=14.

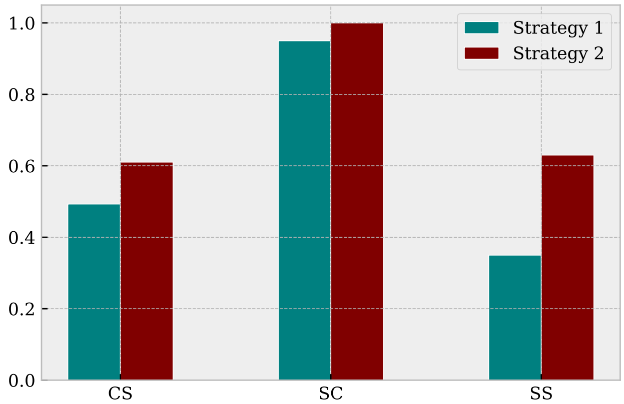


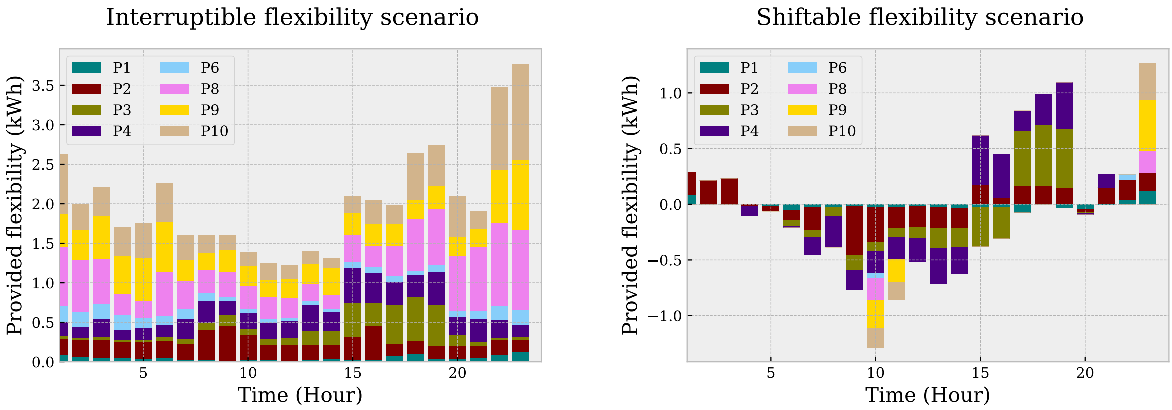
Figure 8: Impact of strategies one and two on the CS of P2P trading ($\times 10^{-1}$¢), the SS and the SC of the local market.

Table 3: Cost-saving based on P2P trading comparison with mid-market for prosumers in our proposed P2P coordinating strategies.

Prosumer #	Strategy 1	mid-market	Strategy 2	mid-market
1	0.161	0.241	0.717	1.001
2	0	0	0.714	1.113
3	1.482	2.224	0.642	0.937
4	0	0	1.967	1.511
5	0	0	1.301	0.976
6	0.290	0.218	0.751	0.564
7	0	0	0	0
8	0.079	0.059	0	0
9	2.775	2.081	0	0
10	0.143	0.107	0	0
Total CS for sellers	1.643	2.465	2.073	3.051
Total CS for buyers	3.287	2.465	4.02	3.051
Total CS for the community	4.93	4.93	6.102	6.102

2 presents costs/ profits for each of prosumers per time slot in our proposed P2P coordinating strategies while negative values (green cells) present the profit of P2P trading for each prosumer in the corresponding time slot. On the other hand, positive values (red cells) represent the cost of P2P trading. For instance, in strategy one at $t = 12$, the profit of P2P trading for P3 is 3.497 ¢, and the costs of P2P trading for P9 and P10 are 2.482 ¢ and 1.015 ¢, respectively. Moreover, we compare our proposed P2P coordinating strategies based on energy communities' criteria including total cost-saving for prosumers based on P2P trading (CS), self-sufficiency (SS) and self-consumption (SC) [36]. As shown in Fig. 8, strategy two is more profitable for the local community. Moreover, the local community is more self-sufficient and self-consumed in strategy two of P2P coordinating.

Table 3 expresses total cost-saving for each prosumer compared with the mid-market pricing method [37]. In the mid-market pricing, the price for P2P trading is predetermined, and is chosen to be the mid-value of ToU buying and selling prices, i.e. $(\lambda_t^+ + \lambda_t^-)/2$. Hence, in contrast to our proposed method, in the mid-market method prosumers do not participate in the market strategically. According to Table 3, total CS for the community in our both proposed P2P coordinating strategies are equal to the mid-market pricing method. However, the CS for buyers in our proposed strategies is higher than the mid-market method which



(a)

(b)

Figure 9: Impact of flexibility scenarios on up/down-ward flexibility provided by prosumers.

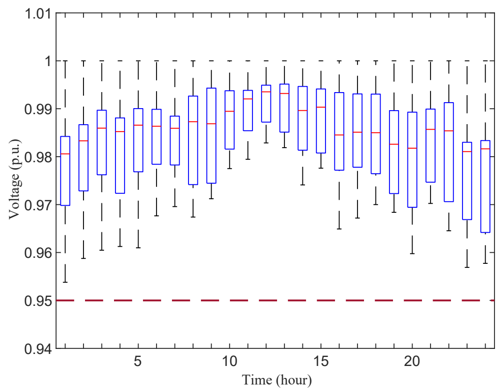


Figure 10: Box plot of voltages (p.u.) at prosumers' nodes.

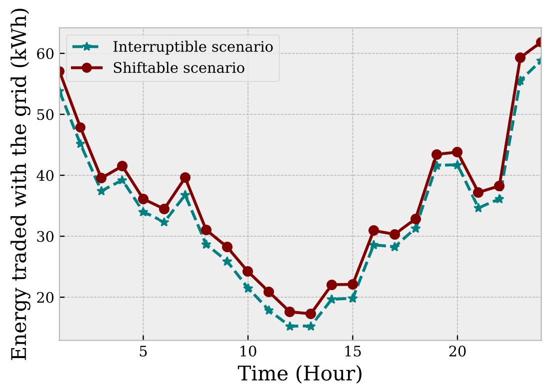


Figure 11: Impact of flexibility scenarios on energy traded between the LEM and upstream grid.

demonstrates that our proposed P2P coordinating strategies are more efficient in local communities with majority of local consumers as same as our studied case study.

3.3. Flexibility Trading Assessment

In this section, the impact of flexibility on local energy trading is studied. Moreover, for simplicity, the performance of the second stage is assessed based on the outputs of strategy one for P2P coordinating. Thus, two scenarios are introduced for assessing flexibility provided by prosumers in this section consisting of interruptible ($\beta_{jt} = 1$) and shiftable ($\beta_{jt} = 0$) flexibility scenarios based on Eq. (10). Fig. 9 shows the impact of interruptible and shiftable scenarios on flexibility services provided by prosumers in the local market. As seen in Fig. 9(a), all prosumers and consumers, except P5 and P7, are willing to provide only positive flexibility, so-called *upward* flexibility service, in the interruptible scenario. Thus, the corresponding local players act as virtual generator with decreasing their desired consumption. However, shiftable scenario pushes prosumers and consumers to provide negative flexibility, so-called *downward* flexibility service, as shown in Fig. 9(b). Moreover, the voltage of buses in the distribution network is shown in Fig. 10 which presents that all of the buses in the distribution network operate in the accepted voltage range ($0.95 \leq V_{nt} \leq 1.05$) according to Eq. (43). Besides, Fig. 11 shows the energy traded between the local market and the upstream grid. As shown in Fig. 11, energy traded between the local community and the upstream grid is less in the interruptible scenario in comparison with the shiftable one. In other words, in

Table 4: Computational time for our proposed P2P energy trading problem.

	Computational time (sec)
Bidding strategy problem for prosumers	≈ 0.01
P2P coordinating problem	≈ 0.14
Flexibility trading problem	0.03

the interruptible scenario, the self-sustainability of the local community is more and the dependency of the local community to the upstream grid is less.

3.4. Time Complexity

In this section, we study the required computational time of our proposed local flexibility and P2P energy trading problem as shown in Table 4. As highlighted before, prosumers make their optimum decisions considering their own bidding strategies independently. Thus, their problems are solved in parallel with computational time ≈ 0.01 sec for 24 time slot in our case study. This way, increasing the number of prosumers does not affect the computational time of the bidding strategy problem for prosumers. However, the LMO is in charge of coordinating of P2P energy trading problem based on submitted offering /bidding curves by prosumers. Thus, increasing in the number of prosumers can increase the number of variables and consequently the time complexity of the LMO coordination problem. In our real case study, with ten prosumers, the computational time for the P2P coordinating problem is 0.14 sec for 24 time slot. It is noted that our proposed P2P coordinating strategies are mixed-integer linear programming (MILP) which can be can be easily solved using solvers such as CPLEX. Our proposed model was solved by CPLEX 12.0 and the implementation was performed on a laptop with 16 GB RAM, Intel Core i7 2.9 GHz. Finally, the computational time for our flexibility trading problem for considering distribution network constraints is 0.03 sec which is sufficient for the DSO in case of rapid flexibility demanding from prosumers to ensure reliability in the distribution network.

3.5. Limitations and Challenges

Here, we discuss limitations and challenges of our studied model. The proposed model enables prosumers to strategically participate in P2P trading. Prosumers' preference for exchanging energy with other prosumers in their neighborhood is one of the factors that affects their decisions and can be considered in their bidding strategy. Also, prosumers can reschedule their energy trading strategies to maximize/minimize their profit/cost based on prediction of communities' behavior and their adapted preferences. Moreover, considering flexibility reward/price incentivizes prosumers to act strategically in the flexibility trading. Hence, an interesting direction for future works is consideration of strategic bidding of prosumers in the flexibility market and the decentralization of market clearing.

4. Conclusion

In this paper, we have presented a 2-stage model for trading energy and flexibility in the local energy market based on a hierarchical approach. According to our proposed model, in the first stage, prosumers trade energy in a P2P market, where each prosumer is able to submit its optimal offering or bidding curves to the local market operator . Two different strategies have been defined for P2P coordinating in the local energy market. In strategy one, the P2P trading has been coordinated based on maximizing matching the offering and bidding blocks submitted by prosumers. However, in strategy two, minimizing energy exchanged among the local community and the upstream grid has been the main object of the local market operator for coordinating P2P tradings. In the second stage, distribution network constraints, based on cooperation among the distribution system operator and the local market operator, have been addressed through flexibility provided by prosumers. Additionally, two scenarios have been assumed for flexible behavior of prosumers consisting of interruptible and shiftable flexibility scenarios. The performance of all stages of the proposed problem have been studied in a test distribution network.

According to the simulation results of a utilized test system, it is found that our proposed strategy two of P2P coordinating increases P2P energy transactions, self-consumption and self-sufficiency of the local energy market comparing with the strategy one. Besides, P2P energy trading is more profitable for the community of prosumers in strategy two. Additionally, our proposed P2P coordinating strategies are more efficient for local energy communities with majority of consumers. Last but not least, dependency of the distribution network to the upstream grid in the shiftable scenario is higher than the interruptible one.

Appendix A

In this section, power flow constraints of the distribution network are described. Thus, the network active and reactive power balancing equations are represented in Eqs. (32) and (33), respectively:

$$\mathcal{P}_{jt} + \sum_{n'}(\mathcal{P}^d_{j'jt} - \mathcal{P}^u_{j'jt}) - \sum_{n'}(\mathcal{P}^d_{jj't} - \mathcal{P}^u_{jj't}) + R_{jj'}\mathcal{I}_{jj't} - \mathcal{L}_{jt} + \mathcal{F}_{jt} = 0, \forall j, j \neq j', \forall t. \tag{32}$$

$$\mathcal{Q}_{nt} + \sum_{n'}(\mathcal{Q}^d_{j'jt} - \mathcal{Q}^u_{j'jt}) - \sum_{n'}(\mathcal{Q}^d_{jj't} - \mathcal{Q}^u_{jj't}) + X_{jj'}\mathcal{I}_{jj't} = 0, \forall j, j \neq j', \forall t. \tag{33}$$

In this way, each line flow variable is presented based on the difference of two non-negative variables so-called *bijection* [32]. As Seen in Eq. (32), $\mathcal{P}^d_{jj't}$ and $\mathcal{P}^u_{jj't}$ represent the active power flows of the distribution line connected between j and j' in the downstream and upstream flows, respectively. Moreover, Eq. (33) presents $\mathcal{Q}^d_{jj't}$ and $\mathcal{Q}^u_{jj't}$ as reactive power flows of the distribution line connected between buses j and j' in the downstream and upstream flows, respectively. Besides, $\mathcal{P}_{jt}$, $\mathcal{L}_{jt}$ and $\mathcal{F}_{jt}$ present potential energy generation, consumption and flexibility provided at bus j and time t. Also, $\mathcal{Q}_{jt}$ represents potential reactive power provided at bus j and time t where the power factor is considered to be 0.8 for each prosumer considering the average power factor of prosumers' appliances in this paper [38]. Moreover, $X_{jj'}$ represents reactance of the line between buses j and j'. Eqs. (34) and (35) restrict the maximum active and reactive power which can flow in the lines:

$$\mathcal{P}^d_{jj't} + \mathcal{P}^u_{jj't} \leq V^r \overline{I}_{jj'}, \forall j, j \neq j', \forall t \tag{34}$$

$$\mathcal{Q}^d_{jj't} + \mathcal{Q}^u_{jj't} \leq V^r \overline{I}_{jj'}, \forall j, j \neq j', \forall t \tag{35}$$

where V^r represents rated voltage which is set to 1 *p.u.*, and $\overline{I}_{jj'}$ expresses maximum current that can flow in distribution line between buses j and j'. Eq. (36) represents the voltage balancing between two buses:

$$\mathcal{V}_{jt} - \mathcal{V}_{j't} - Z^2_{jj'}\mathcal{I}_{jj'} - 2R_{jj'}(\mathcal{P}^d_{jj't} - \mathcal{P}^u_{jj't}) - 2X_{jj'}(\mathcal{Q}^d_{jj't} - \mathcal{Q}^u_{jj't}) = 0, \forall j, j \neq j', \forall t \tag{36}$$

where $\mathcal{V}_{jt}$ is an auxiliary variable for representing the squared voltage V^2_{jt} of bus j at time t. In order to obtain the accurate linearization, Eqs. (37)-(42) are deployed in which the number of blocks used for piece-wise linearizing the power flow constraints:

$$V^r_n \mathcal{I}_{jj't} = \sum_n (2n-1)\Delta\mathcal{S}_{jj'}\Delta\mathcal{P}_{jj'nt} + \sum_n (2n-1)\Delta\mathcal{S}_{jj'}\Delta\mathcal{Q}_{jj'nt}, \forall j, j \neq j', \forall t \tag{37}$$

$$\mathcal{P}^d_{jj't} + \mathcal{P}^u_{jj't} = \sum_n \Delta\mathcal{P}_{jj'nt}, \forall j, j \neq j', \forall t \tag{38}$$

$$\mathcal{Q}^d_{jj't} + \mathcal{Q}^u_{jj't} = \sum_n \Delta\mathcal{Q}_{jj'nt}, \forall j, j \neq j', \forall t \tag{39}$$

$$0 \leq \Delta\mathcal{P}_{jj'nt} \leq \Delta\mathcal{S}_{jj'}, \forall j, j \neq j', \forall t \tag{40}$$

$$0 \leq \Delta\mathcal{Q}_{jj'nt} \leq \Delta\mathcal{S}_{jj'}, \forall j, j \neq j', \forall t \tag{41}$$

$$\Delta\mathcal{S}_{jj'} = \frac{V^r \overline{I}_{jj'}}{\mathcal{N}}, \forall j, j \neq j' \tag{42}$$

where n represent index of linear partitions and $\mathcal{N}$ is set to 10 according to [32]. Additionally, $\Delta\mathcal{S}_{jj'}$ represents maximum bound for the discretization of power flow for line connected buses j and j'. Besides, $\Delta\mathcal{P}_{jj'nt}$ and $\Delta\mathcal{Q}_{jj'nt}$ represent discretized active and reactive power flowing between nodes j and j' at n linear partition and time t, respectively. Finally, maximum and minimum constraints for the squared voltage of each bus are presented by Eq. (43):

$$\underline{V}^2 \leq \mathcal{V}_{nt} \leq \overline{V}^2; \forall j, j \neq j^{'}, \forall t. \tag{43}$$

It is assumed that the minimum ($\underline{V}$) and maximum ($\overline{V}$) voltage ranges for all buses are set to 0.95 $p.u.$ and 1.05 $p.u.$, respectively.

Appendix B

In this section, we present data of the distribution lines of our test network in Table 5.

Table 5: Resistance, reactance, and length of the distribution lines illustrated in Fig. 2 [33].

Distribution line (D) #	R (Ω/km)	X (Ω/km)	Length (m)	Distribution line (D) #	R (Ω/km)	X (Ω/km)	Length (m)
1	0.868	0.104	69	12	0.868	0.104	137
2	0.868	0.104	60	13	1.83	0.088	12
3	1.83	0.088	48	14	1.91	0.108	45
4	0.868	0.104	95	15	3.08	0.09	11
5	1.83	0.088	34	16	0.868	0.104	85
6	0.641	0.101	571	17	1.83	0.088	29
7	3.08	0.09	4	18	0.868	0.104	52
8	1.83	0.088	38	19	1.83	0.088	35
9	0.868	0.104	248	20	1.2	0.106	58
10	0.868	0.104	33	21	3.08	0.09	40
11	1.83	0.088	38				

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