This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.DOI

A Novel Multi-Hierarchical Bidding Strategy for Peer-to-Peer Energy Trading Among Communities

TAYFUR GÖKÇEK[1], (Student Member, IEEE), IBRAHIM SENGOR[2,3], (MEMBER, IEEE), AND OZAN ERDINÇ[4], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Yildiz Technical University, Istanbul 34220, Turkey (e-mail: tgokcek@yildiz.edu.tr)
[2]MaREI Center, Environmental Research Institute, University College Cork, Cork, Ireland (e-mail: isengor@ucc.ie)
[3]Department of Electrical and Electronics Engineering, Izmir Katip Celebi University, Izmir 35620, Turkey
[4]Department of Electrical Engineering, Yildiz Technical University, Istanbul 34220, Turkey (e-mail: ozanerdinc@gmail.com)

Corresponding author: Ibrahim Sengör (e-mail: isengor@ucc.ie).

ABSTRACT Recently, several market types and regulations have been developed in an attempt to handle the increased carbon effect. End-users can also actively participate in the existing distribution system thanks to Peer-to-Peer (P2P) energy trading, which is one of the new emerging market types. In this paper, a novel dual bidding strategy for multi-hierarchical P2P energy trading that includes both intra community and inter communities is proposed considering uncertainties in solar irradiance and temperature. While lower-level problem consists of both optimal bids of households to the own Local Market Operators (LMO) for intra community trades and optimal bids of LMOs to the Central Market Operator (CMO) for inter community trades, profit of both the LMOs and CMO is maximized by clearing the market prices at the upper-level problem. To prove the validity of the devised model, a set of case studies are created. Moreover, the results suggest that the proposed bi-level model is robust and a remarkable amount of cost savings could be provided by integrating the model.

INDEX TERMS Bi-level optimization, local market, market clearing, optimal bidding strategy, peer-to-peer energy trading.

NOMENCLATURE

The nomenclature for the proposed model is introduced in a detailed way in this section.

Sets

i	Set of communities.
m	Set of peers.
s	Set of scenarios.
t	Set of time intervals.

Parameters

C^{P2P}	Cost coefficient for the local services fee.
$CE^{ESS}_{i,m}$	Charging efficiency of the ESS of peer m in community i.
$CR^{ESS}_{i,m}$	Charging rate of the ESS of peer m in community i [kW].
$DE^{ESS}_{i,m}$	Discharging efficiency of the ESS of peer m in community i.
$DR^{ESS}_{i,m}$	Discharging rate of the ESS of peer m in community i [kW].
K	Sufficiently high constant for Big-M method.
N	Sufficiently high constant for power limiting.
p_s	Probability of scenarios.
$P^{Load}_{i,m,t}$	Demand power of peer m in community i in time t [kW].
$P^{Load,tot}_{i,t}$	Total demand power in community i in time t [kW].
$P^{P2P,buy,net}_{i,m,s,t}$	Net demand power of peer m in community i in scenario s in time t [kW].
$P^{P2P,buy,net,tot}_{i,s,t}$	Total net demand power in community i in scenario s in time t [kW].
$P^{P2P,sell,net}_{i,m,s,t}$	Net produced power of peer m in community i in scenario s in time t [kW].
$P^{P2P,sell,net,tot}_{i,s,t}$	Total net produced power in community i in scenario s in time t [kW].
$P^{PV}_{i,m,s,t}$	Power produced by the PV of peer m in community i in scenario s in time t [kW].

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

$P_{i,s,t}^{PV,tot}$ Total power produced by the PVs in community i in scenario s in time t [kW].

$SoE_{i,m}^{ESS,ini}$ Initial state-of-energy of the ESS of peer m in community i [kWh].

$SoE_{i,m}^{ESS,max}$ Maximum state-of-energy of the ESS of peer m in community i [kWh].

$SoE_{i,m}^{ESS,min}$ Minimum state-of-energy of the ESS of peer m in community i [kWh].

$\lambda_t^{Grid,buy}$ Price of energy bought from the grid in time t [TL/kWh].

$\lambda_t^{Grid,sell}$ Price of energy sold to the grid in time t [TL/kWh].

ΔT Time interval duration [h].

Variables

$P_{i,m,s,t}^{ESS,ch}$ Charging power of the ESS of peer m in community i in scenario s in time t [kW].

$P_{i,s,t}^{ESS,ch,tot}$ Total charging power of the ESSs in community i in scenario s in time t [kW].

$P_{i,m,s,t}^{ESS,dsch}$ Discharging power of the ESS of peer m in community i in scenario s in time t [kW].

$P_{i,s,t}^{ESS,dsch,tot}$ Total discharging power of the ESSs in community i in scenario s in time t [kW].

$P_{i,m,s,t}^{Grid,buy}$ Power bought from the grid by peer m in community i in scenario s in time t [kW].

$P_{i,s,t}^{Grid,buy,tot}$ Total power bought from the grid by community i in scenario s in time t [kW].

$P_{i,m,s,t}^{Grid,sell}$ Power sold to the grid by peer m in community i in scenario s in time t [kW].

$P_{i,s,t}^{Grid,sell,tot}$ Total power sold to the grid by community i in scenario s in time t [kW].

$P_{i,m,s,t}^{P2P,buy,inter}$ Local power bought from community i by peer m in scenario s in time t [kW].

$P_{i,s,t}^{P2P,buy,inter,tot}$ Total local power bought from community i in scenario s in time t [kW].

$P_{i,m,s,t}^{P2P,buy,intra}$ Local power bought in community i by peer m in scenario s in time t [kW].

$P_{i,s,t}^{P2P,buy,intra,tot}$ Total local power bought in community i in scenario s in time t [kW].

$P_{i,m,s,t}^{P2P,sell,inter}$ Local power sold to community i by peer m in scenario s in time t [kW].

$P_{i,s,t}^{P2P,sell,inter,tot}$ Total local power sold to community i in scenario s in time t [kW].

$P_{i,m,s,t}^{P2P,sell,intra}$ Local power sold in community i by peer m in scenario s in time t [kW].

$P_{i,s,t}^{P2P,sell,intra,tot}$ Total local power sold in community i in scenario s in time t [kW].

$SoE_{i,m,s,t}^{ESS}$ State-of-energy of the ESS of peer m in community i in scenario s in time t [kW].

$u_{i,m,s,t}^{BigMx}$ Binary variable for Big-M method: 1 if a variable is positive in time t, 0 else.

$u_{i,s,t}^{BigMy}$ Binary variable for Big-M method: 1 if a variable is positive in time t, 0 else.

$u_{i,s,t}^{Com}$ Binary variable: 1 if community i is consumer in time t, 0 else.

$u_{i,m,s,t}^{ESS}$ Binary variable: 1 if ESS is charging in time t, 0 else.

$u_{i,m,s,t}^{Peer}$ Binary variable: 1 if peer m is consumer in time t, 0 else.

$\beta_{i,s,t}^{x}$ Lagrange multipliers for the inequality constraints of community i.

$\gamma_{i,m,s,t}^{x}$ Lagrange multipliers for the inequality constraints of peer m.

$\lambda_{i,s,t}^{P2P,buy,bid,com}$ Bid price for power bought from community i by LMO in scenario s in time t [TL/kWh].

$\lambda_{i,m,s,t}^{P2P,buy,bid,peer}$ Bid price for power bought in community i by peer m in scenario s in time t [TL/kWh].

$\lambda_{s,t}^{P2P,buy}$ Buying price of local market in scenario s in time t [TL/kWh].

$\lambda_{i,s,t}^{P2P,sell,bid,com}$ Bid price for power sold to community i by LMO in scenario s in time t [TL/kWh].

$\lambda_{i,m,s,t}^{P2P,sell,bid,peer}$ Bid price for power sold in community i by peer m in scenario s in time t [TL/kWh].

$\lambda_{s,t}^{P2P,sell}$ Selling price of local market in scenario s in time t [TL/kWh].

$\lambda_{i,m,s,t}^{x}$ Lagrange multipliers for the equality constraints of peer m.

$\lambda_{i,s,t}^{y}$ Lagrange multipliers for the equality constraints of community i.

I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

RECENTLY, several innovative solutions have been proposed in order to use the energy in an efficient manner. End-users have been becoming a part of the distribution system along with the Peer-to-Peer (P2P) energy trading, which is one of these solutions. Therefore, physical supports to the grid and economic savings for the participants are provided [1]. Carbon emissions can be reduced by increasing self consumption of the renewable energy resources especially photovoltaic (PV) by means of such a new emerging market type [2].

Another point in the P2P trading is to encourage all the participated households in terms of economy. In this context, there are available several regulations and market clearing strategies [3]. Furthermore, new energy management strategies could be introduced to the grid with the aim of mitigating some challenges like voltage drops, increment in power losses, and peak loading [4]-[7]. However, selling excess energy between communities has been playing a key

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

role to ensure the participation of any community which has no generation unit.

B. LITERATURE OVERVIEW

Many studies considering energy scheduling and market clearing strategies for P2P energy trading are available in the literature, and it can be categorized into hierarchical approaches and inter-community trades for this paper in order to clarify literature gaps.

In terms of hierarchical market types and inter-community based researches, Liu et al. [8] proposed a bi-level distributed optimization based energy trading system between PV and schedulable loads equipped participants. Cui et al. [9] propounded both real time operation for intra-community P2P energy trading and day ahead scheduling for inter-community P2P energy trading under two stage approach which includes sharing and market clearing. Nezamabadiet al. [10] suggested arbitrage strategy based non-cooperative game considering risk constraint and uncertainties related to renewable generation and real time market prices. Co-operative game for intra-community and non-cooperative game for inter-community were also considered in the paper. Chen et al. [11] presented intra-region and inter-region P2P trading considering multiple energy sharing regions. Game theory based trading system was designed in the paper also considering dynamic pricing of sharing regions, transmission and distribution usage fees and demand response.

Profit of market operator and participants was increased via game theory in [12]. It was achieved that both self-consumption of PV and encouragement to the P2P are improved by being shifted the responsive demands to the time intervals in which high PV generation is available. Liu et al. [13] supported the P2P energy trading with community energy storage in the proposed bi-level Stackelberg game based model. While daily profit of households were maximized in the lower level problem, profit of market operator was maximized by determining clearing prices in the upper level problem. Total electricity bill under P2P trading and distribution usage fee were minimized by ADMM based distributed optimization in [14]. Although hierarchical managements was realized in [9-11], optimal local prices was not determined considering both intra-community and inter-community trading bids under multi-hierarchical manner. In this regard, even if high amount of energy is traded between via inter-community P2P structure, energy prices will not reach fair level according to the economic manner between supply and demand.

In terms of the works related to various market pricing schemes and strategies, Paudel et al. [15] presented a game theory based model for real time P2P energy trading under game based market clearing. Khorasany et al. [16] achieved to reduce computational challenges in the communication considering both community and decentralized based P2P trading. Impacts of the schedulable and deferrable loads on P2P energy trading was investigated in the genetic algorithm based optimization model in [17]. Supply Demand Ratio (SDR), Mid-market Rate and Bill Sharing pricing mechanisms were also examined and it was observed that SDR method provides by 27%–68% bill reduction. In [18], day ahead scheduling and real time operation were presented as to include two stage. While optimal energy sharing profile was carried out via Alternating Direction Method of Multipliers (ADMM) in the first stage, market prices were cleared based on non-cooperative game theory in the second stage. A novel decentralized optimization model without any controller system operator was developed in [19]. Line capacities were also considered in the bilateral contract pricing based study.

Khorasany et al. [20] developed a novel intraday market in which flexibility and independent pricing strategy is implemented besides minimization of the daily cost in day ahead scheduling. It was observed that higher profit can be gained in the case of integrated market model compared to the case in which only day ahead market is considered. In [21], clearing of both traded energy and reserve energy was carried out for the first time in the model which aims the participation of renewable energy producers. Cui et al. [22], reduced energy cost thanks to the controllable air conditioners and reduced dependency on the grid. Li et al. [23] compared the proposed model with the existing pricing mechanisms in the literature and achieved that increment in the participation ratio as well as economic efficiency. Impact of demand response on P2P trading considering penalty system in the case of deviation from scheduled demand was examined in [24]. It was observed that cost reduction in non-optimization based model is greater than optimization based model which includes day ahead and real time operation.

Among the literature studies mentioned above, although P2P energy trading was carried out in [15]-[17] and in [22]-[24], hierarchical approach, inter-community energy trading and uncertainty were ignored. While hierarchical trading was implemented in [8], [12], and [13], inter-community energy trading was not included. Conversely, inter-community trading was contained in [14]. However, hierarchical system was not comprised. Finally, although hierarchical test system, inter-community energy trading and uncertainty were considered in [9], [10], and [11], bidding strategy for multi-hierarchical energy trading system was not investigated. In this regard, there is a still gap in the literature in terms of evaluation of fair market clearing and bidding strategy which simultaneously consider multi-layer hierarchical bidding strategy, and unpredictable behavior of renewable generation.

C. CONTRIBUTIONS AND ORGANIZATION

In this study, a novel hierarchical bidding strategy for both intra-community and inter-community P2P energy trading is proposed in the mixed-integer linear programming (MILP) based mathematical model. To reveal the effectiveness of the proposed model, a bunch of case studies considering different PV installation powers and ESS capacities are carried out. The main contributions are stated as follows:

1) A novel optimal bidding strategy for multi-hierarchical

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

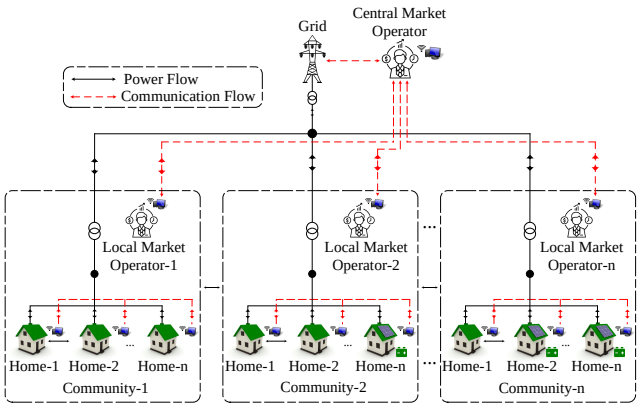


FIGURE 1. The schematic diagram of the proposed energy trading structure

approach considering both intra-community and inter-community P2P energy trading system is proposed for the first time in the literature.

2) A bi-level MILP algorithm is developed, in which while the lower-level aims to minimize the daily electricity bill of households and total bill of communities, upper-level aims to maximize the profit of Local Market Operators (LMO) and Central Market Operator (CMO).
3) The unpredictable profiles of solar irradiation and temperature are considered by generating the scenarios via the historical data.

The remainder of the paper is organized as follows: the proposed trade structure and mathematical model are detailed in Section II. Test results and comments are presented in Section III. Finally, conclusions are evaluated in Section IV.

II. METHODOLOGY

A. OVERVIEW OF THE MULTI COMMUNITIES STRUCTURE

The proposed multi community P2P energy trading structure is shown in Fig. 1. LMO for intra-community energy trading and Central Market Operator CMO for inter-community energy trading, which are manage all the local transactions are available. Furthermore, CMO and Distribution System Operator (DSO) are in communication and coordination in order to manage physical trades and clear market prices. First of all, all participants send their quantity and price bids to the own LMO for intra-community P2P energy trading. After receiving the local bids, all LMOs send excess or deficit energy quantity, and price bids to the CMO as to cumulative after intra-community energy trading. Also, optimal local trading prices are determined by the CMO according to the all energy bids received from LMOs and grid price signals received from DSO. Finally, both participants and LMOs schedule daily consumption profiles along with the determined prices so as to maximize the profits in the hierarchical market structure.

B. MATHEMATICAL FORMULATION

1) Lower Level Problem

Objective of the lower level problem is to minimize total cost for both intra-community and inter-community energy trading. In (1), all households send the quantity ($P^{P2P,buy,intra}_{i,m,s,t}$, $P^{P2P,sell,intra}_{i,m,s,t}$) and price ($\lambda^{P2P,buy,bid,peer}_{i,m,s,t}$, $\lambda^{P2P,sell,bid,peer}_{i,m,s,t}$) bids to the own LMO for intra-community P2P. Apart from, all LMOs simultaneously send the cumulative quantity ($P^{P2P,buy,inter,tot}_{i,s,t}$, $P^{P2P,sell,inter,tot}_{i,s,t}$) and price ($\lambda^{P2P,buy,bid,com}_{i,s,t}$, $\lambda^{P2P,sell,bid,com}_{i,s,t}$) bids to the CMO for inter-community P2P. Furthermore, 0.01 TL/kWh constant service fee is determined as grid sell price (0.3 TL/kWh) divided by the number of total participants (30). It is paid by all the households to the own LMO, and by all the LMOs to the CMO for all the P2P transactions.

$$\begin{aligned} min \sum_i \sum_m \sum_t \sum_s p_s \Big[& (\lambda^{P2P,buy,bid,peer}_{i,m,s,t} + C^{P2P}) \\ & P^{P2P,buy,intra}_{i,m,s,t} - (\lambda^{P2P,sell,bid,peer}_{i,m,s,t} - C^{P2P}) \\ & P^{P2P,sell,intra}_{i,m,s,t} \Big] \Delta T \\ + min \sum_i \sum_t \sum_s p_s \Big[& (\lambda^{P2P,buy,bid,com}_{i,s,t} + C^{P2P}) \\ & P^{P2P,buy,inter,tot}_{i,s,t} - (\lambda^{P2P,sell,bid,com}_{i,s,t} - C^{P2P}) \\ & P^{P2P,sell,inter,tot}_{i,s,t} \Big] \Delta T \end{aligned} \tag{1}$$

Equations (2)-(5) states the bidding constraints of the intra-community and inter-community P2P energy tradings. If a household is a consumer, it can buy the deficit energy after own load and ESS are fed by own PV via intra-community P2P. Similarly, if a household is a prosumer, it can sell the excess energy after own load is fed by own PV and ESS. Similar to the intra-community trading, maximum total energy that can be bought from the P2P by a community is total deficit energy remained after all the load and ESS charge demand are met by all the PV generation and intra-community trading. Furthermore, a community can sell the total excess energy to the another community via inter-community P2P trading after all the load and intra-community P2P demand are met by all the PV generation and ESS.

$$0 \le P^{P2P,buy,intra}_{i,m,s,t} \le P^{P2P,buy,net}_{i,m,s,t} + P^{ESS,ch}_{i,m,s,t}, \quad \forall i,m,s,t : \gamma^1_{i,m,s,t}, \gamma^2_{i,m,s,t} \tag{2}$$

$$0 \le P^{P2P,sell,intra}_{i,m,s,t} \le P^{P2P,sell,net}_{i,m,s,t} + P^{ESS,dsch}_{i,m,s,t}, \quad \forall i,m,s,t : \gamma^3_{i,m,s,t}, \gamma^4_{i,m,s,t} \tag{3}$$

$$0 \le P^{P2P,buy,inter,tot}_{i,s,t} \le P^{P2P,buy,net,tot}_{i,s,t} + P^{ESS,ch,tot}_{i,s,t} - P^{P2P,buy,intra,tot}_{i,s,t}, \quad \forall i,s,t : \beta^1_{i,s,t}, \beta^2_{i,s,t} \tag{4}$$

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

$$0 \leq P^{P2P,sell,inter,tot}_{i,s,t} \leq P^{P2P,sell,net,tot}_{i,s,t} + P^{ESS,dsch,tot}_{i,s,t} - P^{P2P,sell,intra,tot}_{i,s,t}, \quad \forall i,s,t : \beta^3_{i,s,t}, \beta^4_{i,s,t} \tag{5}$$

Equations (6) and (7) define the net energies which consist the difference between load and PV. Also, parameters X and Y represent excess consumption and excess generation, respectively. Finally, cumulative power equations in the bidding constraints are presented in (8)-(15).

$$P^{P2P,buy,net}_{i,m,s,t} = \begin{cases} P^{Load}_{i,m,s,t} - P^{PV}_{i,m,s,t}, (X); & if \;\; X > 0 \\ 0; & if \;\; X \leq 0 \end{cases} \tag{6}$$

$$P^{P2P,sell,net}_{i,m,s,t} = \begin{cases} P^{PV}_{i,m,s,t} - P^{Load}_{i,m,s,t}, (Y); & if \;\; Y > 0 \\ 0; & if \;\; Y \leq 0 \end{cases} \tag{7}$$

$$P^{P2P,buy,net,tot}_{i,s,t} = \sum_m P^{P2P,buy,net}_{i,m,s,t}, \quad \forall i,s,t \tag{8}$$

$$P^{P2P,sell,net,tot}_{i,s,t} = \sum_m P^{P2P,sell,net}_{i,m,s,t}, \quad \forall i,s,t \tag{9}$$

$$P^{ESS,ch,tot}_{i,s,t} = \sum_m P^{ESS,ch}_{i,m,s,t}, \quad \forall i,s,t \tag{10}$$

$$P^{ESS,dsch,tot}_{i,s,t} = \sum_m P^{ESS,dsch}_{i,m,s,t}, \quad \forall i,s,t \tag{11}$$

$$P^{P2P,buy,intra,tot}_{i,s,t} = \sum_m P^{P2P,buy,intra}_{i,m,s,t}, \quad \forall i,s,t \tag{12}$$

$$P^{P2P,sell,intra,tot}_{i,s,t} = \sum_m P^{P2P,sell,intra}_{i,m,s,t}, \quad \forall i,s,t \tag{13}$$

$$P^{P2P,buy,inter,tot}_{i,s,t} = \sum_m P^{P2P,buy,inter}_{i,m,s,t}, \quad \forall i,s,t \tag{14}$$

$$P^{P2P,sell,inter,tot}_{i,s,t} = \sum_m P^{P2P,sell,inter}_{i,m,s,t}, \quad \forall i,s,t \tag{15}$$

Constraints (16)-(17) impose limits on the charging and discharging power of the ESS. Furthermore, ESS cannot charge and discharge simultaneously by means of the binary variable ($u^{ESS}_{i,m,s,t}$). Constraint (18) states the boundaries of the SoE level. ESS cannot be charged greater than maximum capacity and discharged lower than minimum capacity to avoid deep discharge. While equation (19) states the general energy balance of the ESS, initial SoE level is indicated in (20).

$$0 \leq P^{ESS,ch}_{i,m,s,t} \leq CR^{ESS}_{i,m}.u^{ESS}_{i,m,s,t}, \quad \forall i,m,s,t : \gamma^5_{i,m,s,t}, \gamma^6_{i,m,s,t} \tag{16}$$

$$0 \leq P^{ESS,dsch}_{i,m,s,t} \leq DR^{ESS}_{i,m}.(1 - u^{ESS}_{i,m,s,t}), \quad \forall i,m,s,t : \gamma^7_{i,m,s,t}, \gamma^8_{i,m,s,t} \tag{17}$$

$$SoE^{ESS,min}_{i,m} \leq SoE^{ESS}_{i,m,s,t} \leq SoE^{ESS,max}_{i,m}, \forall i,m,s,t : \gamma^9_{i,m,s,t}, \gamma^{10}_{i,m,s,t} \tag{18}$$

$$SoE^{ESS}_{i,m,s,t} = SoE^{ESS}_{i,m,s,t-1} + (P^{ESS,ch}_{i,m,s,t}.CE^{ESS}_{i,m}.\Delta T) - (\frac{P^{ESS,dsch}_{i,m,s,t}}{DE^{ESS}_{i,m}}.\Delta T), \quad \forall i,m,s,t > 1 : \lambda^1_{i,m,s,t} \tag{19}$$

$$SoE^{ESS}_{i,m,s,t} = SoE^{ESS,ini}_{i,m}, \quad \forall i,m,s,t = 1 \tag{20}$$

In (21) and (22), while general energy balances of a household and a community are shown, PV, load, and power bought from and to the grid which take part in the balance of community are stated in (23)-(26) as cumulative powers.

$$P^{Grid,buy}_{i,m,s,t} + P^{PV}_{i,m,s,t} + P^{ESS,dsch}_{i,m,s,t} + P^{P2P,buy,intra}_{i,m,s,t} + P^{P2P,buy,inter}_{i,m,s,t} = P^{Load}_{i,m,s,t} + P^{ESS,ch}_{i,m,s,t} + P^{P2P,sell,intra}_{i,m,s,t} + P^{P2P,sell,inter}_{i,m,s,t} + P^{Grid,sell}_{i,m,s,t}, \quad \forall i,m,s,t : \lambda^{P2P,buy}_{s,t}, \lambda^{P2P,sell}_{s,t} \tag{21}$$

$$P^{Grid,buy,tot}_{i,s,t} + P^{PV,tot}_{i,s,t} + P^{ESS,dsch,tot}_{i,s,t} + P^{P2P,buy,intra,tot}_{i,s,t} + P^{P2P,buy,inter,tot}_{i,s,t} = P^{Load,tot}_{i,s,t} + P^{ESS,ch,tot}_{i,s,t} + P^{P2P,sell,intra,tot}_{i,s,t} + P^{P2P,sell,inter,tot}_{i,s,t} + P^{Grid,sell,tot}_{i,s,t}, \quad \forall i,s,t : \lambda^{P2P,buy}_{s,t}, \lambda^{P2P,sell}_{s,t} \tag{22}$$

$$P^{PV,tot}_{i,s,t} = \sum_m P^{PV}_{i,m,s,t}, \quad \forall i,s,t \tag{23}$$

$$P^{Load,tot}_{i,s,t} = \sum_m P^{Load}_{i,m,s,t}, \quad \forall i,s,t \tag{24}$$

$$P^{Grid,buy,tot}_{i,s,t} = \sum_m P^{Grid,buy}_{i,m,s,t}, \quad \forall i,s,t \tag{25}$$

$$P^{Grid,sell,tot}_{i,s,t} = \sum_m P^{Grid,sell}_{i,m,s,t}, \quad \forall i,s,t \tag{26}$$

2) Upper Level Problem

Objective of the upper level problem is to maximize the profit of both LMOs and CMO. In (27), while LMOs aim to gain profit in the intra-community P2P via arbitrage strategy, CMO aims to gain profit in the inter-community trade similarly. LMOs minimize power bought from the grid and maximize power sold to the grid for all the own households. Furthermore, LMOs take constant service fee (C^{P2P}) per local trade from the households.

$$\begin{aligned} max \sum_i \sum_m \sum_t \sum_s p^s.\Big[& (\lambda^{P2P,buy}_{s,t}.P^{P2P,buy,intra}_{i,m,s,t} + \lambda^{Grid,sell}_t.P^{Grid,sell}_{i,m,s,t}) + C^{P2P}.(P^{P2P,buy,intra}_{i,m,s,t} + P^{P2P,buy,inter}_{i,m,s,t} + P^{P2P,sell,intra}_{i,m,s,t} + P^{P2P,sell,inter}_{i,m,s,t}) \\ & - (\lambda^{P2P,sell}_{s,t}.P^{P2P,sell,intra}_{i,m,s,t} - \lambda^{Grid,buy}_t.P^{Grid,buy}_{i,m,s,t}) \Big].\Delta T \\ + max \sum_i \sum_t \sum_s p^s.\Big[& (\lambda^{P2P,buy}_{s,t}.P^{P2P,buy,inter,tot}_{i,s,t}) - (\lambda^{P2P,sell}_{s,t}.P^{P2P,sell,inter,tot}_{i,s,t}) \Big].\Delta T \end{aligned} \tag{27}$$

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

Equations (28) and (29) present the P2P trading balances for intra-community and inter-community, respectively. All the power bought from the P2P ($P^{P2P,buy,intra}_{i,m,s,t}$, $P^{P2P,buy,inter,tot}_{i,m,s,t}$) must be equal to the power sold to the P2P ($P^{P2P,sell,intra}_{i,m,s,t}$, $P^{P2P,buy,inter,tot}_{i,m,s,t}$) at time t.

$$\sum_{m} P^{P2P,buy,intra}_{i,m,s,t} = \sum_{m} P^{P2P,sell,intra}_{i,m,s,t}, \quad \forall i,s,t \quad (28)$$

$$\sum_{i} P^{P2P,buy,inter,tot}_{i,s,t} = \sum_{i} P^{P2P,sell,inter,tot}_{i,s,t}, \quad \forall s,t \quad (29)$$

Equations (30)-(33) impose a limit on the total power bought and sold for both each household and community. Also, a household and a community cannot be consumer and producer at the same time t via binary variables ($u^{Peer}_{i,m,s,t}$, $u^{Com}_{i,s,t}$).

$$P^{Grid,buy}_{i,m,s,t} + P^{P2P,buy,intra}_{i,m,s,t} + P^{P2P,buy,inter}_{i,m,s,t} \leq N.u^{Peer}_{i,m,s,t}, \quad \forall i,m,s,t \quad (30)$$

$$P^{Grid,sell}_{i,m,s,t} + P^{P2P,sell,intra}_{i,m,s,t} + P^{P2P,sell,inter}_{i,m,s,t} \leq N.(1-u^{Peer}_{i,m,s,t}), \forall i,m,s,t \quad (31)$$

$$P^{Grid,buy,tot}_{i,s,t} + P^{P2P,buy,intra,tot}_{i,s,t} + P^{P2P,buy,inter,tot}_{i,s,t} \leq N.u^{Com}_{i,s,t}, \quad \forall i,s,t \quad (32)$$

$$P^{Grid,sell,tot}_{i,s,t} + P^{P2P,sell,intra,tot}_{i,s,t} + P^{P2P,sell,inter,tot}_{i,s,t} \leq N.(1-u^{Com}_{i,s,t}), \quad \forall i,s,t \quad (33)$$

Constraints of the optimal local trading prices are stated in (34). Both buying and selling prices should be between grid prices in order to encourage the participants. Furthermore, since the local buying price is the buying price of the households while it is the selling price of the market operator, local selling price should be lower than local buying price in order to avoid any loss in the profit of operators.

$$\lambda^{Grid,sell}_{t} \leq \lambda^{P2P,sell}_{s,t} \leq \lambda^{P2P,buy}_{s,t} \leq \lambda^{Grid,buy}_{t}, \forall s,t \quad (34)$$

Finally, Lagrange function is created as indicated in (35). Karush-Kuhn-Tucker optimality conditions as in [25] and Big-M linearization method as in [26] are used in an attempt to solve the bi-level model, and are shown as simplified form in (36) and (37), respectively. Furthermore, strong duality theorem as in [27] is adopted to linearize bilinear terms in the objective function of the upper level problem, and is obtained as demonstrated in (38).

$$L = f(x) + \gamma^{x}_{i,m,s,t}(\beta^{x}_{i,s,t}).g(x) + \lambda^{x}_{i,m,s,t}.h(x) \quad (35)$$

Here, $f(x)$, $g(x)$ and $h(x)$ are the objective function, the inequality constraints, and the equality constraints of lower level problem, respectively. $\gamma^{x}_{i,m,s,t}$, $\beta^{x}_{i,s,t}$ and $\lambda^{x}_{i,m,s,t}$ state the Lagrange multipliers related to the constraints.

$$(0 \leq P^{P2P,buy,intra}_{i,m,s,t}) \perp (0 \leq \gamma^{1}_{i,m,s,t}), \quad \forall i,m,s,t \quad (36)$$

$$\begin{pmatrix} P^{P2P,buy,intra}_{i,m,s,t} \geq 0 \\ \gamma^{1}_{i,m,s,t} \geq 0 \\ P^{P2P,buy,intra}_{i,m,s,t} \leq K.u^{BigM1}_{i,m,s,t} \\ \gamma^{1}_{i,m,s,t} \leq K.(1-u^{BigM1}_{i,m,s,t}), \quad \forall i,m,s,t \end{pmatrix} \quad (37)$$

In (37), the constraint ($P^{P2P,buy,intra}_{i,m,s,t}$) and related multiplier ($\gamma^{1}_{i,m,s,t}$) must be greater than or equal to zero, and must be separated from each other via binary variable ($u^{BigM1}_{i,m,s,t}$).

$$\begin{aligned} &\lambda^{P2P,buy}_{s,t}.P^{P2P,buy,intra}_{i,m,s,t} - \lambda^{P2P,sell}_{s,t}.P^{P2P,sell,intra}_{i,m,s,t} = \\ &- P^{P2P,buy,net}_{i,m,s,t}.\gamma^{2}_{i,m,s,t} - P^{P2P,sell,net}_{i,m,s,t}.\gamma^{4}_{i,m,s,t} \\ &- CR^{ESS}_{i,m}.\gamma^{6}_{i,m,s,t} - DR^{ESS}_{i,m}.\gamma^{8}_{i,m,s,t} \\ &+ SoE^{ESS,min}_{i,m}.\gamma^{9}_{i,m,s,t} - SoE^{ESS,max}_{i,m}.\gamma^{10}_{i,m,s,t} \\ &+ (\lambda^{P2P,buy}_{s,t}; \lambda^{P2P,sell}_{s,t}).(P^{Load}_{i,m,s,t} - P^{PV}_{i,m,s,t}) \end{aligned}$$

$$\begin{aligned} &\lambda^{P2P,buy}_{s,t}.P^{P2P,buy,inter,tot}_{i,s,t} - \lambda^{P2P,sell}_{s,t}.P^{P2P,sell,inter,tot}_{i,s,t} = \\ &- P^{P2P,buy,net,tot}_{i,s,t}.\beta^{2}_{i,m,s,t} - P^{P2P,sell,net,tot}_{i,s,t}.\beta^{4}_{i,s,t} \\ &+ (\lambda^{P2P,buy}_{s,t}; \lambda^{P2P,sell}_{s,t}).(P^{Load,tot}_{i,s,t} - P^{PV,tot}_{i,s,t}) \end{aligned} \quad (38)$$

C. MODELLING OF THE UNCERTAINTIES RELATED TO PV GENERATION

PV power generation has uncertain parameters such as irradiance and temperature. One minute resolution irradiance and temperature data belong to the 30 days of September in 2018-2020 are obtained from National Renewable Energy Laboratory [28]. Afterwards, 10 scenarios consisting irradiance and temperature data are generated via probability density function of Truncated Normal Distribution by using MATLAB [29] as shown in (39).

$$f(x;\mu,\sigma,a,b) = \frac{1}{\sigma}.\frac{\phi.\frac{(x-\mu)}{\sigma}}{\Phi.\frac{(b-\mu)}{\sigma} - \Phi.\frac{(a-\mu)}{\sigma}} \quad (39)$$

Here, μ is mean value of each time interval, σ is standard deviation, ϕ is probability density function of the standard normal distribution and Φ is the cumulative distribution function. Furthermore, truncation ranges (a, b) are implemented to the function under the doubly truncated case since infinity boundaries in normal distribution cause deviation in the desired data generation. Thus, probability generation for each time interval can be determined between the minimum and maximum values of the input data. In addition, 30 household profiles in total for three community are generated probabilistically by referencing consumption profile of a smart home belong to the 30 days of September in 2007-2010 [30].

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

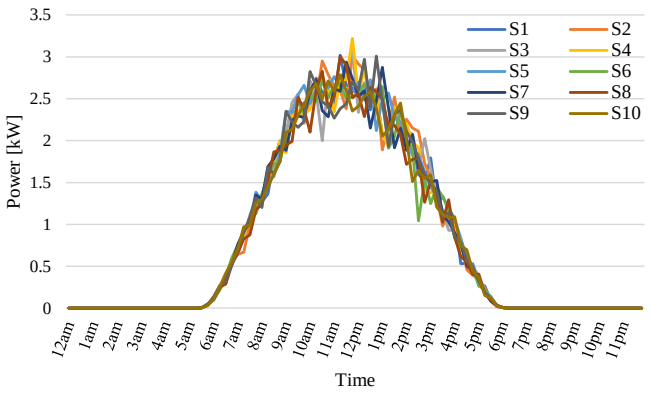


FIGURE 2. Scenarios of PV Generation

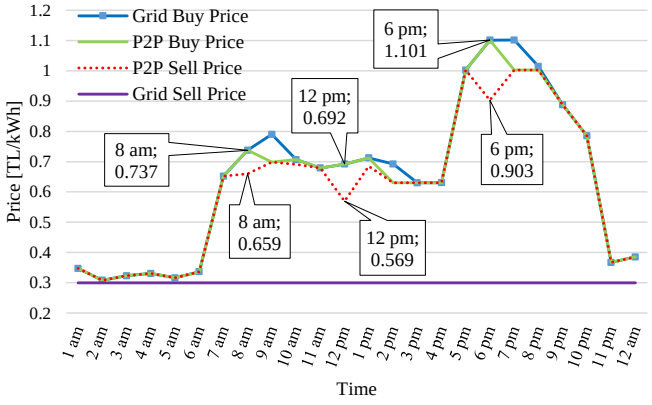


FIGURE 3. Market prices of Community-2 for Scenario-5 in Case-1

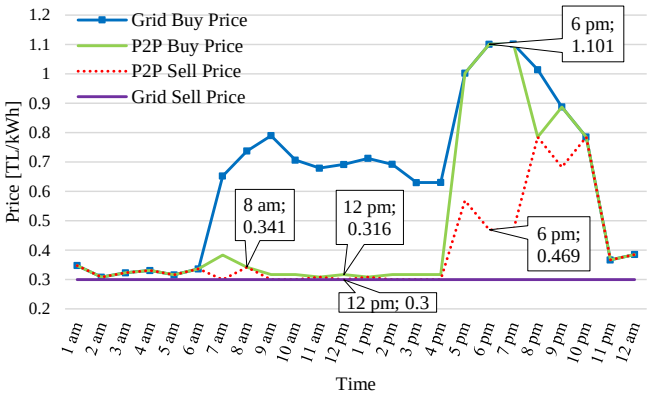


FIGURE 4. Market prices of Community-3 for Scenario-5 in Case-1

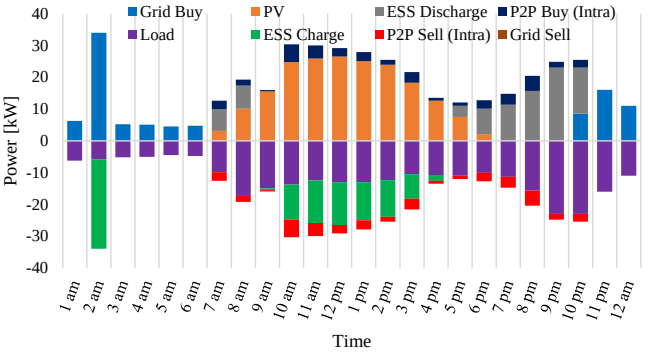


FIGURE 5. Power balance of Community-3 for Scenario-5 in Case-1

III. TEST AND RESULTS

A. INPUT DATA

Consumption profiles of the 30 households placing in 3 communities are randomly generated by referencing daily and yearly consumption dataset obtained from [30]. All households in the Community-1 are consumers which have no PV and ESS. While 5 consumers and 5 prosumers are situated in the Community-2, all the 10 households are prosumers in the Community-3. It is assumed that all the PV and ESS capacities are 4 kW and 10 kWh, respectively for Case-1 and Case-2. Furthermore, capacities of PV and ESS for Case-3 are randomly generated between the boundaries [3,6] kW and [5,15] kWh, respectively. The probabilistically generated PV power scenarios are depicted in Fig. 2.

B. SIMULATION AND RESULTS

The proposed model is implemented in GAMS [31] v.24.1.3 and is solved using the commercial solver CPLEX v.12. Furthermore, three different case studies are examined to prove the effectiveness of the model as follows:

- ***Case-1***: Intra-community P2P without inter-community P2P.
- ***Case-2***: Intra-community and inter-community P2P with same capacities of PVs and ESSs.
- ***Case-3***: Intra-community and inter-community P2P with various capacities of PVs and ESSs.

Only intra-community P2P trading under the management of LMOs is taken into account in the Case-1. In the Case-2, both intra-community and inter-community P2P are examined assuming that all the participants have same PV and ESS capacities. Furthermore, both intra-community and inter-community P2P with various capacities of PVs and ESSs is considered in Case-3 in order to investigate the impact of different investments on the market conditions. In Case-1, it should be noted that LMO-1 equalize the local prices to the grid buy price to avoid loss of the profit since no energy trading in Community-1 is available. Local clearing prices of Community-2 and Community-3 for Scenario-5 in Case-1 are depicted in Fig. 3 and 4, respectively. While prices in Community-2 are high because of the equal number of prosumers and consumers, prices in Community-3 which consists entirely of prosumers are determined lower because of the excessive energy. Furthermore, while P2P trading is provided with the green PV generation at the noon time intervals, it is carried out by the ESSs which are external power suppliers at the peak time intervals as can be seen from the power balance of Community-3 in Fig 5. Thus, market prices at the peak time intervals are reduced lower compared to the noon time intervals. The profit of LMO-1 is zero due to the no transaction in Community-1 and CMO cannot get any profit since do not include in the hierarchical bidding system in the

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

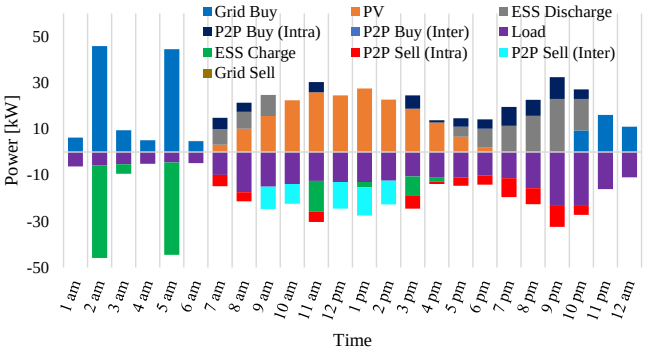


FIGURE 6. Power balance of Community-3 for Scenario-9 in Case-2

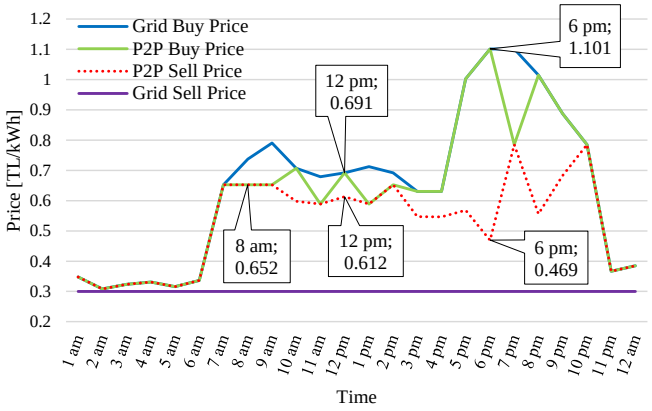


FIGURE 7. Market prices for Scenario-9 in Case-2

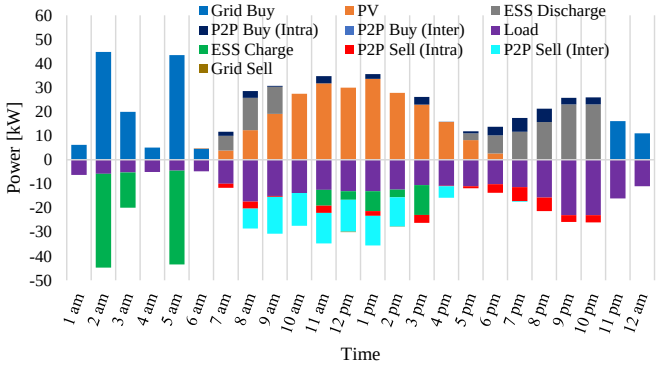


FIGURE 8. Power balance of Community-3 for Scenario-9 in Case-3

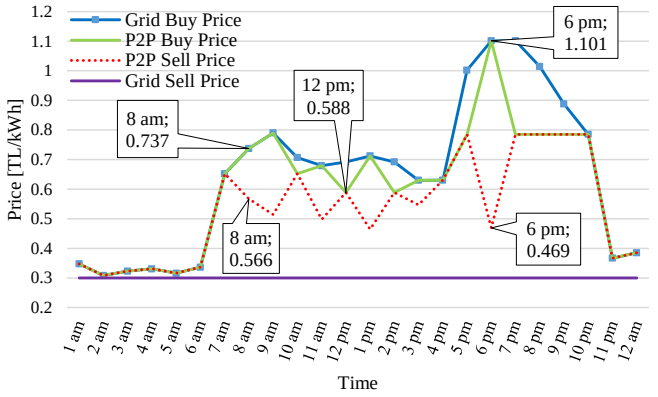


FIGURE 9. Market prices for Scenario-9 in Case-3

Case-1. Also, LMO-2 and LMO-3 get profit as 3.041 TL and 3.873 TL, respectively. Power balance of the Community-3 for Scenario-9 in Case-2 is demonstrated in Fig. 6. Apart from the Case-1, ESSs drawn more power from the grid at 3 am and 5 am which are the lowest price intervals after 2 am in order to participate inter-community P2P trading. Thus, since PV generation at the noon is used for both intra-community and inter-community instead of storing, grid is supported by increasing the capacity of P2P trading with ESSs at the peak time intervals. Optimal buying and selling prices for Scenario-9 in Case-2 is shown in Fig. 7. Furthermore, since all the communities are considered together in the multi-hierarchical system in this case, while Community-3 reduces the local prices, Community-1 and Community-2 rise the prices at the same time. It can be seen that jointly announced local prices to all the communities are determined between the prices of two different communities in Case-1. On the other hand, it is worthy to state that Community-2 has loss in the profit because joint selling price in Case-2 is lower than specific selling price in Case-1. The profits of LMO-1, LMO-2 and LMO-3 are 0.529 TL, 12.153 TL and 6.715 TL, respectively. CMO can also get profit as 4.534 TL from the inter-community P2P via arbitrage strategy.

The power balance of the Community-3 for Scenario-9 in Case-3 is presented in Fig. 8. It can be seen from the figure that ESSs trend to charge more as a result of randomly PV and ESS capacity generation. Furthermore, while intra-community P2P trading for Community-2 and Community-3 decreases due to the increased self sufficiency ratio, inter-community P2P trading also rises. Thus, it is observed that decrement in the total cost of all the communities is available. On the other hand, cost reduction of Community-2 and Community-3 causes loss in the profit of LMO-2 and LMO-3 as expected. However, profit of the LMO-1 and CMO rises in each case since play active role in only inter-community trade. Local clearing prices for Scenario-9 in Case-3 are depicted in Fig. 9. It can be seen that local selling prices in Case-3 slightly lower than Case-2's because of the increased capacities.

For instance, while selling prices at 8 am and 12 pm for Case-2 are 0.652 TL and 0.612 TL, respectively, they are determined as 0.566 TL and 0.588 TL for Case-3, respectively. The profits of LMO-1, LMO-2, LMO-3 and CMO are 0.922 TL, 10.796 TL, 4.999 TL and 8.549 TL in Case-3, respectively. It is observed that total bill cost for Case-1, Case-2 and Case-3 is obtained as 348.716 TL, 333.759 TL and 295.706 TL, respectively. According to the results obtained from the bi-level MILP based model, cost saving by %15 in Case-3 compared to Case-1 is achieved.

Finally, amount of traded energy in best and worst scenario, and cost of communities and profit of LMOs and CMO for each case are shared with Table 1 and Table 2, respectively. Traded energy in best scenarios for both inter-community based cases increases compared to the worst

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

TABLE 1. Amount of traded energy for best and worst scenarios

Energy [kWh]	Best Scenario	Worst Scenario
Case-1	111.38	93.81
Case-2	176.68	144.14
Case-3	197.19	181.71

TABLE 2. Cost of communities and profit of operators for each case

Cost/Profit [TL]	Case-1	Case-2	Case-3
Community-1	199.489	189.581	186.911
Community-2	108.102	114.403	107.004
Community-3	41.125	29.775	1.791
LMO-1	0	0.529	0.922
LMO-2	3.041	12.153	10.796
LMO-3	3.873	6.715	4.999
CMO	-	4.534	8.549

scenarios. However, total trade volume in Case-3 is more than Case-2 regardless of the scenarios because of the increment in PV and ESS capacities. Furthermore, total energy for all the scenarios in Case-2 and Case-3 is greater than Case-1 since ESS units trend to drawn more power from the grid at the low price time intervals in order to participate inter-community energy trading. On the other hand, different capacity investments and uncertainties in PV generation influence daily bill cost and market conditions as can be seen from the results. Thus, the profit of the operators changes depending the amount of traded energy and the market clearing prices. Another important point is that Community-2 has loss in the profit unexpectedly because joint selling price in Case-2 is lower than specific selling price in Case-1.

IV. CONCLUSION

In this study, a novel multi-hierarchical bidding strategy for P2P energy trading considering both intra-community and inter-community energy trading was proposed. According to the results obtained from the bi-level MILP based model, while total cost saving of communities was achieved by 15%, Community-1, Community-2 and Community-3 separately got decrement in the cost by 6.31%, 1.01%, and 95.64%, respectively.

The results in terms of both economic and energy showed that inter-community P2P trading provides some advantages to the households and power system since trading with the grid during the off peak periods and P2P trading during the on peak periods are significantly increased. Furthermore, it was observed that optimal buying and selling prices are influenced by the number of participants and installed capacities of PV and ESS units. Thus, households gained more profit in case of high investment capacities compared to both intra-community based case and low investment based case. However, while local operators had loss in the profits, CMO increased the benefit as a result of hierarchical opposite situation as expected. As future extension of this work, impact of P2P energy trading on the coordination between Transmission System Operator and DSO will be investigated.

REFERENCES

[1] W. Tushar, T. K. Saha, C. Yuen, D. Smith and H. V. Poor, "Peer-to-Peer Trading in Electricity Networks: An Overview" in IEEE Transactions on Smart Grid, vol. 11, no. 4, pp. 3185-3200, July 2020, doi: 10.1109/TSG.2020.2969657.

[2] J. M. Zepter, A. Lüth, P. C. del Granado and R. Egging, "Prosumer integration in wholesale electricity markets: Synergies of peer-to-peer trade and residential storage", Energy and Buildings, vol. 184, pp. 163-176, 2019, doi: 10.1016/j.enbuild.2018.12.003.

[3] J. Li, Y. Ye, D. Papadaskalopoulos and G. Strbac, "Computationally Efficient Pricing and Benefit Distribution Mechanisms for Incentivizing Stable Peer-to-Peer Energy Trading," in IEEE Internet of Things Journal, vol. 8, no. 2, pp. 734-749, 15 Jan.15, 2021, doi: 10.1109/JIOT.2020.3007196.

[4] M. I. Azim, W. Tushar and T. K. Saha, "Coalition Graph Game-based P2P Energy Trading with Local Voltage Management," in IEEE Transactions on Smart Grid, doi: 10.1109/TSG.2021.3070160.

[5] F. Moret, A. Tosatto, T. Baroche and P. Pinson, "Loss Allocation in Joint Transmission and Distribution Peer-to-Peer Markets," in IEEE Transactions on Power Systems, vol. 36, no. 3, pp. 1833-1842, May 2021, doi: 10.1109/TPWRS.2020.3025391.

[6] L. Chen, N. Liu, C. Li, S. Zhang and X. Yan, "Peer-to-peer energy sharing with dynamic network structures", Applied Energy, vol. 291, pp. 116831, 2021, doi: 10.1016/j.apenergy.2021.116831.

[7] W. Tushar et al., "Grid Influenced Peer-to-Peer Energy Trading," in IEEE Transactions on Smart Grid, vol. 11, no. 2, pp. 1407-1418, March 2020, doi: 10.1109/TSG.2019.2937981.

[8] N. Liu, X. Yu, C. Wang, C. Li, L. Ma, J. Lei, "Energy-sharing model with price-based demand response for microgrids of peer-to-peer prosumers," IEEE Transactions on Power Systems, vol. 32, no. 5, pp. 3569–3583, 2017. DOI: 10.1109/TPWRS.2017.2649558.

[9] S. Cui, Y. W. Wang, Y. Shi, J. W. Xiao, "An efficient peer-to-peer energy-sharing framework for numerous community prosumers," IEEE Transactions on Industrial Informatics, vol. 16, no. 12, pp. 7402–7412, 2020. DOI: 10.1109/TII.2019.2960802.

[10] H. Nezamabadi and V. Vahidinasab, "Arbitrage Strategy of Renewable-Based Microgrids via Peer-to-Peer Energy-Trading," in IEEE Transactions on Sustainable Energy, vol. 12, no. 2, pp. 1372-1382, April 2021, doi: 10.1109/TSTE.2020.3045216.

[11] L. Chen, N. Liu and J. Wang, "Peer-to-Peer Energy Sharing in Distribution Networks With Multiple Sharing Regions," in IEEE Transactions on Industrial Informatics, vol. 16, no. 11, pp. 6760-6771, Nov. 2020, doi: 10.1109/TII.2020.2974023.

[12] L. Chen, N. Liu, C. Li and J. Wang, "Peer-to-Peer Energy Sharing With Social Attributes: A Stochastic Leader–Follower Game Approach," in IEEE Transactions on Industrial Informatics, vol. 17, no. 4, pp. 2545-2556, April 2021, doi: 10.1109/TII.2020.2999328.

[13] N. Liu, M. Cheng, X. Yu, J. Zhong and J. Lei, "Energy-Sharing Provider for PV Prosumer Clusters: A Hybrid Approach Using Stochastic Programming and Stackelberg Game," in IEEE Transactions on Industrial Electronics, vol. 65, no. 8, pp. 6740-6750, Aug. 2018, doi: 10.1109/TIE.2018.2793181.

[14] T. Baroche, P. Pinson, R. L. G. Latimier, H. B. Ahmed, "Exogenous cost allocation in peer-to-peer electricity markets," IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 2553–2564, 2019. DOI: 10.1109/TPWRS.2019.2896654.

[15] A. Paudel, K. Chaudhari, C. Long, H. B. Gooi, "Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model," IEEE Transactions on Industrial Electronics, vol. 66, no. 8, pp. 6087–6097, 2019. DOI: 10.1109/TIE.2018.2874578.

[16] M. Khorasany, Y. Mishra, B. Babaki, G. Ledwich, "Enhancing scalability of peer-to-peer energy markets using adaptive segmentation method," Journal of Modern Power Systems and Clean Energy, vol. 7, no. 7, pp. 791–801, 2019. DOI: 10.1007/s40565-019-0510-0.

[17] B. Hanumantha Rao, S. L. Arun, M. P. Selvan, "An electric power trading framework for smart residential community in smart cities," IET Smart Cities, vol. 1, no. 2, pp. 40–51, 2019. DOI: 10.1049/iet-smc.2019.0055.

[18] S. Cui, Y. W. Wang, J. W. Xiao, "Peer-to-peer energy sharing among smart energy buildings by distributed transaction," IEEE Transactions on Smart Grid, vol. 10, no. 6, pp. 6491–6501, 2019. DOI: 10.1109/TSG.2019.2906059.

[19] M. Khorasany, Y. Mishra, G. Ledwich, "A decentralized bilateral energy trading system for peer-to-peer electricity markets," IEEE Transactions on Industrial Electronics, vol. 67, no. 6, pp. 4646–4657, 2020. DOI: 10.1109/TIE.2019.2931229.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3154393, IEEE Access

[20] M. Khorasany, A. Najafi-Ghalelou and R. Razzaghi, "A Framework for Joint Scheduling and Power Trading of Prosumers in Transactive Markets," in IEEE Transactions on Sustainable Energy, vol. 12, no. 2, pp. 955-965, April 2021, doi: 10.1109/TSTE.2020.3026611.

[21] 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," in IEEE Transactions on Smart Grid, vol. 12, no. 1, pp. 798-809, Jan. 2021, doi: 10.1109/TSG.2020.3019603.

[22] S. Cui, Y. -W. Wang, Y. Shi and J. -W. Xiao, "A New and Fair Peer-to-Peer Energy Sharing Framework for Energy Buildings," in IEEE Transactions on Smart Grid, vol. 11, no. 5, pp. 3817-3826, Sept. 2020, doi: 10.1109/TSG.2020.2986337.

[23] J. Li, Y. Ye, D. Papadaskalopoulos and G. Strbac, "Computationally Efficient Pricing and Benefit Distribution Mechanisms for Incentivizing Stable Peer-to-Peer Energy Trading," in IEEE Internet of Things Journal, vol. 8, no. 2, pp. 734-749, 15 Jan.15, 2021, doi: 10.1109/JIOT.2020.3007196.

[24] Rao, B. H., Arun, S. L., Selvan, M. P. (2020). Framework of locality electricity trading system for profitable peer-to-peer power transaction in locality electricity market. IET Smart Grid, 3(3), 318–330, doi.org/10.1049/iet-stg.2019.0131

[25] A. Taşcıkaraoğlu, N. G. Paterakis, O. Erdinç and J. P. S. Catalão, "Combining the Flexibility From Shared Energy Storage Systems and DLC-Based Demand Response of HVAC Units for Distribution System Operation Enhancement," in IEEE Transactions on Sustainable Energy, vol. 10, no. 1, pp. 137-148, Jan. 2019, doi: 10.1109/TSTE.2018.2828337.

[26] E. G. Kardakos, C. K. Simoglou and A. G. Bakirtzis, "Optimal Offering Strategy of a Virtual Power Plant: A Stochastic Bi-Level Approach," in IEEE Transactions on Smart Grid, vol. 7, no. 2, pp. 794-806, March 2016, doi: 10.1109/TSG.2015.2419714.

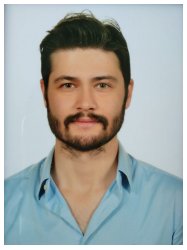
[27] Conejo, A., Castillo, E., Bertrand, R.G.: 'Decomposition techniques in mathematical programming' (Springer, New York, NY, USA, 2006).

[28] National Renewable Energy Laboratory, https://midcdmz.nrel.gov/, Online access: 23 March 2021.

[29] MATLAB, Version 7.10.0 (R2021a). Natick, Massachusetts, MA, USA: The MathWorks Inc., 2021.

[30] Kaggle: Your Machine Learning and Data Science Community, https://www.kaggle.com/uciml/electric-power-consumption-data-set/version/1, Online access: 23 March 2021.

[31] General Algebraic Modeling System (GAMS), https://www.gams.com/latest/docs/UG_MAIN.html



TAYFUR GOKCEK (S'20) received the B.Sc. and M. Sc. degrees from Yildiz Technical University (YTU), Istanbul, Turkey, in 2019 and 2021, respectively. He is presently a Research Assistant with the Department of Electrical Engineering (YTU). His research interests are local electricity markets, renewable energy systems, electric vehicles and power system operation within the smart grid technologies.

IBRAHIM SENGOR (S'15–M'19) received the B.Sc. degree from Istanbul Technical University (ITU), M.Sc. and Ph.D. degrees from Yıldız Technical University (YTU), İstanbul, Turkey all in Electrical Engineering in 2013, 2016, and 2019 respectively. By the way, he was working as a Research and Teaching Assistant at the Electrical Engineering Department of YTU between 2013-2020. He has been working as an Assistant Professor at the Electrical Electronics Engineering Department of Izmir Katip Celebi University since March 2020. He is currently Head of the Electric Power Systems Division with the Department of Electrical and Electronics Engineering (IKCU). Dr. Şengör has joined the MaREI Centre/Envionmental Research Institute at University College Cork (UCC) as a Postdoctoral Researcher as of June 2021. His research interests include grid integration of electric vehicles, renewable energy systems, and power system operation within the smart grid concept.

OZAN ERDINC (M'14—SM'16) received the B.Sc., M. Sc., and Ph.D. degrees from Yildiz Technical University (YTU), Istanbul, Turkey, in 2007, 2009, and 2012, respectively. Until May 2013, he was in the private sector in different positions including electrical installations, renewable energy investments, and as a procurement expert. In June 2013, he became a Postdoctoral Fellow in Portugal, under the EU-FP7 funded SINGULAR Project. He is currently a Full Professor at the the Department of Electrical Engineering, YTU. He is currently IEEE Power and Energy Society (PES) Turkey Chapter Chair, the Head of IT Department of YTU, the Director of Energy Application and Research Center of YTU and Head of Alternative Energy Based Electric Systems Division at the Department of Electrical Engineering (YTU). Prof. Erdinç was the recipient of the *Turkish Science Academy Distinguished Young Scientist Award (TUBA GEBIP)* of 2020. Prof. Erdinç is an Editor for the *IEEE Transactions on Sustainable Energy, IEEE Power Engineering Letters, IEEE Open Access Journal of Power and Energy, Turkish Journal of Electrical Engineering Computer Sciences* and an Associate Editor for the *IEEE Access, IEEE Systems Journal, IET Smart Grid, IET Renewable Power Generation*, and *IET Generation, Transmission&Distribution*.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/