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Local energy communities with strategic behavior of multi-energy players for peer-to-peer trading: A techno-economic assessment

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ABSTRACT

Peer-to-peer (P2P) energy trading for profit-driven communities in distribution networks (DNs) has become increasingly critical in terms of economic view especially in the absence of supportive subsidies for renewable generation. However, the risk behavior of local energy communities (LECs), as well as their inherent flexibility options, can affect the profit achieved through local energy trading. This paper seeks to carefully examine to what extent the aforementioned factors contribute to the economic value of P2P energy trading for LECs. To do this, a mathematical model is developed as a multi-leader–multi-follower game which is formulated as equilibrium problems with equilibrium constraints (EPEC). In this game, operators of different LECs are leaders while the market operator who is in charge of clearing the local community market and the distribution system operator (DSO) who is responsible for addressing security constraints of the grid are deemed as followers. In addition, the conditional value at risk (CVaR) technique is utilized to model the risk-averse behavior of communities' operators. Finally, the model is implemented into a typical DN modified by three different types of LECs. The findings of the simulation highlight that P2P energy trading can bring financial gains for a typical community under certain conditions. Flexibility originated from distributed energy resources (DERs) and sector coupling within a community provide more profit in local energy trading for the community, but risk-averse strategies have the opposite effect.

1. Introduction

According to the Paris Agreement, countries involved in the agreement have proposed schemes to encourage market participants to invest in carbon-neutral businesses, such as increasing the integration of renewables into distribution networks (DNs). Feed-in tariffs and net-metering are examples of those schemes. Nevertheless, the implementation of subsidized renewable energy schemes could result in economic pressure as well as the installation of unnecessary renewable energy sources in the grid. Consequently, some countries have decided to remove those schemes and replace them with market-oriented approaches, such as developing a transactive market for peer-to-peer (P2P) energy trading among communities [1]. Creating an energy trading framework among local energy communities (LECs) in distribution grids can not only eliminate the economic inefficiency of subsidized schemes, but also allow LECs and DNs to make a profit. Additionally, it can aid the transition to deep decarbonization and predominantly use of renewable energy in DNs. Apart from the possible benefits of a market-driven approach for LECs, the remaining question would be to what extent flexibility resulted from different distributed energy resources (DERs) within a community as well as risk aversion of the LEC's operator affect the economic efficiency of P2P energy transactions among LECs.

The context of P2P energy trading provides a platform for an independent operator of a typical LEC to trade energy with other involved LECs based on independent decisions on the amount and price of energy [2]. Several ambitions are envisaged for energy trading among LECs which are including but not limited to reaching carbon-neutrality targets, providing a low-cost energy trading mechanism, providing flexibility for distribution grids, and activating local communities towards participating on renewable energy transition [3]. In recent years, several studies have revealed the effectiveness of energy trading among prosumers or LECs in distribution grids which can be categorized into three main groups namely determining optimal decision-making process for an independent LEC to reach its defined aims [4], assessing effectiveness of P2P energy trading on providing flexibility for distribution grids [5], and developing state-of-art platforms for facilitating secure energy trading in this context [6]. However, the economic efficiency of participating in P2P energy trading for the individual LEC depends on different factors such as the effect of

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Nomenclature

Indices

t	Index for dispatch interval.
n	Index for grid node.
l	Index for grid line.
k	Index for type of LEC.
w	Index for uncertainty scenario.

Parameters

$\underline{P}_{LEC}^{Load}, \overline{P}_{LEC}^{Load}$	Min and max value of power consumption in LEC (MW).
$\underline{P}_{LEC}^{CHP}, \overline{P}_{LEC}^{CHP}$	Min and max value of electric power generation of CHP unit (MW).
$\overline{P}_{LEC}^{Bat}, \overline{H}_{LEC}^{Elz}, \overline{P}_{LEC}^{FC}$	Power rating of battery, capacity of installed electrolyzer and fuel cell (MW).
$P_{n}^{Load,E}$	Expected power consumption at node n (MW).
P_{RW}^{Exp}	Expected renewable power generation at node n (MW).
$E_{LEC}^{Load,Exp}$	Expected energy consumption of loads in LEC per 24 h (MWh).
$\overline{EL}_{LEC}^{Bat}$	Maximum allowable energy level of battery (MWh).
DoD_{LEC}^{Bat}	Depth of discharge of battery in % of maximum energy level.
$Ramp_{LEC}^{Load,up/down}$	Up and down ramp rate of flexible load in LECs (MW/h).
$Ramp_{LEC}^{Elz,up/down}$	Up and down ramp rate of electrolyzer (MW/h).
$Ramp_{LEC}^{CHP,up/down}$	Up and down ramp rate of CHP unit (MW/h).
$Ramp_{LEC}^{FC,up/down}$	Up and down ramp rate of fuel cell (MW/h).
$Ramp_{LEC}^{EB,up/down}$	Up and down ramp rate of electrical boiler (MW/h).
$\eta_{LEC}^{Bat}, \eta_{LEC}^{Elz}, \eta_{LEC}^{FC}$	Efficiency of battery, electrolyzer, and fuel cell (%).
$\eta_{LEC}^{CHP}, \eta_{LEC}^{CO_2}, \eta_{LEC}^{P2H}$	Efficiency of power generation of CHP, Coefficient of carbon generation, and coefficient of heat generation (%).
$\pi^{M}, \pi^{H}, \pi^{G}$	Retail electricity price, heat price, and gas price (Euro/MWh).
π^{C}, π^{H_2}	Carbon price (Euro/ton), and hydrogen price (Euro/MWh).
$\pi_{O\&M}^{CHP}, \pi_{O\&M}^{EB}, \pi_{O\&M}^{RW}$	Operation cost of CHP unit, electrical boiler, and renewable generator (Euro/MWh).
$\pi_{O\&M}^{Bat}, \pi_{O\&M}^{HS}$	Operation cost of battery and heat storage (Euro/MWh).
$\pi_{Curt}^{Load}, \pi_{Curt}^{Gen}$	Value of loss load, and generation curtailment cost (Euro/MWh).
$\cos(\phi)_{Load}$	Power factor of grid consumer.
R_{Line}, X_{Line}	Resistance and reactance of the line (P.U.).
θ, β	Binary parameter for determining risk-averse condition, and confidence level
ω	Probability of each uncertain scenario.

Sets

$ß(n)$	Set of branches located after nth grid node.
X	Set of primal variables for LEC.
Y	Set of uncertain variables.
F^{DN}, F_{LEC}, F_{LCM}	Objective function for distribution grid, LEC, and local community market.

Variables

$P_{LEC}^{Load}, P_{LEC}^{Load,Dis}$	Expected power, and Actual delivered power in LEC (MW).
$P_{LEC}^{Load,Curt}$	Curtailed power in LEC (MW).
$P_{LEC}^{Bat,ch}, P_{LEC}^{Bat,dch}$	Charging and discharging power of battery (MW).
EL_{LEC}^{Bat}	Energy level of battery (MWh).
$P_{LEC}^{CHP,G}, P_{LEC}^{CHP,E}, P_{LEC}^{CHP,H}$	CHP unit's consumed gas, and generated electrical and heat power (MW).
$H_{LEC}^{Elz}, P_{LEC}^{Elz,E}$	Generated hydrogen and consumed electrical power of electrolyzer (MW).
$H_{LEC}^{FC}, P_{LEC}^{FC,E}$	Consumed hydrogen and generated electrical power of fuel cell (MW).
$P_{LEC}^{EB,H}, P_{LEC}^{EB,E}$	Generated heat and consumed electrical power (MW).
P_{LEC}^{DN}	Amount of power bought from the grid by LEC (MW).
P_{LEC}^{RW}	Amount of renewable generator generated in LEC (MW).
P^{Load}, Q^{Load}	Amount of active (MW) and reactive power (MVaR) consumption at each node of the grid .
P^{gen}, Q^{gen}	Amount of active (MW) and reactive power (MVaR) traded with upstream grid.
$P^{Line}, Q^{Line}, P^{Loss}$	Active (MW) and reactive power (MVaR) of each line, and active power loss (MW).
$P_{k}^{offer}/P_{k}^{bid}$	Dispatched offer and bid of LEC type k (MW).
V	Voltage level of grid node (P.U.).
S^{Line}	Apparent power of each line (MW).
$\pi_{k}^{offer}/\pi_{k}^{bid}$	offer/bid price of LEC type k (Euro/MWh).
π_{n}^{grid}	Cost share of node n from grid's congestion and loss costs (Euro/MWh).
λ^{LCM}	Local community market price (Euro/MWh).
β	Confidence level in risk modeling
υ, Z	β_{VaR} and auxiliary variable in risk modeling.

exogenous energy carriers' prices, flexibility potential of LECs, and risk aversion behavior of operator. Therefore, it is necessary to evaluate in what conditions, participating in P2P energy trading can bring financial gains for individual LECs. This research gap is deeply fulfilled in this paper.

A study is conducted in this paper to assess whether risk averse/neutral behavior of the strategic operator of a LEC as well as flexibility resulting from optimal positioning of various DERs along with sector coupling within a community can contribute to the economic value of P2P energy trading for that community in the absence of subsidized renewable energy schemes. This goal is achieved by strategically scheduling LEC's day-ahead operations taking into account the possibility of P2P energy trading with other LEC's as well as the effect of the price signal received from the distribution system operator (DSO). In this paper, a local community market is developed for the purpose of facilitating local power transactions among LECs. Furthermore, the DSO determines the distribution locational marginal price (DLMP) at nodes where LECs are connected according to the total amount of power injected/absorbed into/from the grid as a result of LECs trading with the grid and with each other. The DLMP is a price signal issued by the DSO and sent to different LECs to let them know how their community contributes to grid congestion and loss costs. Technically, the proposed model in this paper for determining the optimal day-ahead strategy of each LEC is a multi-leader–multi-follower game which is formulated as an equilibrium problem with equilibrium constraints (EPEC). Throughout the game, operators of LECs are treated as leaders, while market operator and DSO are treated as followers. Moreover, the conditional value at risk (CVaR) mathematical technique is used for modeling the risk averse behavior of an independent operator of LEC considering uncertainties associated with the wholesale electricity price, output power of renewables, and load consumption. Finally, the main contributions of this study can be summarized as follows:

- ◇ A multi-leader–multi-follower game is developed for addressing economic effectiveness of P2P energy trading for LECs in case of the absence of subsidized renewable energy schemes.
- ◇ Impact of risk averse/neutral behavior of an individual profit-driven operator of LEC on economic value of local energy trading for all LECs is analyzed.
- ◇ Impact of flexibility driven by local DERs on the benefit of the LEC from P2P energy trading is addressed.
- ◇ Sensitivity analyses are done to study impact of exogenous energy carriers' prices on economic efficiency of local energy trading.

The organization of this paper is as follows: the second section provides literature review. The third section which is comprised of two subsections describes the model framework along with its mathematical modeling. Section 4 presents the results obtained from applying the proposed model on a typical case study and finally our conclusions are drawn in the final section.

2. Literature review

The aim of this section is to review the recent literature regarding P2P energy trading in distribution grids. As known, there is a large volume of published studies describing the role of P2P energy trading in improving energy efficiency in individual entities in distribution grids. However, this section addresses the main ambitions of recent articles for developing a platform for local energy trading.

Two-stage control mechanism has been proposed in [7] for enabling P2P energy trading between two groups of consumers and producers within a community microgrid in low voltage distribution grid. Authors in [7] demonstrated that the P2P energy trading is able to reduce the community's energy bills by 30%. Lüth et al. in [8] have designed local electricity market for smoothing P2P energy trading in a small community. They illustrated that P2P energy trading along with flexibility arisen from the private battery can reduce end-user's costs by 31%. Nguyen et al. in [9] have suggested a mathematical model for owners of PV-battery systems to maximize their profit via P2P energy trading within a local community with 500 households. For typical households equipped with both a PV system and battery, they stated that maximum savings of 28% could be achieved. In addition, [10] discussed the positive impact of P2P energy trading on the optimal sizing of PV systems and electrical storage systems (ESSs) for prosumers in distribution grids. Likewise, Perger et al. in [11] have demonstrated profitability of the P2P energy trading for PV systems and ESSs in local communities. Zhou et al. in [12] have investigated the efficiency of P2P energy trading from both technical and economic perspectives by developing a multiagent framework to simulate it. In their study, they showed that P2P trading can be profitable for Great Britain on both technical and economic levels. Görgülü et al. in [13] have examined the effectiveness of P2P energy trading among smart homes considering price-responsive loads and PV systems. In the case study studied in [13], local trading resulted in a 31.51% reduction in electricity bills. Wang et al. in [14] have developed a rolling horizon optimization for minimizing operational costs of prosumers considering P2P energy trading. Results achieved in [14] declared that the proposed optimization method is able to utilize all flexibility of prosumer's resources towards improving operational economics. Davoudi et al. in [15] have designed a local energy market for P2P energy trading among agents considering the inter-dependencies between heat and electrical grid. Results provided in [15] demonstrated that participated agents could get profit from engaging in this market. Cui et al. in [16] have implemented P2P energy trading mechanism for a typical building cluster including residential, commercial, and industrial buildings to address its economic efficiency. They proved that this way of energy trading can lead to the sustainable building cluster. Aminlou et al. in [17] have examined the efficiency of combined P2P energy trading and shared energy storage on reducing operational cost in a typical industrial town. They demonstrated that 29% savings can be obtained through applying this strategy. Through the development of a decentralized platform, Luo et al. in [18] have addressed the impact of DER ownership on the profitability of P2P energy trading within a microgrid. Liu et al. in [19] have developed a model for providing possibility of P2P energy trading among diversified communities equipped with WT, PV systems, and hydrogen-powered vehicle storage. They showed that local trading can lead to 14.54% reduction in operation cost as well as 8.93% reduction in emission generation. The effectiveness of the P2P energy trading in terms of economic view for consumers in a typical Portuguese residential community which are flexible through PV systems and active loads has been addressed in [20]. According to the results in [20], the better sizing of PV system can bring higher financial gain for the consumer. Value of P2P energy trading for industries in a typical site has been addressed in [21]. In [21], authors found that electricity costs could be reduced in the industrial site by 6.8% to 11.0% considering local trading.

Noorfatima et al. in [22] have developed an appropriate compensation cost mechanism for consumers and prosumers in distribution grids who participate in pay-as-bid P2P energy trading in order to offset grid usage and to improve the performance of local trading. Zhang et al. [5] have addressed how DLMP as an incentive signal can control the P2P transactions in distribution grids in a way that not to lead for grid constraints violation.

In addition, Morstyn et al. in [23] have suggested a new local market for P2P energy trading among prosumers in low voltage distribution grid considering probabilistic DLMP. They demonstrated that P2P energy trading in this framework brings profit for both prosumers and system because of decreasing generation curtailment. Umer et al. in [24] have proposed a two-stage social maximization optimization problem in order to consider the importance of grid technical constraints besides of economic issues regarding P2P trading among consumers within a community. They demonstrated that the net social welfare increases by 10% without voltage rise problem in P2P energy trading in this model. A non-cooperative game is used in [25] to formulate day-ahead P2P energy trading among microgrids in distribution grids, taking into account its effect on congestion and losses on distribution networks. Jiang et al. in [26] have developed a decentralized model for P2P energy trading among microgrids in the concept of energy local area network (e-LAN). The results showed that this method provided better outcomes for participants and was more efficient compared to other decentralized e-LAN methods that already existed. Lin et al. [27] have adopted event-trigger rolling horizon technique for reducing congestion in the grid as a result of P2P energy trading among microgrids.

Zhang et al. in [28] have utilized an iterative double auction algorithm and blockchain to facilitate P2P energy trading among microgrids. In comparison to the zero-intelligence approach, this method led to a 22.3% improvement in social welfare. Sorin et al. in [29] have formulated a P2P market as multi-bilateral economic dispatch problem and have applied Consensus + Innovation (C+I) algorithm for solving that problem. They revealed that this mechanism of energy trading not only maximizes social welfare but also meets to consumers preferences. In order to encourage more consumers to participate in P2P energy trading, a motivational psychology structure has been proposed in [30]. This study showed that P2P trading can reduce emissions by 18.38% and 9.82% per day in summer and winter, respectively. P2P trading within a residential community has been performed in [31] in order to increase efficiency of local batteries operation and better management of surplus generation. To do this, a reinforcement learning technique has been utilized for facilitating the decision-making process for market players. Tushar et al. in [32] have proposed a coalition formation game for providing a platform for energy trading among prosumers equipped with batteries. They revealed that the developed model can lead to user-centric outcomes. Lyu et al. in [33] have proposed a decentralized framework for P2P energy trading among buildings equipped with battery and electrical vehicles in order to consider the privacy issue. They demonstrated the overall positive welfare for all buildings engaged in the local energy trading. A new decentralized market clearing approach has been suggested in [34] for P2P trading among market participants considering privacy of players as well as grid's technical and economic constraints. Ahrarinouri et al. in [35] have utilized distributed reinforcement learning technique for energy sharing among energy hubs within a typical industrial cluster. [35] found that energy sharing among energy hubs reduced daily costs by 3.3%. Ullah et al. in [36] have proposed a two-tier distributed market clearing approach for P2P energy trading among prosumers located in multi regions because of privacy consideration and encouraging more prosumers to be involved in the local energy trading. Finally, Zhou et al. in [37] have summarized and addressed the reason of global developing of P2P energy trading considering various academia articles and research projects. Likewise, to highlight the role of P2P trading on deep decarbonization and clean energy transition, Soto et al. in [38] have reviewed existing approaches, and challenges ahead. In addition, authors in [39] have reviewed recent different methodologies used for P2P energy trading as well as addressing future opportunities in this regard.

As appraised, several studies have revealed to what extent P2P energy trading can bring positive impacts from different perspectives, such as economic, technical, and environmental. However, many of them have prioritized facilitating energy trading between individuals within a particular community. A significant business opportunity is available in trading energy among different types of communities that possess unique features, such as power consumption patterns and types of installed DERs. This presents a potential for each community to improve its performance by leveraging the specific flexibility offered by the other communities involved. In contrast, such flexibility may not be available in energy trading among players with similar characteristics in a single community. Therefore, businesses should explore the possibilities of energy trading across different community types to gain access to such benefits. Aside from this, with the advent of technologies that enable increased sector coupling within a typical community, the inherent flexibility of each distinct community has grown. The higher potential of flexibility might result in greater financial gain for the community in trading energy locally. Therefore, it is crucial to investigate to what extent the internal flexibility resulting from converting different energy carriers to one another in a typical community contributes to the economic efficiency of P2P energy trading for that community and others involved in that market. Furthermore, the varying risk behaviors of operators from different communities within the local energy market can have a notable impact on their respective benefits and, by extension, on the benefits of their competitors. This highlights the importance of understanding how the risk-based attitude of the profit-driven operator of the typical community influences benefits for all involved parties in the local energy market. Therefore, the subsequent sections of this paper aim to assess how the mentioned concerns impact the economic value of P2P energy trading for various types of communities that have not been thoroughly examined thus far.

3. Method of exploration

This section attempts to clearly explain how the model developed in this paper can assess to what extent local energy trading can be economic for LECs in distribution grids considering technical constraints. To achieve this, Section 3 is divided into two subsections. The first subsection characterizes the model framework, and the second subsection provides a mathematical formulation of the model.

3.1. Model framework

The model provided in this subsection seeks to study to what extent different risk behavior of LECs' operators, inherent flexibility of each individual LEC as well as exogenous energy carriers' prices can influence the economic value of local energy trading among LECs in medium-voltage distribution grids. In this model, three different types of LECs are considered. The type one is associated to the residential community and includes photovoltaic (PV) system, electrical energy storage, combined heat and power (CHP) system, and electrical boiler (EB). The industrial community is considered for the second type of the LEC in this model. This community comprises of set of wind turbines (WT), CHP unit, EB, and heat storage. The last type of the LEC is related to the typical commercial community that involves PV system, electrolyzer, fuel cell, and electrical boiler. In this model, it is assumed that heat consumers are inflexible in all communities. However, electrical consumers are price-responsive in all LECs and are able to provide flexibility by amending their consumption level. In addition, due to the presence of technologies that convert power to other energy carriers, sector-coupling is further made possible

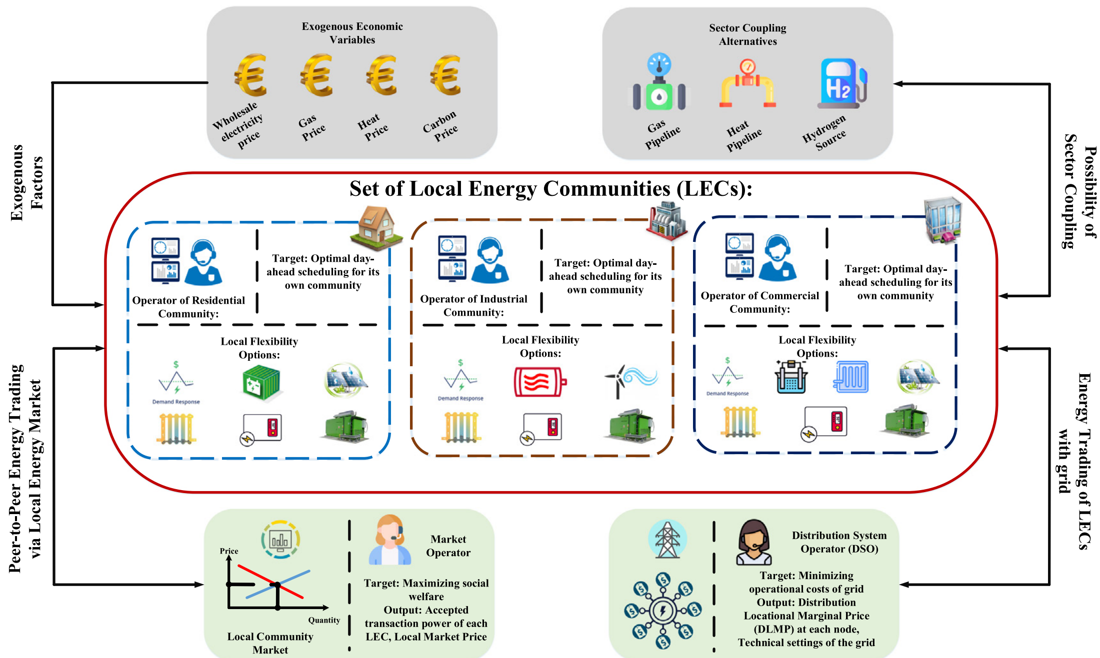


Fig. 1. The schematic of LECs and their way of connection to different entities.

within each community. Fig. 1 represents a schematic of LECs and their way of connecting with local market operator, distribution system operator (DSO), and exogenous energy sources.

In this model, local energy community is considered as a platform for P2P energy trading among LECs. In this context, the market operator receives bids and offers from LECs for each dispatch interval and then maximizes social welfare through an auction-based clearing mechanism. Finally, the calculated uniform local market energy price, along with dispatched bids and offers in this local market, is transferred to LECs. LECs are assumed to be connected to different nodes of the grid in this model. The operator of each one informs the DSO of her/his net injected/absorption power to/from the grid at each time by summing up the amount of the power bought/sold from/to the local market and traded directly with the retailers. The DSO is responsible for assessing whether power injection/absorption to/from the grid at each dispatch interval violates the security constraints of the grid or not. Following that, the DSO determines DLMP at each node based on the generation and consumption patterns as a price signal to encourage the grid subscribers to reshape their energy consumption/generation patterns in a way that keeps the grid in the optimal situation. As seen in this framework, the power dispatched in the local market is delivered via the grid. Therefore, its impact on the distribution marginal congestion price and loss price must be considered. This can be done by the DSO who informs operators of LECs about possible violations and charges. This helps strategic operators of LECs to adopt their decisions on the local market considering their effect on DLMP at the points of coupling.

In this framework, each profit-driven LEC seeks to minimize its day-ahead operation scheduling considering uncertainties associated with electricity price, average load consumption, and output powers of renewables. In fact, the strategic operator of the particular LEC minimizes its community operation costs through optimally adjusting local DERs as well as effectively participating in the local trading. In addition, this strategic operator considers DLMP in its optimization problem in order to take into account its energy trading's effect on the grid. The similar strategy is also valid for rival LECs participated in the local market. Therefore, our model in this paper is mathematically formulated as a multi-leader–multi-follower game (see Fig. 2).

As depicted in Fig. 2, operators of LECs are leaders of the game while market operator as well as DSO are followers. Each individual leader attempts to predict the equilibrium reaction of followers. In addition, the followers consider the decision actions of the leaders as exogenous and fixed variables. In this model, as a coordinator of the local community market, the market operator receives bids and offers from a variety of LECs, and after clearing the market, the local energy market price and dispatched power amounts are transferred to each profit-driven LEC. Additionally, the DSO at a follower layer is given the net amount of power from the leaders at different nodes by which it calculates DLMPs at nodes to which LECs are connected. Then, it sends the computed DLMPs to the leaders as price signals indicating their contribution to network congestion and loss.

3.2. Mathematical formulation

This subsection presents mathematical formulation for the model structured in the previous section. First, the operational constraints of DERs utilized in different LECs are explained and then, the optimization problem of different entities of the model are explained.

3.2.1. Operational constraints of DERs

As declared, this part seeks to introduce technologies used in different LECs along with their operational constraints.

◇ Flexible active load

Flexible active loads are able to provide flexibility for a community through amending their power consumption amount at both incremental and decremental directions at each dispatch interval. To achieve this, the operator requires access to data pertaining to all flexible consumers within the community. This information is used to create an aggregated model of the active flexible load for the community, which encompasses all adaptable consumers, including in that particular community. Operational

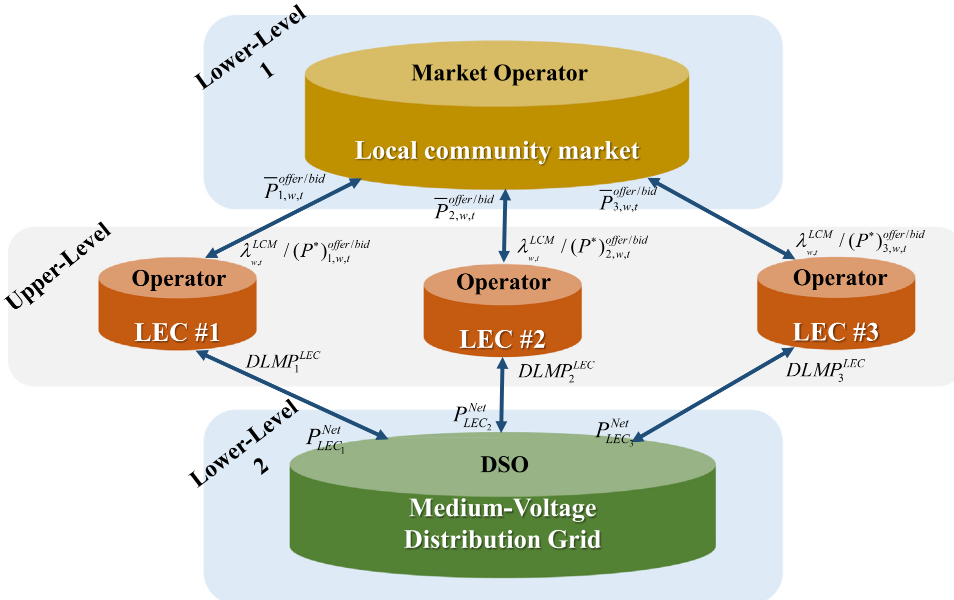


Fig. 2. Interactions among players in different levels for solving the day-ahead scheduling of LECs.

constraints for the aggregated model of the active flexible load in the particular LEC can be formulated as follows:

$$\underline{P}^{Load}_{LEC_k,t,w} \le P^{Load}_{LEC_k,t,w} \le \overline{P}^{Load}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{Load,1-}_{LEC_k,t,w}, \chi^{Load,1+}_{LEC_k,t,w} \tag{1}$$

$$P^{Load}_{LEC_k,t,w} - P^{Load}_{LEC_k,t-1,w} \le Ramp^{Load,up}_{LEC_k} \Delta t \quad \forall k, \forall t \ge 2, \forall w \quad : \chi^{Load,2}_{LEC_k,t,w} \tag{2}$$

$$P^{Load}_{LEC_k,t-1,w} - P^{Load}_{LEC_k,t,w} \le Ramp^{Load,down}_{LEC_k} \Delta t \quad \forall k, \forall t \ge 2, \forall w \quad : \chi^{Load,3}_{LEC_k,t,w} \tag{3}$$

$$P^{Load,Curt}_{LEC_k,t,w} + P^{Load,Dis}_{LEC_k,t,w} = P^{Load}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{Load,4}_{LEC_k,t,w} \tag{4}$$

$$\sum_t P^{Load}_{LEC_k,t,w} \Delta t = E^{Load,Exp}_{LEC_k,w} \quad \forall k, \forall w \quad : \chi^{Load,5}_{LEC_k,w} \tag{5}$$

Eq. (1) shows the permissible bound for changing the expected amount of power being consumed in LEC type k at each time. Eqs. (2) and (3) refer to the ramp-up and down limitations of the aggregated active load in LEC type k. Eq. (4) declares that sum of the actual power delivered to consumers in the typical LEC and the amount of the curtailed power must be equal to the expected amount of consumed power. Finally, the last equation shows that the required expected energy of total active consumers in LEC type k must be met within a day.

◇ Electrical energy storage (EES)

It is possible for electrical energy storage to play the role of a buffer in a particular community by storing energy during low-priced electricity times and injecting it back into the system at a higher price. The operation constraints of such flexible technologies are formulated as follows:

$$0 \le P^{Bat,ch}_{LEC_k,t,w} \le \overline{P}^{Bat}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{Bat,1-}_{LEC_k,t,w}, \chi^{Bat,1+}_{LEC_k,t,w} \tag{6}$$

$$0 \le P^{Bat,dch}_{LEC_k,t,w} \le \overline{P}^{Bat}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{Bat,2-}_{LEC_k,t,w}, \chi^{Bat,2+}_{LEC_k,t,w} \tag{7}$$

$$EL^{Bat}_{LEC_k,t,w} - EL^{Bat}_{LEC_k,t-1,w} = (\eta^{Bat}_{LEC_k} P^{Bat,ch}_{LEC_k,t,w} - P^{Bat,dch}_{LEC_k,t,w} / \eta^{Bat}_{LEC_k}) \Delta t \quad \forall k, \forall t \ge 2, \forall w : \chi^{Bat,3}_{LEC_k,t,w} \tag{8}$$

$$EL^{Bat}_{LEC_k,1,w} - EL^{Bat}_{LEC_k,ini} = (\eta^{Bat}_{LEC_k} P^{Bat,ch}_{LEC_k,1,w} - P^{Bat,dch}_{LEC_k,1,w} / \eta^{Bat}_{LEC_k}) \Delta t \quad \forall k, t = 1, \forall w : \chi^{Bat,4}_{LEC_k,w} \tag{9}$$

$$(1 - DoD^{Bat}_{LEC_k}) \overline{EL}^{Bat}_{LEC_k} \le EL^{Bat}_{LEC_k,t,w} \le \overline{EL}^{Bat}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{Bat,5-}_{LEC_k,t,w}, \chi^{Bat,5+}_{LEC_k,t,w} \tag{10}$$

The charging and discharging power rates of the battery are limited by their respective maximum rates for charging and discharging. These limitations have been considered by Eqs. (6) and (7). The other operational limitation of EES concerns its energy level during each time step. The battery's energy level at a given time depends on the energy level of the battery during the previous time step and the amount of power that has been injected or absorbed. Eqs. (8) and (9) have been developed to address this constraint. According to the last equation, the battery's energy level is limited to an acceptable level. In addition, in order to keep the battery in the expected lifetime, the amount of the absorbed energy from the battery cannot exceed its depth of discharge (DoD) level. Hence, the minimum energy level of the battery has been adjusted to correspond with the battery's DoD value (see Eq. (10).

◇ CHP units

CHP units can provide simultaneous heat and electricity in return for consuming fuel. In this work, three different technologies namely reciprocating engine, gas turbine, and microturbine with different characteristics are considered as a prime mover of these units in different LECs. Eqs. (11)–(16) show the operational constraints of CHP units.

$$P^{CHP,G}_{LEC_k,t,w} = P^{CHP,E}_{LEC_k,t,w} / \eta^{CHP}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{CHP,1}_{LEC_k,t,w} \tag{11}$$

$$P^{CHP,C}_{LEC_k,t,w} = \eta^{CO_2}_{LEC_k} P^{CHP,G}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{CHP,2}_{LEC_k,t,w} \tag{12}$$

$$P^{CHP,H}_{LEC_k,t,w} = \eta^{P2H}_{LEC_k} P^{CHP,E}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{CHP,3}_{LEC_k,t,w} \tag{13}$$

$$\underline{P}^{CHP}_{LEC_k} \le P^{CHP,E}_{LEC_k,t,w} \le \overline{P}^{CHP}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{CHP,4-}_{LEC_k,t,w}, \chi^{CHP,4+}_{LEC_k,t,w} \tag{14}$$

$$P^{CHP,E}_{LEC_k,t,w} - P^{CHP,E}_{LEC_k,t-1,w} \leq Ramp^{CHP,up}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{CHP,5}_{LEC_k,t,w} \tag{15}$$

$$P^{CHP,E}_{LEC_k,t-1,w} - P^{CHP,E}_{LEC_k,t,w} \leq Ramp^{CHP,up}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{CHP,6}_{LEC_k,t,w} \tag{16}$$

The amount of natural gas consumption and consequent carbon generation of the unit are related to the amount of generated electricity by relevant ratios in Eqs. (11) and (12). The generated amount of heat as other output of these units is computed according to Eq. (13). Electricity generation of this unit at each dispatch interval is restricted to its permissible bound using Eq. (14) and the last two constraints emphasize the ramp up and down limitations. The start-up and down constraints of CHP units have been skipped by this assumption that LEC operators plan to participate in the local market based on the times they predict they will run CHP units.

◇ Electrolyzer and Fuel cell

Electrolyzer and fuel cell are two technologies that convert electricity power and hydrogen to each other with respect to their converting efficiency. In fact, they can provide cross-sectoral flexibility through coupling of electricity and hydrogen grids. However, they are limited by their operation constraints as follows:

$$H^{Elz}_{LEC_k,t,w} = \eta^{Elz}_{LEC_k} P^{Elz,E}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{Elz,1}_{LEC_k,t,w} \tag{17}$$

$$0 \leq H^{Elz}_{LEC_k,t,w} \leq \overline{H}^{Elz}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{Elz,2-}_{LEC_k,t,w}, \chi^{Elz,2+}_{LEC_k,t,w} \tag{18}$$

$$H^{Elz}_{LEC_k,t,w} - H^{Elz}_{LEC_k,t-1,w} \leq Ramp^{Elz,up}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{Elz,3}_{LEC_k,t,w} \tag{19}$$

$$H^{Elz}_{LEC_k,t-1,w} - H^{Elz}_{LEC_k,t,w} \leq Ramp^{Elz,down}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{Elz,4}_{LEC_k,t,w} \tag{20}$$

$$P^{FC,E}_{LEC_k,t,w} = \eta^{FC}_{LEC_k} H^{FC}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{FC,1}_{LEC_k,t,w} \tag{21}$$

$$0 \leq P^{FC,E}_{LEC_k,t,w} \leq \overline{P}^{FC}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{FC,2-}_{LEC_k,t,w}, \chi^{FC,2+}_{LEC_k,t,w} \tag{22}$$

$$P^{FC,E}_{LEC_k,t,w} - P^{FC,E}_{LEC_k,t-1,w} \leq Ramp^{FC,up}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{FC,3}_{LEC_k,t,w} \tag{23}$$

$$P^{FC,E}_{LEC_k,t-1,w} - P^{FC,E}_{LEC_k,t,w} \leq Ramp^{FC,down}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{FC,4}_{LEC_k,t,w} \tag{24}$$

The amount of hydrogen generated by electrolyzer is obtained through Eq. (17). The maximum hydrogen generation is limited by this conversion system's capacity (see Eq. (18)). In addition, the ramp up and down limitations for this device are considered through Eqs. (19) and (20). A similar explanation can also be used for the fuel cell in Eqs. (21)–(24) just in the opposite direction where hydrogen is converted to electricity.

◇ Electrical Boiler (EBs)

EBs are able to convert electricity to heat during the times in which electricity price is lower than the heat price. The operational limitations for this technology are characterized as follows:

$$P^{EB,H}_{LEC_k,t,w} = \eta^{EB}_{LEC_k} P^{EB,E}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{EB,1}_{LEC_k,t,w} \tag{25}$$

$$0 \leq P^{EB,H}_{LEC_k,t,w} \leq \overline{P}^{EB}_{LEC_k} \quad \forall k, \forall t, \forall w \quad : \chi^{EB,2-}_{LEC_k,t,w}, \chi^{EB,2+}_{LEC_k,t,w} \tag{26}$$

$$P^{EB,H}_{LEC_k,t,w} - P^{EB,H}_{LEC_k,t-1,w} \leq Ramp^{EB,up}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{EB,3}_{LEC_k,t,w} \tag{27}$$

$$P^{EB,H}_{LEC_k,t-1,w} - P^{EB,H}_{LEC_k,t,w} \leq Ramp^{EB,down}_{LEC_k} \Delta t \quad \forall k, \forall t \geq 2, \forall w \quad : \chi^{EB,4}_{LEC_k,t,w} \tag{28}$$

The amount of heat generated can be related to its consumed electrical power by power-to-heat ratio in Eq. (25). The acceptable bound for heat generation is limited by its maximum capacity in Eq. (26). Ramp up and down constraints for this power-to-heat conversion system are considered through Eqs. (27) and (28) as well.

◇ Renewable technology

PV systems and WTs are considered two clean distributed generators in this study, and it is assumed that the output power of both technologies is controlled by power electronic devices. This allows the LEC to adjust their output generation according to the maximum amount expected. The below equation shows that adjustment.

$$0 \leq P^{RW}_{LEC_k,t,w} \leq \overline{P}^{RW}_{LEC_k,t,w} \quad \forall k, \forall t, \forall w \quad : \chi^{RW,1-}_{LEC_k,t,w}, \chi^{RW,1+}_{LEC_k,t,w} \tag{29}$$

Finally, electrical and heat power balance for each of LECs can be formulated as follows respectively:

$$P^{DN}_{LEC_k,t,w} + P^{bid}_{k,t,w} + P^{CHP,E}_{LEC_k,t,w} + P^{RW}_{LEC_k,t,w} + P^{Bat,dch}_{LEC_k,t,w} + P^{FC,E}_{LEC_k,t,w} - P^{offer}_{k,t,w} - P^{Bat,ch}_{LEC_k,t,w} - P^{EB,E}_{LEC_k,t,w} - P^{Load,Dis}_{LEC_k,t,w} - P^{Elz,E}_{LEC_k,t,w} = 0 \quad : \chi^{Bal,E}_{LEC_k,t,w} \tag{30}$$

$$P^{EB,H}_{LEC_k,t,w} + P^{CHP,H}_{LEC_k,t,w} + P^{HS,dch}_{LEC_k,t,w} - P^{HS,dch}_{LEC_k,t,w} - P^{DH}_{t,w} - P^{Load,H}_{LEC_k,t,w} = 0 \quad : \chi^{Bal,H}_{LEC_k,t,w} \tag{31}$$

3.2.2. *Optimization problem of individual profit-driven entity:*

This subsection elaborates on the optimization problems of operators of LECs, DSO, as well as market operator, and way of risk modeling.

◇ Objective function for operation scheduling of LECs

As described in the previous subsection, three different types of LECs have been considered in this study, namely residential, industrial, and commercial. These three different LECs include various DERs that provide flexibility to keep the operation scheduling in the optimal manner. The first type of LEC (residential one) includes PV systems, CHP unit with microturbine as a prime mover, electrical boiler, ESS, price-responsive residential electrical consumers, and inflexible heat consumers. The objective function of this type can be organized as follows:

$$\begin{aligned} F_{LEC_1}: \text{ Min} \sum_t \sum_w \omega_w \Big[& (\pi^M_{t,w,n} + \pi^{grid}_{t,w,n}) P^{DN}_{LEC_1,t,w} + \pi^H P^{DH}_{t,w} \\ & + \pi^G P^{CHP,G}_{LEC_1,t,w} + \pi^C P^{CHP,C}_{LEC_1,t,w} \\ & \pi^{CHP_1}_{O\&M} P^{CHP,E}_{LEC_1,t,w} + \pi^{Bat_1}_{O\&M} (P^{Bat,ch}_{LEC_1,t,w} + P^{Bat,dch}_{LEC_1,t,w}) \\ & + \pi^{EB_1}_{O\&M} P^{EB,H}_{LEC_1,t,w} + \pi^{RW_1}_{O\&M} P^{RW}_{LEC_1,t,w} + \\ & (\lambda^{LCM}_{t,w} + \pi^{grid}_{t,w,n})(P^{bid}_{1,t,w} - P^{offer}_{1,t,w}) + \pi^{Load}_{curt} P^{Load,Curt}_{LEC_1,t,w} \Big] \end{aligned} \tag{32}$$

The objective function for the first type of LEC includes eleven terms. The first and the second terms refer to the cost of buying electrical power and heat from the electrical grid and district heating system, respectively. The next two terms demonstrate costs of gas consumption and consequent carbon emission generation by the CHP unit. The fifth term refers to the operation cost of that unit. The operation cost of ESS is considered in the next term. In addition, this term enforces that charging and discharging of battery could not be done simultaneously. The operation cost of electrical boiler and renewable sources comprise the next two terms. The ninth term shows the cost of buying electrical power from the local community market and the next one refers to the benefit obtained from the power transaction in that local market. Finally, the last term refers to the load shedding cost.

Another type of LEC, which follows the industrial load profile, includes a CHP unit, electric boiler, heat storage, inflexible thermal consumers, and price-responsive industrial consumers. The objective function for this type can be formulated as follows:

$$F_{LEC_2}: \text{ Min} \sum_t \sum_w \omega_w \Big[(\pi^M_{t,w,n} + \pi^{grid}_{t,w,n}) P^{DN}_{LEC_2,t,w} + \pi^H P^{DH}_{LEC_2,t,w} + \pi^G P^{CHP,G}_{LEC_2,t,w} + \pi^C P^{CHP,C}_{LEC_2,t,w} \\ \pi^{CHP_2}_{O\&M} P^{CHP,E}_{LEC_2,t,w} + \pi^{HS_2}_{O\&M} (P^{HS,ch}_{LEC_2,t,w} + P^{HS,dch}_{LEC_2,t,w}) + \pi^{EB_2}_{O\&M} P^{EB,H}_{LEC_2,t,w} + \pi^{RW_2}_{O\&M} P^{RW}_{LEC_2,t,w} + \\ (\lambda^{LCM}_{t,w} + \pi^{grid}_{t,w,n})(P^{bid}_{2,t,w} - P^{offer}_{2,t,w}) + \pi^{Load}_{curt} P^{Load,Curt}_{LEC_2,t,w} \Big] \tag{33}$$

Similar to the definition of the objective function of the first LEC, eleven terms comprise the objective function of this type. The cost of buying electrical power from the grid, cost of buying heat from the district heating system, cost of gas consumption, and cost of carbon emission generation are considered from the first term to the fourth one. The operational cost of technologies assumed in this community are taken into account using fifth term to eighth one. The next two terms show the net benefit of the LEC from participating in the local market and finally the last one refers to the load shedding cost for this community.

The last type of LEC, which is a representative of the commercial community involves electrolyzer and fuel cell as technologies that provide flexibility through converting power to hydrogen and vice versa along with other DERs such as PV systems, electrical boiler, CHP unit and active commercial loads. The objective function for operation scheduling of this LEC is set up as follows:

$$F_{LEC_3}: \text{ Min} \sum_t \sum_w \omega_w \Big[(\pi^M_{t,w,n} + \pi^{grid}_{t,w,n}) P^{DN}_{LEC_3,t,w} + \pi^H P^{DH}_{LEC_3,t,w} + \pi^G P^{CHP,G}_{LEC_3,t,w} + \pi^C P^{CHP,C}_{LEC_3,t,w} \\ \pi^{H_2}(H^{FC}_{LEC_3,t,w} - H^{Elz}_{LEC_3,t,w}) + \pi^{CHP_3}_{O\&M} P^{CHP,E}_{LEC_3,t,w} + \pi^{EB_3}_{O\&M} P^{EB,H}_{LEC_3,t,w} + \pi^{RW_3}_{O\&M} P^{RW}_{LEC_3,t,w} + \\ (\lambda^{LCM}_{t,w} + \pi^{grid}_{t,w,n})(P^{bid}_{3,t,w} - P^{offer}_{3,t,w}) + \pi^{Load}_{curt} P^{Load,Curt}_{LEC_3,t,w} \Big] \tag{34}$$

Most of terms in (34) have already been defined, except the fifth and sixth terms. The cost of hydrogen bought and sold on the hydrogen grid is determined by those terms.

◇ Risk Modeling

Uncertainties which come from variable outputs of renewables, load consumption and electricity price cause that operators of LECs consider risk regarding the adopted decisions. Those of them who are risk averse seeks to minimize the system risk which might be in exposure of higher operational costs. The risk measurement considered in this study for capturing the behavior of risk aversion operators is conditional value at risk (CVaR) [40]. This measurement can be explained as the expected value of the cost above the $(1-\beta)$ quantile for a given confidence level (β). Taking the general objective function of a particular LEC as $F_{LEC}(X, Y)$, where X represents the vector of decision variables and Y represents the uncertain parameters, then CVaR can be defined mathematically as follows:

$$\beta_{CVaR} \triangleq Exp_{(Y)}\Big[F_{LEC}(X,Y) | F_{LEC}(X,Y) \geq \beta_{VaR}\Big] \tag{35}$$

A CVaR minimization for linear objective functions can be formulated as linear programming, ensuring globality and being suitable for practical applications. As the developed objective function for optimal operation scheduling of each LEC is linear, the following linear optimization problem can be viewed as CVaR minimization.

$$\text{Min}\left[(1-\theta) \times F_{LEC_k}(X,Y) + \theta \times \left[\upsilon + \frac{1}{(1-\beta)} \sum_w \omega_w Z_w\right]\right] \tag{36}$$

Subject to:

$$Z_{k,w} \geq 0 \quad \forall w \quad : \chi^{risk,1}_{k,w} \tag{37}$$

$$Z_{k,w} \geq F_{LEC_k}(X, Y_w) - \upsilon_k \quad \forall w \quad : \chi^{risk,2}_{k,w} \tag{38}$$

Operational constraints regarding DERs in LEC type k (39)

The parameter (θ) shows whether the operator of LEC is risk seeker $(\theta = 0)$ or risk averse $(\theta = 1)$. In addition, in this model, different scenarios for uncertain parameters are generated based on the assumption that forecast error has a normal distribution with a zero mean and specific standard deviation. The next step is to reduce the number of generated scenarios to an acceptable level using the fast forward scenario reduction approach. A more detailed description of this method can be found at [41].

◇ Optimization problem of DSO

The DSO in the medium-voltage distribution grid seeks to evaluate whether technical and security constraints of the grid are met at each dispatch interval according to a given generation and consumption status. This is accomplished by solving the optimal power flow (OPF) problem. To assure global optimality of the outputs, we use the simplified Distflow approach [42] for formulating the OPF problem as follows:

$$F^{DN}_{t,w}: \text{Min} \sum_l \pi^M_{t,w} P^{Loss}_{Line_l,t,w} + \sum_n \pi^{curt}_{Load} P^{Load}_{curt_n,t,w} + \sum_n \pi^{curt}_{Gen} P^{RW}_{curt_n,t,w} \tag{40}$$

$$P^{Load}_{n,t,w} - P^{gen}_{n,t,w} - P^{RW}_{n,t,w} = P^{Line}_{l_{back(n)},t,w} - \sum_{l \in ß(n)} P^{Line}_{l,t,W} \quad \forall n, \forall t, \forall w \quad : \pi^{grid}_{t,w,n} \tag{41}$$

$$Q^{Load}_{n,t,w} - Q^{gen}_{n,t,w} = Q^{Line}_{l_{back(n)},t,w} - \sum_{l \in \hbar(n)} Q^{Line}_{l_{ahead(n)},t,w} \quad \forall n, \forall t, \forall w \quad : \phi_{n,t,w} \tag{42}$$

$$(V^{back}_{l_n,t,w})^2 - (V^{ahead}_{l_n,t,w})^2 = 2R_{Line,l} P_{Line_l,t,w} + 2X_{Line,l} Q_{Line_l,t,w} \\ \forall l, \forall t, \forall w \quad : \zeta_{l,t,w} \tag{43}$$

$$P^{Load}_{n,t,w} + P^{Load}_{curt_n,t,w} = P^{Load,E}_{n,t,w} \quad \forall n, \forall t, \forall w \quad : \psi^{Load,P}_{n,t,w} \tag{44}$$

$$Q^{Load}_{n,t,w} = \frac{\sqrt{1-(\cos(\phi))^2_{Load_n}}}{\cos(\phi)_{Load_n}} P^{Load}_{n,t,w} \quad \forall n, \forall t, \forall w \quad : \psi^{Load,Q}_{n,t,w} \tag{45}$$

$$P^{RW}_{n,t,w} + P^{RW}_{curt_n,t,w} = P^{Exp}_{RW_n,t,w} \quad \forall n, \forall t, \forall w \quad : \psi^{RW}_{n,t,w} \tag{46}$$

$$(\underline{V})^2 \leq (V_{n,t,w})^2 \leq (\overline{V})^2 \quad \forall n \geq 2, \forall t, \forall w \quad : \nu^-_{n,t,w}, \nu^+_{n,t,w} \tag{47}$$

$$(V_{1,t,w})^2 = 1 \quad \forall t, \forall w \quad : \nu_{1,t,w} \tag{48}$$

$$|S^{Line}_{l,t,w}| \leq |\overline{S}_l| \quad \forall l, \forall t, \forall w \quad : \varpi_{l,t,w} \tag{49}$$

According to Eq. (40), grid active power loss cost, cost of load shedding, and the generation curtailment cost comprise the objective function. Active and reactive power balances at each grid node are considered through Eqs. (41), and (42). Voltage drop at each line as a result of power flow is shown in Eq. (43). Eq. (44) declares that the sum of power dispatched and cut for each consumption node must equal the amount given. The next equation demonstrates the amount of reactive power consumption. Eq. (46) refers to the fact that the sum of actual injected power as well as curtailed power at every producer node equals the given amount. A final emphasis is placed on the security constraints of the grid in the last three equations.

As seen, all constraints considered for the OPF problem of DSO are convex and guarantee the global optimality of the results except the last one. That constraint can be replaced with following constraints in order to be convex [43].

$$P^{Line}_{l,t,w} + Q^{Line}_{l,t,w} \leq \sqrt{2}\overline{S}_l \quad \forall l, \forall t, \forall w \quad : \varpi^1_{l,t,w} \tag{50}$$

$$P^{Line}_{l,t,w} - Q^{Line}_{l,t,w} \leq \sqrt{2}\overline{S}_l \quad \forall l, \forall t, \forall w \quad : \varpi^2_{l,t,w} \tag{51}$$

$$-P^{Line}_{l,t,w} + Q^{Line}_{l,t,w} \leq \sqrt{2}\overline{S}_l \quad \forall l, \forall t, \forall w \quad : \varpi^3_{l,t,w} \tag{52}$$

$$-P^{Line}_{l,t,w} - Q^{Line}_{l,t,w} \leq \sqrt{2}\overline{S}_l \quad \forall l, \forall t, \forall w \quad : \varpi^4_{l,t,w} \tag{53}$$

After convex formulation of the technical and security constraints of the grid, the left term which refers to the active power loss at the objective function causes non-convexity. Assuming that the voltage magnitude at each node on the radial distribution grid is around 1 [42], this non-convex term can be approximated to the convex one.

$$P^{Loss}_{Line_l,t,w} = R_{Line_l} \frac{(P^{Line}_{l,t,w})^2 + (Q^{Line}_{l,t,w})^2}{(V^{ahead}_{l_n,t,w})^2} \approx R_{Line_l} \times \left[(P^{Line}_{l,t,w})^2 + (Q^{Line}_{l,t,w})^2\right] \tag{54}$$

As described, in this model, the DSO as an individual entity is placed at the lower level and seeks to address the grid's technical and security constraints based on the given data. Further, it computes the DLMP for each node as a grid price signal. In DLMP, three terms are included, namely the retail price, the congestion price, and the loss price. The retail price is determined after wholesale market clearing, which is considered an exogenous variable in this study. Furthermore, the dual variable associated with the active power balance (Eq. (41)) determines the congestion price and loss price. ($DLMP_{t,w,n} = \pi^M_{t,w} + \pi^{grid}_{t,w,n}$)

◇ Optimization problem of market operator

Operators of LECs willing to trade P2P energy send their offers/bids for selling/buying energy to the market operator at each time. The operator of the local market is responsible for clearing the market based on the received offers/bids. After clearing the market, local electricity price and dispatching energy are sent to operators of LECs. Therefore, the market operator needs to maximize social welfare based on the received offer/bids. The optimization problem for reaching this aim can be formulated as follows:

$$F_{LCM} : \min_{\{P^{offer}_{k,t,w}, P^{bid}_{k,t,w}\}} \sum_k \pi^{offer}_{k,t,w} P^{offer}_{k,t,w} - \sum_k \pi^{bid}_{k,t,w} P^{bid}_{k,t,w} \tag{55}$$

$$\sum_k P^{offer}_{k,t,w} - \sum_k P^{bid}_{k,t,w} = 0, \quad \forall k, \forall w, \forall t \quad : \gamma^1_{k,t,w} \tag{56}$$

$$0 \leq P^{offer}_{k,t,w} \leq \overline{P}^{offer}_{k,t,w} \quad \forall k, \forall w, \forall t \quad : \gamma^{2-}_{k,t,w}, \gamma^{2+}_{k,t,w} \tag{57}$$

$$0 \leq P^{bid}_{k,t,w} \leq \overline{P}^{bid}_{k,t,w} \quad \forall k, \forall w, \forall t \quad : \gamma^{3-}_{k,t,w}, \gamma^{3+}_{k,t,w} \tag{58}$$

The minus social welfare is considered as an objective function in Eq. (55). This market requires a match between the amount of energy sold and the amount bought at each dispatch interval. This constraint is followed by Eq. (56). As a result of the last two constraints, each agent has a maximum amount of energy that can be sold or bought.[2]

In the developed model, local community market is placed in the lower layer and facilitates energy trading among LECs without controlling internal DERs of each community. Thus, in this model, each profit-driven LEC's operator adopts optimal decisions for her/his community's operation scheduling considering the possibility for P2P energy trading with other LECs via the considered local platform and the price signal received from the DSO as a consequent of the grid usage. Hence, the developed multi-leader–multi-follower game can be mathematically formulated as in Box I.

As seen in Eq. (59), optimization problem of each LEC is affected by the followers' reactions. In fact, each LEC tries to solve a mathematical problem with equilibrium constraints. Therefore, the developed model in this study involves all mathematical problems with equilibrium constraints (MPECs) of LECs and tries to find an equilibrium among them. Indeed, the model is mathematically formulated as equilibrium problems with equilibrium constraints (EPEC). This version of the model seems to be hard to be solved by commercial solvers. However, different solutions have been suggested for dealing with complexity of finding an equilibrium. The description of the applied solution method for finding an equilibrium in this model has been provided in Appendix.

4. Simulation and results

This section implements the developed model into the test system to examine to what extent P2P energy trading can bring profit for each individual entity. In this regard, first the case study is introduced, then the obtained results are discussed in the next subsection.

4.1. Case study

A representative model for the medium voltage distribution grid of the Netherlands is considered as case study in this section [44]. This test system has been equipped with renewable generators and three different types of LECs located at different nodes of the grid. The schematic of the case study is seen in Fig. 3.

As discussed, different DERs are considered for LECs to see how their flexibilities in operation can influence the effectiveness of the local trading. Their features are presented in Table 1.

2 A colon is placed after each constraint to identify the dual variable associated with that constraint. Dual variables are used for finding an equilibrium for the developed model.

$$
Model^{EPEC}\left\{\begin{array}{ll}
\text{O.F. of LEC type k=1 :} & \text{Eq. (36)}\\
\text{Operational Constraints: :} & \text{Eqs. (1) -- (16), (25) -- (29), Eq. (32), Eqs. (30)-(31),}\\
 & \text{Eqs. (37) -- (38)}\\
P^{offer}_{1,t,w},\ P^{bid}_{1,t,w},\ \lambda^{LCM}_{t,w}\ : & \in \text{argmin}\quad [\text{Eq. (55)}|\text{Eq. (56)} - \text{Eq. (57)}]\\
\pi^{grid}_{t,w,n\Longleftrightarrow LEC_1}\ : & \in \text{argmin}\quad [\text{Eq. (40)}|\text{Eq. (41)} - \text{Eq. (48), Eq. (50)} - \text{Eq. (54)}]\\
\dots\dots\dots\dots & \\
\text{O.F. of LEC type k=2 :} & \text{Eq. (36)}\\
\text{Operational Constraints: :} & \text{Eqs. (1) -- (16), (25) -- (29), Eq. (33), Eq. (37), Eq. (38),}\\
 & \text{Eqs. (30)-(31)}\\
P^{offer}_{2,t,w},\ P^{bid}_{2,t,w},\ \lambda^{LCM}_{t,w}\ : & \in \text{argmin}\quad [\text{Eq. (55)}|\text{Eq. (56)} - \text{Eq.(57)}]\\
\pi^{grid}_{t,w,n\Longleftrightarrow LEC_2}\ : & \in \text{argmin}\quad [\text{Eq. (40)}|\text{Eq. (41)} - \text{Eq. (48), Eq. (50)} - \text{Eq. (54)}]\\
\dots\dots\dots\dots & \\
\text{O.F. of LEC type k=3 :} & \text{Eq. (36)}\\
\text{Operational Constraints: :} & \text{Eqs. (1) -- (29), Eq. (34), Eq. (37), Eq. (38),}\\
 & \text{Eqs. (30)-(31)}\\
P^{offer}_{3,t,w},\ P^{bid}_{3,t,w},\ \lambda^{LCM}_{t,w}\ : & \in \text{argmin}\quad [\text{Eq. (55)}|\text{Eq.(56)} - \text{Eq. (57)}]\\
\pi^{grid}_{t,w,n\Longleftrightarrow LEC_3}\ : & \in \text{argmin}\quad [\text{Eq. (40)}|\text{Eq. (41)} - \text{Eq. (48), Eq. (50)} - \text{Eq. (54)}]
\end{array}\right. \tag{59}
$$

Box I.

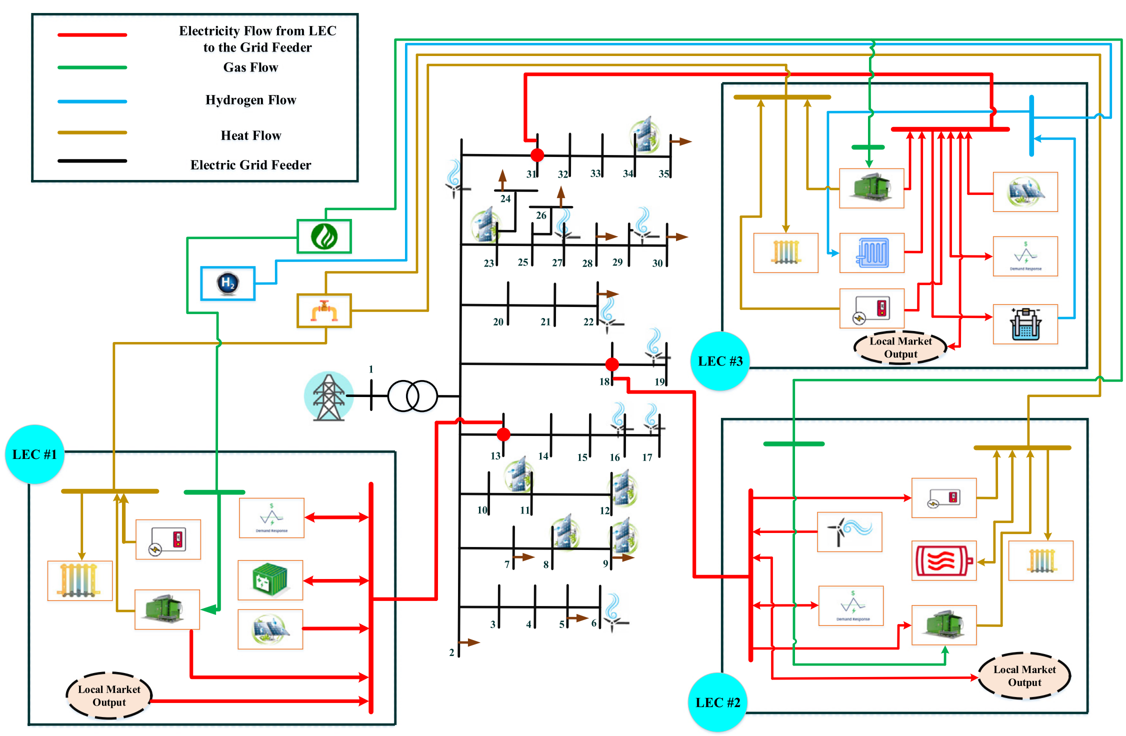


Fig. 3. The schematic of the test system in this simulation.

In this study, the type of battery is Lithium-Ion Battery, and its DoD is 90% of its maximum capacity. Three different LECs in this case study are assumed to model different communities with different load patterns namely, residential, industrial and commercial. The expected load profile for each of them within 24 h is illustrated in Fig. 4.

In addition, it is assumed that active loads in residential community, industrial community, and commercial community are flexible by increasing/decreasing their consumption power up to 30%, 20% and 10% of their expected values, respectively.

CHP units and EBs are assumed to be installed in all LECs with different capacity level and technologies used. Their technical and economic features are summarized in Table 2.

In this simulation, it is assumed that the gas price, heat price, and hydrogen price are 21.5 Euro/MWh, 31.5 Euro/MWh, and 50 Euro/MWh, respectively. As seen, to ensure that all energy

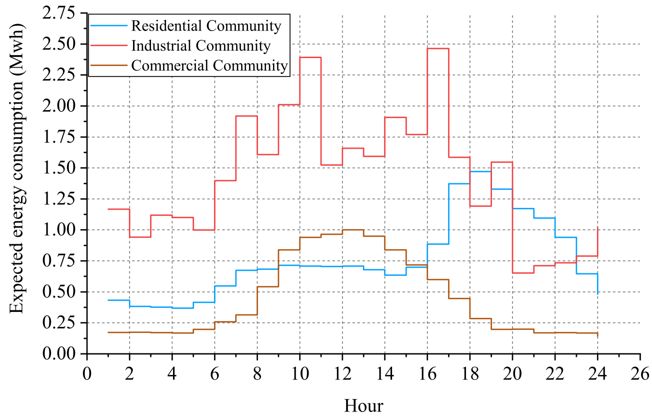


Fig. 4. Expected load profile for each type of LEC.

Table 1
The characteristics of DERs installed in LECs.

DERs Type	Location –	Rating power MW	Capacity MWh	Efficiency %
Battery	LEC1	0.50	1.50	90
Heat storage	LEC2	0.50	1.00	95
Electrolyzer	LEC3	1.00	–	75
Fuel cell	LEC3	1.00	–	55

Table 2
Technical and economic features of CHP units and EBs.

Technology Type	Location –	Rating power MW	Power-to-heat Ratio	O&M cost Euro/MWh	Efficiency %
CHP	LEC1	1.25	0.65	11	27
EB	LEC1	0.50	0.98	0.50	–
CHP	LEC2	1.00	0.90	9	36
EB	LEC2	0.75	0.98	0.50	–
CHP	LEC3	0.75	0.80	5	30
EB	LEC3	0.37	0.98	0.50	–

Table 3
Expected electricity price for 24 h (Euro/MWh).

Hour	1	2	3	4	5	6
Price	43.68	40.81	41.21	38.35	38.33	38.34
Hour	7	8	9	10	11	12
Price	41.69	43.01	45.73	52.98	53.44	49.42
Hour	13	14	15	16	17	18
Price	48.29	43.98	42.61	45.13	50.28	54.42
Hour	19	20	21	22	23	24
Price	58.80	64.41	55.46	48.90	44.79	42.33

carriers are being compared using the same unit, all units have been converted to megawatt-hours based on their lower heating value (LHV), which is a measure of their energy content. The LHV of natural gas was assumed to be 10.55 kWh per cubic meter, while the LHV of hydrogen was assumed to be 33.33 kWh per kilogram in this study. Electricity price varies within 24 h and its average value is provided in Table 3. The prices shown here were taken from data for 2019 in the Netherlands [45].

Electricity price, output power of renewables and expected consumption power of active load are three sources of uncertainty in this simulation. As declared in the previous section the forecast error which has a normal distribution with a zero mean and standard deviation of 0.1%, 0.1%, and 0.2% for electricity price, load consumption, and output power of renewables is used for generating scenarios. The load shedding cost is assumed to be 10000 Euro/MWh. Finally, the assumptions mentioned in this subsection comprise the based case for performing simulations.

Table 4
The expected local market price and DLMP at each hour (€/MWh)

Hour	λ^{LCM}	DLMP at LEC1	DLMP at LEC2	DLMP at LEC3
1	0.000	40.548	40.516	40.516
2	0.000	41.114	41.087	41.087
3	0.000	41.232	41.210	41.210
4	0.000	41.849	41.824	41.824
5	0.000	42.226	42.198	42.198
6	0.000	40.690	40.645	40.645
7	0.000	42.313	42.293	42.293
8	0.000	41.185	41.201	41.201
9	0.000	44.332	44.363	44.363
10	0.000	52.629	52.676	52.676
11	3.134	52.552	52.564	52.564
12	0.000	47.902	47.965	47.965
13	3.553	47.428	47.445	47.445
14	3.588	46.482	46.527	46.527
15	0.000	44.717	44.760	44.760
16	0.000	47.136	47.189	47.189
17	0.000	48.186	48.230	48.230
18	18.672	54.119	53.434	53.434
19	27.603	58.513	57.459	57.459
20	17.371	59.036	58.286	58.286
21	24.884	53.489	52.398	52.398
22	14.350	45.501	44.718	44.718
23	14.366	40.978	40.702	40.702
24	12.251	40.479	40.043	40.043

4.2. Simulation outputs

This subsection provides the results obtained using conditions described previously for the considered case study. These results are discussed in three parts as follows:

◇ Effectiveness assessment of local trading on operation planning of LECs

Possibility for P2P energy trading with different LECs can provide an opportunity for each profit-driven operator to achieve additional financial gains by strategically participation in that local trading besides of energy trading with the grid. Fig. 5 shows the dispatched power transaction among LECs via local community market within 24 h.

As seen in Fig. 5, the horizontal axis shows hours in which the power transaction among LECs has been done. This figure demonstrates that the operator of LEC type 2 prefers to participate as a seller in the market to get profit through selling its surplus generation. However, the operators of LEC type 1, and 3 participate as a buyer and seek to supply their demand requirement through an affordable option.

Table 4 presents the expected clearing market price and expected DLMP at each connected node of LEC for 24 h.

What stands out in Table 4 is that the amount of the local market price during the times in which DLMP is high is relatively less than the price of buying power from the grid. Therefore, local trading can be profitable for those LECs that participate in the market as buyer to obtain cheap electrical power. In addition, in the absence of subsidized scheme for supporting surplus generation, local market provides an exciting market-oriented platform for those LECs that seek to increase their revenue through selling their extra generation. Furthermore, the amount of DLMP at each node comprises of the energy price and contribution of each node on the grid's congestion and loss cost as result of power transaction with the grid and local market. As seen, it is different per node.

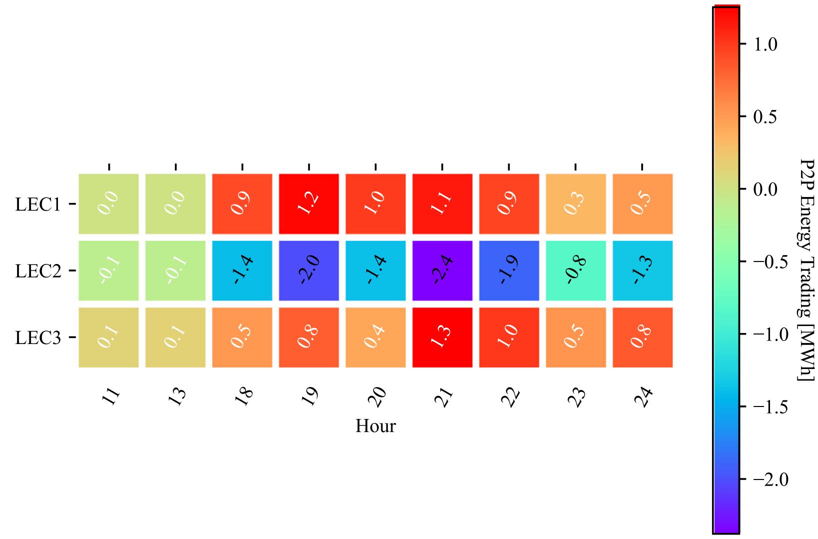


Fig. 5. Power transactions among LECs via local community market.

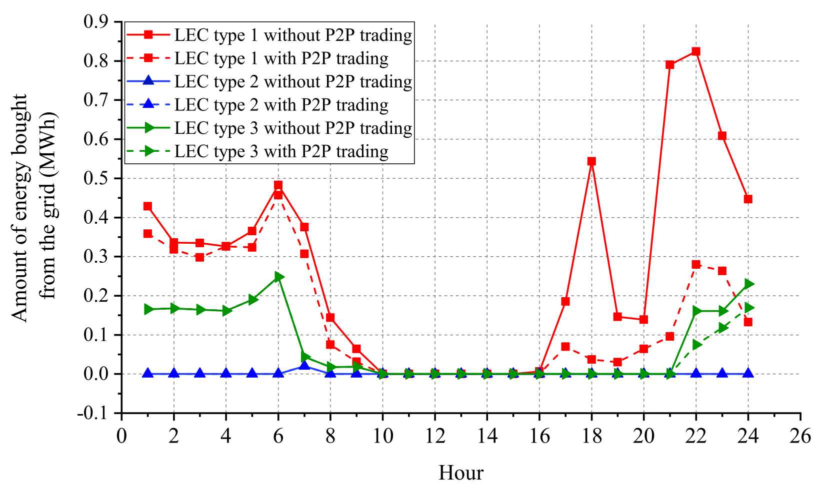


Fig. 6. Amount of the power traded with the grid by LEC.

Fig. 6 shows how the existing of local trading influences on the amount of the power traded with the grid per different LECs.

Looking at Fig. 6, it is apparent that LEC type 2 prefers to optimize its operation planning without dependency to the grid in most of times because of its local sufficient and inexpensive generation. Therefore, participating on the local community market cannot affect the amount of traded power with the grid. However, this cannot be true for other LECs. As seen, there is a clear trend of decreasing on the amount of power traded with the grid for the LEC type 1 in most of the times. In addition, LEC type 3 decreases its absorbed power from the grid after participation in the local trading. Moreover, it can be stressed that all LECs with their specific features seek not to import power from the grid once the electricity power is high enough but to meet their demand requirement through their DERs or local energy market.

Finally, Table 5 compares the operational cost of each LEC with and without possibility of local energy trading.

What is interesting about the data in this table is that local energy trading among LECs has a positive impact on their operational costs whatever their role (buyer/seller) is. However, this effectiveness is more significant for the LEC, which prefers to sell its excess power when there is no other rival as a seller in most of the time.

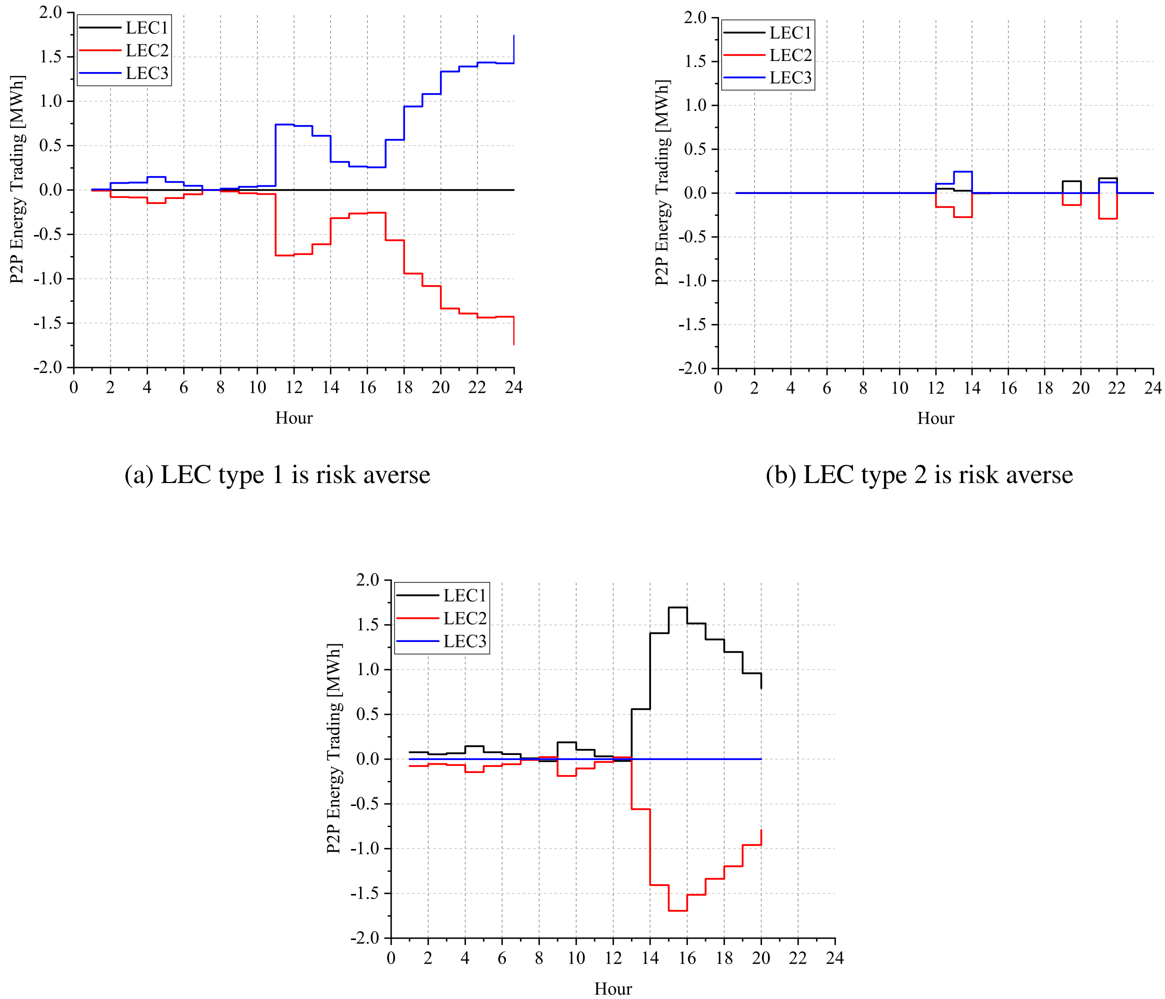
Table 5
Operation cost of LECs with and without possibility of local trading.

Community	Operation cost without P2P (€)	Operation cost with P2P (€)	Improvement rate %
LEC1	1179.62	1119.89	4.92
LEC2	1341.23	1136.78	15.24
LEC3	792.903	750.76	5.13

◇ Effect of risk averse behavior of LEC's operator on local energy trading

One of the important parameters that can influence the effectiveness of the local energy trading for each profit-driven LEC is its operator's behavior. It is interesting to see how risk averse action of a particular player can influence its benefit taken from the local trading and also its rivals. Fig. 7 which includes three sub-figures includes the dispatched power transactions among LECs when LEC type 1, LEC type 2, and LEC type 3 act risk aversely.

The most interesting aspect of Figs. 7(a), 7(b), and 7(c) is that risk aversely acting of a particular operator of LEC results in reducing being successful in trading power with other LECs in the market. However, for those LECs that participate in the



(a) LEC type 1 is risk averse

(b) LEC type 2 is risk averse

(c) LEC type 3 is risk averse

Fig. 7. The dispatched power transaction among LECs in case of being risk averse.

Table 6
Operation cost improvement percent per different risk behavior of market participant after P2P energy trading (%)

Community	Risk-averse player			
Name	No one	LEC1	LEC2	LEC3
LEC1	4.92	0.00	0.75	21.77
LEC2	15.24	3.68	0.11	2.17
LEC3	5.13	34.86	1.64	0.00

market as buyer, risk averse acting of the rival results in collecting more benefit from participating in the market. As seen in Fig. 7(a), the local trading is just done between LEC type 2 and type 3 when the operator of LEC type 1 acts risk aversely. The same event holds when the operator of LEC type 3 is risk averse (See Fig. 7(c)). Additionally, if the operator of LEC type 2 which tends to be a seller in this market is risk averse, the amount of power transactions between this community and others decreases and less benefit is obtained by this player.

Table 6 compares effectiveness of the local energy trading among LECs in terms of operation cost improvement in different risk behavior of the local market participants.

As seen in Table 6, when the operator of LEC type 1 is risk averse, it cannot be successful in local energy trading. Therefore, there is no percent of improvement (0.00%) in its community's operational costs after participating in this market. However, the operator of LEC type 3 can get more from the local market when its rival is risk averse. As seen, the percent of improvement is increased from 5.13% to 34.86% for this LEC. In addition, comparing the percent of operational cost improvements for LEC type 1 when LEC type 3 is risk seeking (4.92%) versus risk averse (21.77%) shows that the risk averse behavior of LEC type 3 positively impacts the percent of operational cost improvement for LEC type 1. In this case study, LEC type 1 and type 3 prefer to participate in the local energy market mostly as buyer. Denoting that, when one of them acts risk adversely, the other one can get higher benefits form participating in the market. However, LEC type 2 which is a sole seller most of the time can obtain less benefit from the market when one of the buyers decides to act risk aversely. In addition, when this LEC decides not to be risk seeker, less benefit is gained for all players involved in the local energy trading. Therefore, what stands out in Table 6 is that risk averse action of a particular LEC operator causes that it could not trade in the local energy market effectively and consequently misses out on the opportunity to collect higher financial gains. Such risk averse behavior is, however, beneficial for its rival in the same role in terms of improving operation cost by participating in the local energy trading.

◇ Effect of exogenous variables on local energy trading

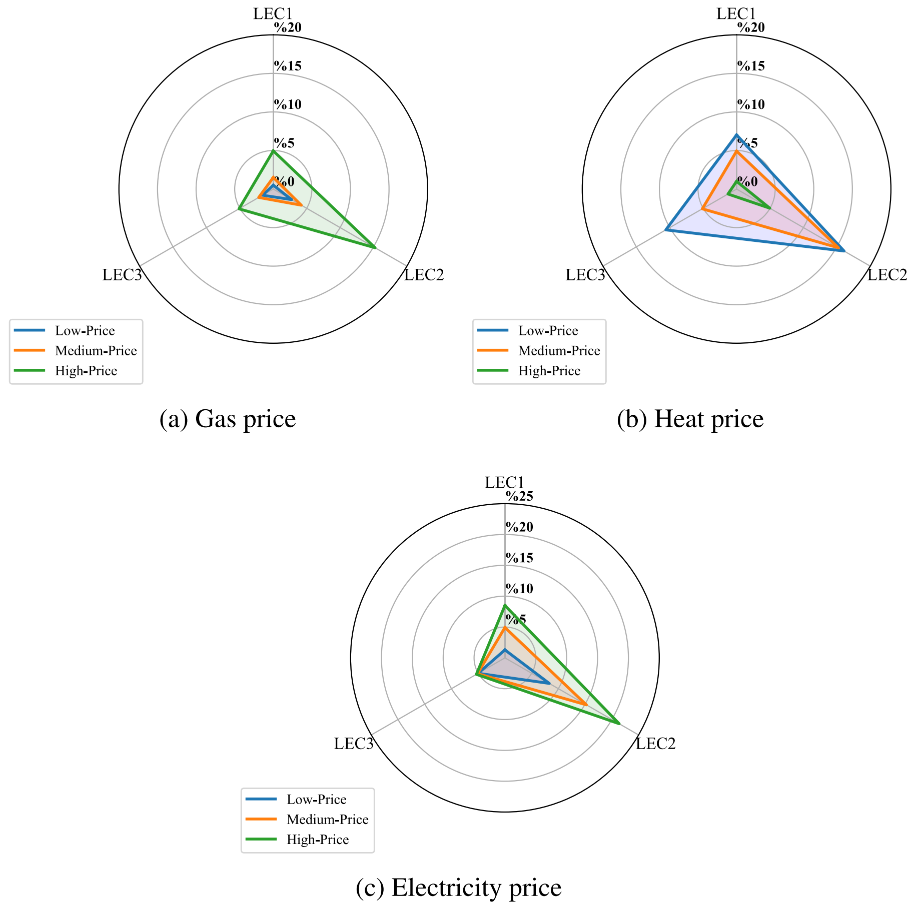


Fig. 8. Effect of energy carriers' prices on the economic effectiveness of the local energy trading.

Fig. 8 demonstrates how the change in the amount of exogenous energy carriers (gas, heat, and electricity) prices can impact on the effectiveness of the local energy trading on improving the operation cost of LECs.

As seen in Fig. 8, the sensitivity analysis has been done separately for each energy carrier price. According to Fig. 8(a), the economic value of local energy trading increases when gas price increases. The reason is that an increase of gas price causes that LECs cannot operate their CHP units for generating electrical and heat power. Therefore, they prefer to buy their required demand through the local market. Therefore, in this circumstance, players in the role of buyers can reduce their operational cost through buying the cheap electrical power and the seller can receive much more attractive price for selling energy blocks. Fig. 8(b) demonstrates that the higher price for the heat power leads to less economic value of the local trading for LECs. Due to the fact that higher heat price encourages LECs to operate their CHP units more frequently to simultaneously generate heat and electrical power. Therefore, in this situation they need less to trade locally and consequently the economic effectiveness of the local energy trading decreases. Finally, Fig. 8(c) illustrates how the change in the electricity price can affect the local market efficiency. What stands out in this figure is the growth in the improvement rate of operational cost of LECs after participating in the local market in case of high electricity price. A reasonable price for buying electric power in this market compared to the grid encourages LECs in role of the buyer to participate more in this market leading to higher economic value of P2P energy trading for the LEC in the role of seller. Fig. 9 shows the dispatched power transaction among LECs in three different cases for the electricity price. (Case A = Low-Price, Case B = Medium-Price, Case C = High-Price)

As can be seen in Fig. 9 higher electricity prices encourage the LECs in role of buyer to actively participate in the local energy market and supply their energy needs at a lower cost. In addition, this situation enables LECs which stand in role of seller to gain higher benefits for energy provision. Notably, this condition is more favorable to the sellers where they want to sell their surplus generations with higher local electricity price instead of curtailing them. To investigate this issue carefully, Fig. 10 displays the local electricity price at each dispatch interval for different electricity price cases.

As expected, the local electricity price increases by an increase of the wholesale electricity price. This can be concluded from Fig. 10 at each hour. The reason is that the marginal cost for providing electrical power at each LEC increases as a result of higher wholesale price and this consequently has an impact on its bidding strategy in the local market. In this circumstance, the LEC with surplus generation has higher improvement rate in its operation cost because of receiving higher local electricity price for selling the power.

◇ Effect of DERs flexibility on the local energy trading

Table 7 addresses how flexibility associated with demand response at each LEC can affect the improvement rate of operational costs of market participants. In this analysis, it has been assumed that active loads at each LEC can be flexible by decreasing/increasing their output power up to 40% of their forecasted amount.

As seen in Table 7, when a particular LEC is flexible through amending its loads' consumption pattern, its profitability from participating in local energy trading increases. In addition, this

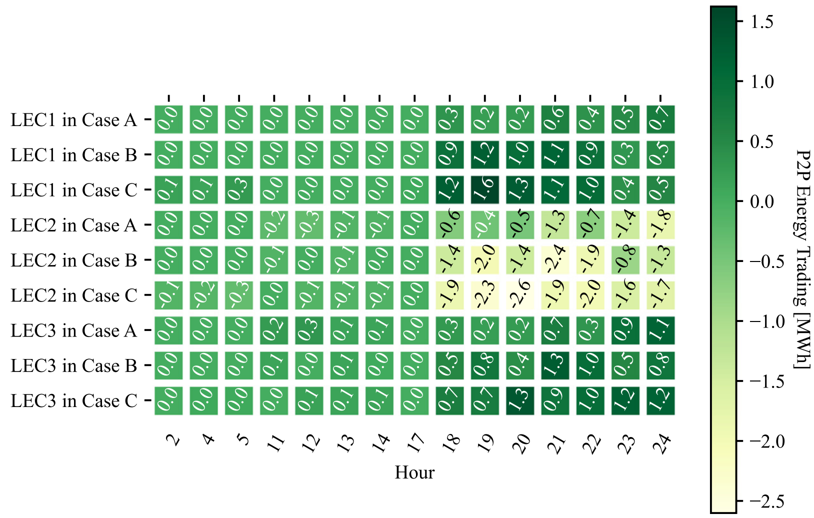


Fig. 9. Power transactions among LECs in three cases for electricity price.

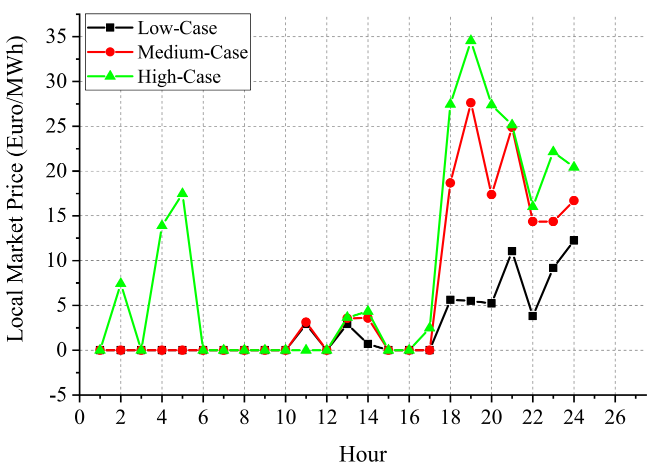


Fig. 10. Local electricity prices at each operation time for three different scenarios of electricity price.

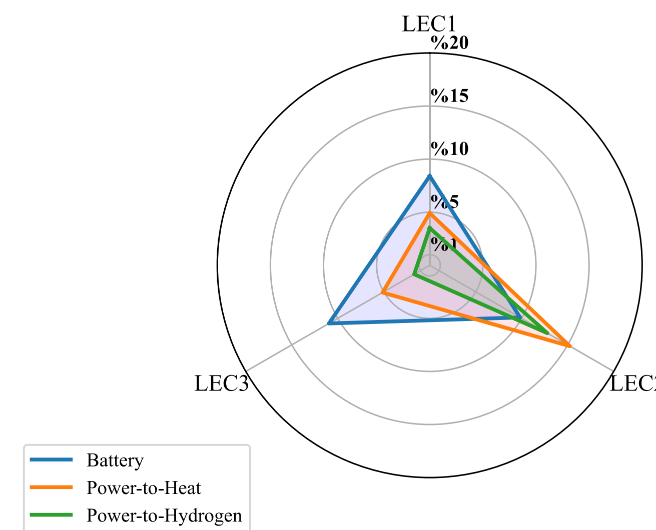


Fig. 11. An improvement rate of operation cost of LECs in different P2X technologies in LEC type 2.

Table 7
An improvement rate of operation cost of LECs affected by demand response (%)

Community	Demand response in			
Name	No where	LEC1	LEC2	LEC3
LEC1	6.21	10.27	5.28	4.48
LEC2	16.26	12.27	19.62	10.84
LEC3	6.27	2.82	4.63	8.84

flexibility can reduce the profitability of the market for the other market participants. As depicted in Table 7, when LEC type 1 is flexible through decreasing/increasing its loads consumption level up to 40% of the expected amount, a higher improvement rate of operation cost is observed; however, it reduces the economic value of the local energy trading for the other LECs. This event can also happen when other LECs enrich their flexibility by their active electrical power consumers. In fact, when the inner flexibility of a particular community increases, its operator can make effective offers/bids in the local energy market and consequently improves operation economy.

In this simulation, the LEC type 2 has surplus generation that can be sold in the local community market. However, it would be interesting to address how flexibility of power-to-X (PtX) technologies in this community can change the economic value of the local energy trading for this technology as well as other market participants. In order to have a fair comparison, the electrical boiler with the capacity of 0.75 MW as power-to-heat option in the base case is replaced with 0.75 MW_{H_2} electrolyzer (power-to-hydrogen option). In addition, a buffer storage option is provided just by adding a battery with the power rating of 0.75 MW. Fig. 11 shows how different P2X technologies on the LEC type 2 can change the profitability of the local energy trading for all participants.

Closer inspection of Fig. 11 implies that the presence of energy storage devices in the LEC type 2 as a dominant seller in the market increases the economic value of the local energy trading for the other LECs which are in role of the buyer most of the time. However, the economic value of the local trading for the LEC type 2 is high when power is converted to other energy carriers such as heat or hydrogen. It means that, in this case study, sector coupling among two different energy carriers provides more inner flexibility for the LEC type 2 and this increases the economic value of the local energy trading for this community. In fact, the value of producing electric power for the LEC type 2 increases in case of converting power to other energy carriers via

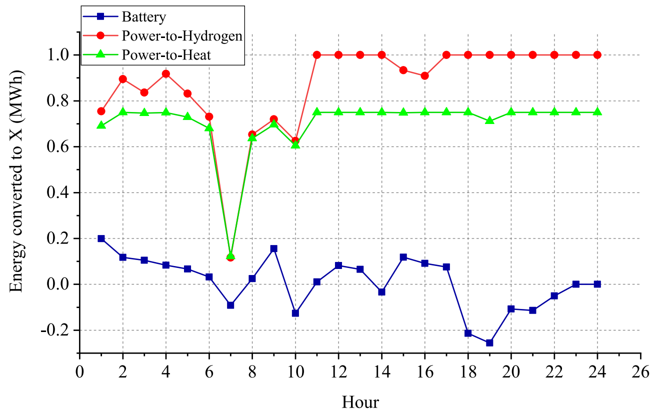


Fig. 12. The amount of power converted to X in LEC type 2.

sector-coupling. Such rise in the value of producing electricity for this LEC caused to getting more benefits from participating the local energy trading. However, such flexibility for the LEC type 2 have a negative impact on the economic value of the local energy trading for LECs participated mostly as buyer.

Fig. 12 demonstrates the amount of the power converted to other energy carriers at each dispatch interval in this community.

As seen in Fig. 12, the operator of LEC type 2 converts more electrical power to heat and hydrogen than storing it in the battery and injecting it into the electrical grid later. As a result, the battery-powered LEC type 2 will have more surplus electricity. This surplus power can benefit other LECs that mostly buy electricity from the local energy market. However, as Fig. 12 shows, the amount of electrical power used for generating hydrogen is more than the amount for generating heat due to technologies' different conversion efficiency. In this simulation, less electricity can be sold in local markets because the power-to-hydrogen option consumes more electricity than the power-to-heat option. Accordingly, the improvement rate of operational costs for the LECs in the role of the buyer in the market is much great when power is converted to heat in the LECs in the role of the seller than in the case of power being converted to hydrogen.

Fig. 13 demonstrates the transaction powers among LECs in the local community market once the penetration level of PV system in the LEC type one increases 50% of its base case.

This figure shows that the operator of the LEC type 1 can participate in the local market both as a buyer and a seller in accordance with its community's needs. LEC type 1 can be a seller due to its surplus generation via PV during sunshine hours. At night, however, this community plays the role of a buyer and seeks to lower its operation costs by purchasing low-priced electricity. The results obtained in this part indicate that the economic efficiency of local energy trading for LEC type 1 has increased from 4.92% in the base case to 5.64% in this situation. Further, effectiveness has dropped from 15.24% to 14% for LEC type 2. Furthermore, a significant improvement has been observed for LEC type 3 from 5.13% to 15.86%. In this simulation, it is possible to hypothesize that the participation of more sellers in the local energy market decreases the economic value of local energy trading for the LEC, which previously participated mostly as a sole seller. Additionally, the presence of more sellers provides more financial gains for buyers.

5. Conclusion

The purpose of this paper was to analyze the conditions under which a typical community can contribute to economic success by participating in P2P energy trading. To meet this need, three different types of communities with various DERs and aggregated loads with different consumption patterns were considered that could take part in local community market. A multi-leader–multi-follower game model was developed in order to assess how decisions made by multiple profit-driven players could influence local market efficiency. In this model, the DSO was able to examine the impact of energy traded in local energy communities on grid costs by computing DLMP after receiving the net consumption and generation data from LECs. Then, this price signal (DLMP) was sent to each of LECs located in different nodes to ensure that their net injected/absorbed power to/from the grid could not violate the security constraints of the grid. As part of the model, the market operator was also responsible for maximizing social welfare based on offers and bids received from LECs at the lower level. A simulation conducted by the study considering the assumptions found that when the internal flexibility of a typical LEC increases through optimal settings of DERs or sector-coupling, the value of local energy trading for that LEC increases. Additionally, the operator's risk-averse strategy makes it impossible for that LEC to compete with its rivals that are risk seekers in the market, so there is no economic benefit for the LEC. As expected, the higher retail price resulted in higher financial gains for both sellers and buyers in local energy trading. Furthermore, the generation of electricity for a community in the role of seller in the local energy market is more valuable when it converts power to other energy carriers compared to storing power in batteries and injecting it later into the electrical grid. Its higher value allowed that community to succeed in gaining more financial benefits by participating in local energy trading as a sole seller. However, we concluded in this simulation that when the number of players in the role of sellers increases, the economic effectiveness of the LEC, which previously participated in the market as a sole seller, reduces.

CRediT authorship contribution statement

Sina Ghaemi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Amjad Anvari-Moghaddam:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix. Solution method

This section tries to describe the solution method applied to the developed model. As discussed in the formulation section, all equations and objective functions have been formulated linearly

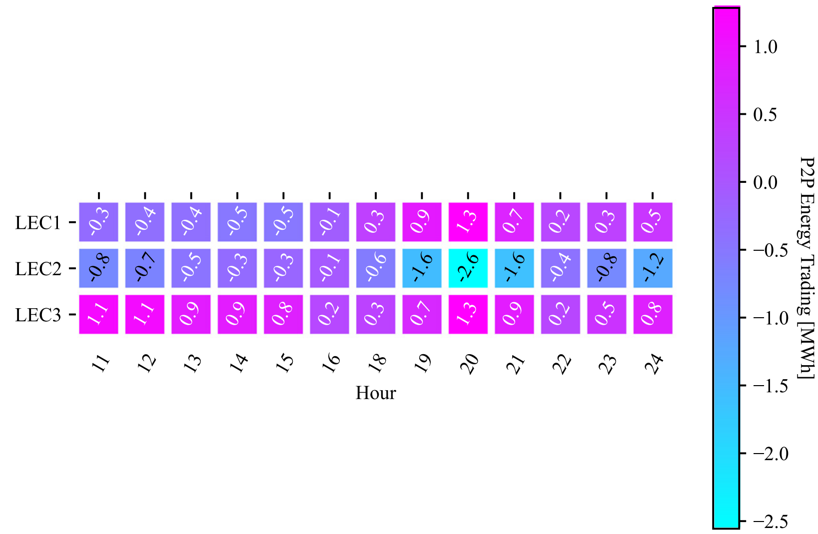

Fig. 13. The dispatched power transaction among LECs in case of higher integration level of PV in LEC type 1.

in order to make the model convex. According to the model, the optimization problem for the kth leader can be formulated generally as follows:

$$OP_k \begin{cases} \text{Objective function}: & \min: F_k(\mathbf{X}_{LEC_k}, \mathbf{X}_{LCM}, \mathbf{X}_{DN}) \\ \text{Constraints}: & \\ \text{Equality Constraints}: & H(\mathbf{X}_{LEC_k}, \mathbf{X}_{LCM}, \mathbf{X}_{DN}) = 0: \quad \lambda_{\mathbf{X}_{LEC_k}} \\ \text{Inequality constraints}: & G(\mathbf{X}_{LEC_k}, \mathbf{X}_{LCM}, \mathbf{X}_{DN}) \le 0: \quad \mu_{\mathbf{X}_{LEC_k}} \\ \text{Lower level 1}: & \mathbf{X}_{LCM} = \operatorname{argmin}\{F_{LCM}(\mathbf{X}_{LCM}, \mathbf{X}_{LEC}) \\ & H_{LCM}(\mathbf{X}_{LEC}, \mathbf{X}_{LCM}) = 0: \quad \lambda_{\mathbf{X}_{LCM}} \\ & G_{LCM}(\mathbf{X}_{LEC}, \mathbf{X}_{LCM}) = 0: \quad \mu_{\mathbf{X}_{LCM}}\} \\ \text{Lower level 2}: & \mathbf{X}_{DN} = \operatorname{argmin}\{F_{DN}(\mathbf{X}_{DN}, \mathbf{X}_{LEC}) \\ & H_{DN}(\mathbf{X}_{DN}, \mathbf{X}_{LEC}) = 0: \quad \lambda_{\mathbf{X}_{DN}} \\ & G_{DN}(\mathbf{X}_{DN}, \mathbf{X}_{LEC}) = 0: \quad \mu_{\mathbf{X}_{DN}}\} \end{cases} \tag{A.1}$$

Where $\mathbf{X}_{LEC}, \mathbf{X}_{LCM}$, and $\mathbf{X}_{DN}$ refer to vectors of primal variables associated with optimization problem of LECs, local community market and distribution network. In addition, vectors of dual variables regarding equality and inequality constraints of each optimization problem have been provided after colon. The lower level problems including optimization problem for local market clearing and the optimization problem for optimum power flow of distribution grid can be substituted with their Karush–Kuhn–Tucker (KKT) conditions. Therefore, Eq. (A.1) can be reformulated as follows:

$$MPEC_k \begin{cases} \min: F_k(\mathbf{X}_{LEC_k}, \mathbf{X}_{LCM}, \mathbf{X}_{DN}) \\ \text{Subject to}: \\ H(\mathbf{X}_{LEC_k}, \mathbf{X}_{LCM}, \mathbf{X}_{DN}) = 0 \\ G(\mathbf{X}_{LEC_k}, \mathbf{X}_{LCM}, \mathbf{X}_{DN}) \le 0 \\ \nabla_{\mathbf{X}_{LCM}} F_{LCM}(\mathbf{X}_{LEC}, \mathbf{X}_{LCM}) + \lambda_{\mathbf{X}_{LCM}} \nabla_{\mathbf{X}_{LCM}} H_{LCM}(\mathbf{X}_{LEC}, \mathbf{X}_{LCM}) + \\ \mu_{\mathbf{X}_{LCM}} \nabla_{\mathbf{X}_{LCM}} G_{LCM}(\mathbf{X}_{LEC}, \mathbf{X}_{LCM}) = 0 \\ H_{LCM}(\mathbf{X}_{LEC}, \mathbf{X}_{LCM}) = 0 \\ 0 \le \mu_{\mathbf{X}_{LCM}} \perp G_{LCM}(\mathbf{X}_{LEC}, \mathbf{X}_{LCM}) \le 0 \\ \nabla_{\mathbf{X}_{DN}} F_{DN}(\mathbf{X}_{LEC}, \mathbf{X}_{DN}) + \lambda_{\mathbf{X}_{DN}} \nabla_{\mathbf{X}_{DN}} H_{DN}(\mathbf{X}_{LEC}, \mathbf{X}_{DN}) + \\ \mu_{\mathbf{X}_{DN}} \nabla_{\mathbf{X}_{DN}} G_{DN}(\mathbf{X}_{LEC}, \mathbf{X}_{DN}) = 0 \\ H_{DN}(\mathbf{X}_{LEC}, \mathbf{X}_{DN}) = 0 \\ 0 \le \mu_{\mathbf{X}_{LEC}} \perp G_{DN}(\mathbf{X}_{LEC}, \mathbf{X}_{DN}) \le 0 \end{cases} \tag{A.2}$$

Eq. (A.2) demonstrates the mathematical problem with equilibrium constraints (MPEC) for the kth leader of the game. Finally, the equilibrium problems with equilibrium constraints (EPEC) of the developed model is a problem that seeks to find a Nash equilibrium among k leaders with associated MPEC formulated in Eq. (A.2).

$$EPEC \begin{cases} \text{Find}: \{x_{LEC_1}, x_{LEC_2}, \ldots, x_{LEC_{N_{LEC}}}, \mathbf{X}_{LCM}, \mathbf{X}_{DN}\} \\ \text{MPEC}_k, \quad \forall k = 1, 2, \ldots, N_{LEC} \qquad : \text{Eq.(A.2)} \end{cases} \tag{A.3}$$

The rest of this Appendix attempts to carefully present the KKT conditions regarding each of optimization problems in different levels of the model in more details. As described in the section of model framework, different LECs can participate in the local community market to trade energy with each other. After that, the net consumption/generation power of each LEC injected/absorbed to/from the grid is transferred to the DN to calculate the DLMP. Finally, the calculated DLMP is sent to each LEC for amending their net power if needed.

◇ Optimality Conditions for optimization problem of market operator in lower level 1:

$$\sum_k P^{offer}_{k,w,t} - \sum_k P^{bid}_{k,w,t} = 0, \quad \forall k, \forall w, \forall t \quad : \gamma^1_{k,w,t} \tag{A.4}$$

$$0 \le P^{offer}_{k,w,t} \le \overline{P}^{offer}_{k,w,t} \quad \forall k, \forall w, \forall t \quad : \gamma^{2-}_{k,k',w,t}, \gamma^{2+}_{k,k',w,t} \tag{A.5}$$

$$0 \le P^{bid}_{k,w,t} \le \overline{P}^{bid}_{k,w,t} \quad \forall k, \forall w, \forall t \quad : \gamma^{3-}_{k,k',w,t}, \gamma^{3+}_{k,k',w,t} \tag{A.6}$$

$$\pi^{offer}_{k,w,t} - \lambda^{LCM}_{w,t} - \mu^{min}_{offer,k,w,t} + \mu^{max}_{offer,k,w,t} = 0 \quad \forall k, \forall w, \forall t \quad : \gamma^4_{k,k',w,t} \tag{A.7}$$

$$-\pi^{bid}_{k,w,t} + \lambda^{LCM}_{w,t} - \mu^{min}_{bid,k,w,t} + \mu^{max}_{bid,k,w,t} = 0 \quad \forall k, \forall w, \forall t \quad : \gamma^5_{k,k',w,t} \tag{A.8}$$

$$\sum_k \left[\pi^{offer}_{k,w,t} P^{offer}_{k,w,t} - \pi^{bid}_{k,w,t} P^{bid}_{k,w,t} + \mu^{max}_{offer,k,w,t} \overline{P}^{offer}_{k,w,t} + \mu^{max}_{bid,k,w,t} \overline{P}^{bid}_{k,w,t} \right] = 0$$
$$\forall w, \forall t \quad : \gamma^6_{k,w,t} \tag{A.9}$$

$$\mu^{min}_{offer,k,w,t} \ge 0, \quad \mu^{max}_{offer,k,w,t} \ge 0 \quad \forall k, \forall w, \forall t \quad : \gamma^{7-}_{k,k',w,t}, \gamma^{7+}_{k,k',w,t} \tag{A.10}$$

$$\mu^{min}_{bid,k,w,t} \geq 0, \quad \mu^{max}_{bid,k,w,t} \geq 0 \quad \forall k, \forall w, \forall t \quad : \gamma^{8-}_{k,k',w,t}, \gamma^{8+}_{k,k',w,t} \tag{A.11}$$

As seen, optimality conditions for the optimization problem of the local community market have been provided per leader of the game. Finally, KKT conditions for each developed MPEC provides the EPEC of the model.

◇ KKT conditions of the developed MPEC for the kth leader:

$$-\chi^{Load,1-}_{LEC_k,t,w} + \chi^{Load,1+}_{LEC_k,t,w} + \chi^{Load,2}_{LEC_k,t,w} - \chi^{Load,2}_{LEC_k,t+1,w} - \chi^{Load,3}_{LEC_k,t,w} + \chi^{Load,3}_{LEC_k,t+1,w} - \chi^{Load,4}_{LEC_k,t,w} + \chi^{Load,5}_{LEC_k,1,w} = 0 \quad \forall (2 \leq t \leq 23) \quad \forall w \tag{A.12}$$

$$-\chi^{Load,1-}_{LEC_k,1,w} + \chi^{Load,1+}_{LEC_k,1,w} - \chi^{Load,2}_{LEC_k,2,w} + \chi^{Load,3}_{LEC_k,2,w} - \chi^{Load,4}_{LEC_k,1,w} + \chi^{Load,5}_{LEC_k,1,w} = 0 \forall t = 1 \tag{A.13}$$

$$-\chi^{Load,1-}_{LEC_k,24,w} + \chi^{Load,1+}_{LEC_k,24,w} + \chi^{Load,2}_{LEC_k,24,w} - \chi^{Load,3}_{LEC_k,2,w} - \chi^{Load,4}_{LEC_k,24,w} + \chi^{Load,5}_{LEC_k,24,w} = 0 \forall t = 24 \tag{A.14}$$

$$((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{Curt}_{Load} + \chi^{Load,4}_{LEC_k,t,w} - \chi^{shed}_{LEC_k,t,w} = 0 \quad \forall t \tag{A.15}$$

$$-\chi^{Bal,E}_{LEC_k,t,w} + \chi^{Load,4}_{LEC_k,t,w} = 0 \quad \forall t \tag{A.16}$$

$$-\chi^{Bal,E}_{LEC_k,t,w} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{O\&M}_{Bat} - \chi^{Bat,1-}_{LEC_k,t,w} + \chi^{Bat,1+}_{LEC_k,t,w} - \eta^{Bat}_{LEC_k}\chi^{Bat,3}_{LEC_k,t,w} \quad \forall t \geq 2 \tag{A.17}$$

$$-\chi^{Bal,E}_{LEC_k,1,w} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{O\&M}_{Bat} - \chi^{Bat,1-}_{LEC_k,1,w} + \chi^{Bat,1+}_{LEC_k,1,w} - \eta^{Bat}_{LEC_k}\chi^{Bat,4}_{LEC_k,w} \quad \forall t = 1 \tag{A.18}$$

$$\chi^{Bal,E}_{LEC_k,t,w} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{O\&M}_{Bat} - \chi^{Bat,2-}_{LEC_k,t,w} + \chi^{Bat,2+}_{LEC_k,t,w} + \chi^{Bat,3}_{LEC_k,t,w}/\eta^{Bat}_{LEC_k} \quad \forall t \geq 2 \tag{A.19}$$

$$\chi^{Bal,E}_{LEC_k,1,w} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{O\&M}_{Bat} - \chi^{Bat,2-}_{LEC_k,1,w} + \chi^{Bat,2+}_{LEC_k,1,w} + \chi^{Bat,4}_{LEC_k,w}/\eta^{Bat}_{LEC_k} \quad \forall t = 1 \tag{A.20}$$

$$\chi^{Bat,3}_{LEC_k,t,w} - \chi^{Bat,3}_{LEC_k,t+1,w} - \chi^{Bat,5-}_{LEC_k,t,w} + \chi^{Bat,5+}_{LEC_k,t,w} = 0 \quad \forall (2 \leq t \leq 23) \tag{A.21}$$

$$\chi^{Bat,3}_{LEC_k,24,w} - \chi^{Bat,5-}_{LEC_k,24,w} + \chi^{Bat,5+}_{LEC_k,24,w} = 0 \quad \forall (t = 24) \tag{A.22}$$

$$-\chi^{Bat,3}_{LEC_k,2,w} + \chi^{Bat,4}_{LEC_k,w} + \chi^{Bat,5+}_{LEC_k,24,w} = 0 \quad \forall (t = 1) \tag{A.23}$$

$$((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{G} + \chi^{CHP,1}_{LEC_k,t,w} - \eta^{CO_2}_{LEC_k}\chi^{CHP,2}_{LEC_k,t,w} = 0 \tag{A.24}$$

$$((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{G} + \chi^{CHP,1}_{LEC_k,t,w} - \eta^{CO_2}_{LEC_k}\chi^{CHP,2}_{LEC_k,t,w} = 0 \tag{A.25}$$

$$((1-\theta)\omega_w + \chi^{risk}_{k,w})\pi^{C} + \chi^{CHP,2}_{LEC_k,t,w} = 0 \tag{A.26}$$

$$-\chi^{Bal,H}_{LEC_k,t,w} + \chi^{CHP,3}_{LEC_k,t,w} = 0 \tag{A.27}$$

$$\chi^{Bal,E}_{LEC_k,t,w} - (1/\eta^{CHP}_{LEC_k})\chi^{CHP,1}_{LEC_k,t,w} - \eta^{P2H}_{LEC_k}\chi^{CHP,3}_{LEC_k,t,w} - \chi^{CHP,4-}_{LEC_k,t,w} + \chi^{CHP,4+}_{LEC_k,t,w} + \chi^{CHP,5}_{LEC_k,t,w} - \chi^{CHP,1}_{LEC_k,t+1,w} - \chi^{CHP,6}_{LEC_k,t,w} + \chi^{CHP,1}_{LEC_k,t+1,w} = 0 \quad \forall (2 \leq t \leq 23) \tag{A.28}$$

$$\chi^{Bal,E}_{LEC_k,1,w} - (1/\eta^{CHP}_{LEC_k})\chi^{CHP,1}_{LEC_k,1,w} - \eta^{P2H}_{LEC_k}\chi^{CHP,3}_{LEC_k,1,w} - \chi^{CHP,4-}_{LEC_k,1,w} + \chi^{CHP,4+}_{LEC_k,1,w} - \chi^{CHP,1}_{LEC_k,2,w} + \chi^{CHP,1}_{LEC_k,2,w} = 0 \tag{A.29}$$

$$\chi^{Bal,E}_{LEC_k,24,w} - (1/\eta^{CHP}_{LEC_k})\chi^{CHP,1}_{LEC_k,24,w} - \eta^{P2H}_{LEC_k}\chi^{CHP,3}_{LEC_k,24,w} - \chi^{CHP,4-}_{LEC_k,24,w} + \chi^{CHP,4+}_{LEC_k,24,w} + \chi^{CHP,1}_{LEC_k,24,w} - \chi^{CHP,1}_{LEC_k,24,w} = 0 \tag{A.30}$$

$$-\eta^{Elz}_{LEC_k}\chi^{Elz,1}_{LEC_k,t,w} - \chi^{Bal,E}_{LEC_k,t,w} = 0 \tag{A.31}$$

$$-((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2} + \chi^{Elz,1}_{LEC_k,t,w} - \chi^{Elz,2-}_{LEC_k,t,w} + \chi^{Elz,2+}_{LEC_k,t,w} \chi^{Elz,3}_{LEC_k,t,w} - \chi^{Elz,3}_{LEC_k,t+1,w} - \chi^{Elz,3}_{LEC_k,t,w} + \chi^{Elz,3}_{LEC_k,t+1,w} = 0 \quad \forall (2 \leq t \leq 23) \tag{A.32}$$

$$-((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2} + \chi^{Elz,1}_{LEC_k,1,w} - \chi^{Elz,2-}_{LEC_k,1,w} + \chi^{Elz,2+}_{LEC_k,1,w} - \chi^{Elz,3}_{LEC_k,2,w} + \chi^{Elz,4}_{LEC_k,2,w} = 0 \tag{A.33}$$

$$-((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2} + \chi^{Elz,1}_{LEC_k,24,w} - \chi^{Elz,2-}_{LEC_k,24,w} + \chi^{Elz,2+}_{LEC_k,24,w} + \chi^{Elz,3}_{LEC_k,24,w} - \chi^{Elz,4}_{LEC_k,24,w} = 0 \tag{A.34}$$

$$\chi^{FC,1}_{LEC_k,t,w} + \chi^{Bal,E}_{LEC_k,t,w} = 0 \tag{A.35}$$

$$((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2} - \eta^{FC}_{LEC_k}\chi^{FC,1}_{LEC_k,t,w} - \chi^{FC,2-}_{LEC_k,t,w} + \chi^{FC,2+}_{LEC_k,t,w} \chi^{FC,3}_{LEC_k,t,w} - \chi^{FC,3}_{LEC_k,t+1,w} - \chi^{FC,3}_{LEC_k,t,w} + \chi^{FC,3}_{LEC_k,t+1,w} = 0 \quad \forall (2 \leq t \leq 23) \tag{A.36}$$

$$((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2} - \eta^{FC}_{LEC_k}\chi^{FC,1}_{LEC_k,1,w} - \chi^{FC,2-}_{LEC_k,1,w} + \chi^{FC,2+}_{LEC_k,1,w} - \chi^{FC,3}_{LEC_k,2,w} + \chi^{FC,4}_{LEC_k,2,w} = 0 \tag{A.37}$$

$$((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2} - \eta^{FC}_{LEC_k}\chi^{FC,1}_{LEC_k,24,w} - \chi^{FC,2-}_{LEC_k,24,w} + \chi^{FC,2+}_{LEC_k,24,w} + \chi^{FC,3}_{LEC_k,24,w} - \chi^{FC,4}_{LEC_k,24,w} = 0 \tag{A.38}$$

$$-\chi^{Bal,E}_{LEC_k,t,w} - \eta^{EB}_{LEC_k}\chi^{EB,1}_{LEC_k,t,w} = 0 \tag{A.39}$$

$$-\chi^{Bal,H}_{LEC_k} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2}\pi^{O\&M}_{EB_k} + \chi^{EB,1}_{LEC_k,t,w} - \chi^{EB,2-}_{LEC_k,t,w} + \chi^{EB,2+}_{LEC_k,t,w} + \chi^{EB,3}_{LEC_k,t,w} - \chi^{EB,3}_{LEC_k,t+1,w} - \chi^{EB,4}_{LEC_k,t,w} + \chi^{EB,4}_{LEC_k,t+1,w} = 0 \quad \forall (2 \leq t \leq 23) \tag{A.40}$$

$$-\chi^{Bal,H}_{LEC_k} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{O\&M}_{EB_k} + \chi^{EB,1}_{LEC_k,1,w} - \chi^{EB,2-}_{LEC_k,1,w} + \chi^{EB,2+}_{LEC_k,1,w} - \chi^{EB,3}_{LEC_k,2,w} + \chi^{EB,4}_{LEC_k,2,w} = 0 \tag{A.41}$$

$$-\chi^{Bal,H}_{LEC_k} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{H_2}\pi^{O\&M}_{EB_k} + \chi^{EB,1}_{LEC_k,24,w} - \chi^{EB,2-}_{LEC_k,24,w} + \chi^{EB,2+}_{LEC_k,24,w} + \chi^{EB,3}_{LEC_k,24,w} - \chi^{EB,4}_{LEC_k,24,w} = 0 \tag{A.42}$$

$$\chi^{Bal,E}_{LEC_k,t,w} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})\pi^{O\&M}_{RW_k} - \chi^{RW,1-}_{LEC_k,t,w} + \chi^{RW,1+}_{LEC_k,t,w} = 0 \tag{A.43}$$

$$\chi^{Bal,E}_{LEC_k,t,w} - \chi^{DN,1-}_{LEC_k,t,w} + \chi^{DN,1+}_{LEC_k,t,w} + ((1-\theta)\omega_w + \chi^{risk,2}_{k,w})(\pi^{M}_{t,w,n} + \pi^{grid}_{t,w,n}) = 0 \tag{A.44}$$

$$-\chi^{Bal,H}_{LEC_k,t,w} - \chi^{DHS,1-}_{LEC_k,t,w} + \chi^{DHS,1+}_{LEC_k,t,w} + ((1-\theta)\omega_w + \chi^{risk}_{k,w})\pi^{H} = 0 \tag{A.45}$$

$$\frac{\theta}{(1-\beta)}\omega_w - \chi_{k,w}^{risk,1} - \chi_{k,w}^{risk,2} = 0 \tag{A.46}$$

$$\theta - \sum_w \chi_{k,w}^{risk,2} = 0 \tag{A.47}$$

$$-\chi_{k,t,w}^{offer} + P_{k,t,w}^{offer}\gamma_{k,t,w}^{6} + \gamma_{k,k',t,w}^{4} = 0 \tag{A.48}$$

$$-\chi_{k,t,w}^{bid} + P_{k,t,w}^{bid}\gamma_{k,t,w}^{6} - \gamma_{k,k',t,w}^{5} = 0 \tag{A.49}$$

$$-((1-\theta)\omega_w + \chi_{k,w}^{risk,2}) \times (\pi_{t,w,n}^{grid} + \lambda_{t,w}^{LCM}) + \pi_{k,t,w}^{offer}\gamma_{k,t,w}^{6} + \gamma_{k,t,w}^{1} - \gamma_{k,k,t,w}^{7-} + \gamma_{k,k,t,w}^{7+} = 0 \quad \forall k \neq k' \tag{A.50}$$

$$\pi_{k',t,w}^{offer}\gamma_{k,t,w}^{6} + \gamma_{k,t,w}^{1} - \gamma_{k,k',t,w}^{2-} + \gamma_{k,k',t,w}^{2+} = 0 \quad \forall k \neq k' \tag{A.51}$$

$$((1-\theta)\omega_w + \chi_{k,w}^{risk,2}) \times (\pi_{t,w,n}^{grid} + \lambda_{t,w}^{LCM}) - \pi_{k,t,w}^{bid}\gamma_{k,t,w}^{6} - \gamma_{k,t,w}^{1} - \gamma_{k,k,t,w}^{8-} + \gamma_{k,k,t,w}^{8+} = 0 \quad \forall k \neq k' \tag{A.52}$$

$$-\pi_{k',t,w}^{bid}\gamma_{k,t,w}^{6} - \gamma_{k,t,w}^{1} - \gamma_{k,k',t,w}^{3-} + \gamma_{k,k',t,w}^{3+} = 0 \tag{A.53}$$

$$\sum_{k'}(\underline{P}^{trade}\alpha_{k',t,w}^{5} + \overline{P}^{trade}\alpha_{k',t,w}^{6} - \overline{P}^{trade}\alpha_{k',t,w}^{7} - \underline{P}^{trade}\alpha_{k',t,w}^{8}) + \sum_{k'}(\gamma_{k,k',t,w}^{5} - \gamma_{k,k',t,w}^{4}) = 0 \tag{A.54}$$

$$-\gamma_{k,k',t,w}^{4} - \gamma_{k,k',t,w}^{7-} = 0 \tag{A.55}$$

$$\gamma_{k,t,w}^{6}\overline{P}_{k,t,w}^{offer} + \gamma_{k,k',t,w}^{4} - \gamma_{k,k',t,w}^{7+} = 0 \tag{A.56}$$

$$-\gamma_{k,k',t,w}^{5} - \gamma_{k,k',t,w}^{8-} = 0 \tag{A.57}$$

$$\gamma_{k,t,w}^{6}\overline{P}_{k,t,w}^{bid} + \gamma_{k,k',t,w}^{5} - \gamma_{k,k',t,w}^{8+} = 0 \tag{A.58}$$

Eqs. (4), (5), (8), (9), (11)-(13), (17), (21), (25), (35), (36), (30), (31), (A.4), (A.7)-(A.9) (A.59)

Finally the complementarity conditions are added to the above optimality conditions to provide KKT conditions for each LEC. As known, these constraints can be written according to the inequality constraints of each optimization problem and their associated dual variables. In order to eliminate repetitive writing of inequality constraints, the general form of complementarity conditions is expressed as follows:

$$0 \leq \boldsymbol{\chi}_{LEC_k,t,w} \perp \mathbf{G}_{LEC_K,t,w} \geq 0 \tag{A.60}$$

Hence, all inequality equations including Eqs. (1)–(3), (6), (7), (10), (14)–(16), (18)–(20), (22)–(24), (26)–(28), (29), (40), (41), (A.5), (A.6), and (A.10)–(A.19), are modeled as Eq. (A.60) to make the KKT conditions for each LEC. All equations considered for KKT conditions of the kth LEC are linear except Eq. (A.9) which shows the strong duality constraint for the lower level 1 of the problem. This equation is switched with the below complementary constraints to keep all constraints linear.

$$0 \leq \gamma_{k,w,t}^{2-} \perp P_{k,w,t}^{offer} \geq 0 \tag{A.61}$$

$$0 \leq \gamma_{k,w,t}^{2+} \perp \overline{P}_{k,w,t}^{offer} - P_{k,w,t}^{offer} \geq 0 \tag{A.62}$$

$$0 \leq \gamma_{k,w,t}^{3-} \perp P_{k,w,t}^{bid} \geq 0 \tag{A.63}$$

$$0 \leq \gamma_{k,w,t}^{3+} \perp \overline{P}_{k,w,t}^{bid} - P_{k,w,t}^{bid} \geq 0 \tag{A.64}$$

As declared in Section 3, LECs send their net generation or consumption status at each dispatch interval to the DSO after participating in local energy trading. In the second lower level of the model, we are facing with the optimization problem of the DSO minimizing grid costs based on the given data received from grid's producers and consumers. In addition, the DSO computes DLMP at each node and transfer it to LECs located in different buses. Hence, the KKT conditions for the optimization problem of the DSO must be added to the developed mathematical problem of each LEC.

◇ KKT Conditions for optimization problem in lower level 2:

$$2\pi_{t,w}^{M}R_{Line,l}P_{Line_l,t,w} - \sum_{n|l\in\hbar_n^{back}}\pi_{t,w}^{grid} + \sum_{n|l\in\hbar_n^{ahead}}\pi_{t,w}^{grid} - 2R_{Line,l}\zeta_{l,t,w} + \varpi_{l,t,w}^{1} + \varpi_{l,t,w}^{2} - \varpi_{l,t,w}^{3} - \varpi_{l,t,w}^{4} = 0 \tag{A.65}$$

$$2\pi_{t,w}^{M}R_{Line,l}Q_{Line_l,t,w} - \sum_{n|l\in\hbar_n^{back}}\phi_{n,t,w}^{grid} + \sum_{n|l\in\hbar_n^{ahead}}\phi_{n,t,w}^{grid} - 2X_{Line,l}\zeta_{l,t,w} + \varpi_{l,t,w}^{1} - \varpi_{l,t,w}^{2} + \varpi_{l,t,w}^{3} - \varpi_{l,t,w}^{4} = 0 \tag{A.66}$$

$$\pi_{Load}^{Curt} + \psi_{n,t,w}^{Load,P} - \xi_{Curt_n,t,w}^{Load} = 0 \tag{A.67}$$

$$\pi_{Gen}^{Curt} + \psi_{n,t,w}^{RW} - \xi_{Curt_n,t,w}^{RW} = 0 \tag{A.68}$$

$$\pi_{n,t,w}^{grid} + \psi_{n,t,w}^{Load,P} - \frac{\sqrt{1-(\cos(\phi))_{Load_n}^{2}}}{\cos(\phi)_{Load_n}}\psi_{n,t,w}^{Load,Q} = 0 \tag{A.69}$$

$$\phi_{n,t,w} + \psi_{n,t,w}^{Load,Q} = 0 \tag{A.70}$$

$$-\pi_{n,t,w}^{grid} - \xi_{n,t,w}^{gen} = 0 \quad \forall n = 1 \tag{A.71}$$

$$-\pi_{n,t,w}^{grid} + \psi_{n,t,w}^{RW} = 0 \tag{A.72}$$

$$\sum_{l|n\in\hbar_l^{back}}\zeta_{l,t,w} - \sum_{l|n\in\hbar_l^{ahead}}\zeta_{l,t,w} - \nu_{n,t,w}^{1-} + \nu_{n,t,w}^{1+} = 0 \quad \forall n \geq 2 \tag{A.73}$$

$$\sum_{l|n\in\hbar_l^{back}}\gamma_{l,t} - \sum_{l|n\in\hbar_l^{ahead}}\zeta_{l,t,w} - \nu_{n,t,w}^{1-} + \nu_{n,t,w}^{1+} + +\nu_{1,t,w} = 0 \quad \forall n = 1 \tag{A.74}$$

Eqs: (43) − (48), (50) (A.75)

$$0 \leq \xi_{Curt_n,t,w}^{Load} \perp P_{Curt_n,t,w}^{Load} \geq 0 \tag{A.76}$$

$$0 \leq \xi_{Curt_n,t,w}^{RW} \perp P_{Curt_n,t,w}^{RW} \geq 0 \tag{A.77}$$

$$0 \leq \xi_{n,t,w}^{gen} \perp P_{n,t,w}^{gen} \geq 0 \tag{A.78}$$

$$0 \leq \nu_{n,t,w}^{1-} \perp (V_{n,t,w})^2 - (\underline{V})^2 \geq 0 \tag{A.79}$$

$$0 \leq \nu_{n,t,w}^{1+} \perp (\overline{V})^2 - (V_{n,t,w})^2 \geq 0 \tag{A.80}$$

$$0 \leq \varpi_{l,t,w}^{1} \perp \sqrt{2}\overline{S}_l - P_{l,t,w}^{Line} - Q_{l,t,w}^{Line} \geq 0 \tag{A.81}$$

$$0 \leq \varpi_{l,t,w}^{2} \perp \sqrt{2}\overline{S}_l - P_{l,t,w}^{Line} + Q_{l,t,w}^{Line} \geq 0 \tag{A.82}$$

$$0 \leq \varpi_{l,t,w}^{3} \perp \sqrt{2}\overline{S}_l + P_{l,t,w}^{Line} - Q_{l,t,w}^{Line} \geq 0 \tag{A.83}$$

$$0 \leq \varpi^{4}_{l,t,w} \perp \sqrt{2}\overline{S}_{l} + P^{Line}_{l,t,w} + Q^{Line}_{l,t,w} \geq 0 \tag{A.84}$$

After writing k sets of KKT conditions for leaders of the model (LECs), the method described by Leyffer and Munson in [46] is utilized to find a Nash equilibrium in two stages. According to this method, the complementarity constraints are removed ($\boldsymbol{\chi}_{LEC_{k},t,w} \times \mathbf{G}_{LEC_{K},t,w} = 0$) and a new objective function is defined which minimizes the sum of the taken out complementarity constraints. As expected, the objective function must be zero at the Nash equilibrium. As said, this optimization problem is done in two stages. Variables $\gamma^{6}_{k,t,w}$ and $\chi^{risk,2}_{k,w}$ provide non-linearity in some constraints of MPEC for each leader of the game. In order to reach to the relevant solution, they could be parameterized. To do this, at the first stage, the optimization problem comprises of the objective function including complementarity constraints as well as remaining constraints for MPEC of each leader is solved. Then, $\gamma^{6}_{k,t,w}$ and $\chi^{risk,2}_{k,w}$ are treated as parameters based on the results obtained for them in the first stage. Finally, in the second stage, the objective function is minimized considering all linear constraints. Since the value of the objective function is zero, the developed solution method guarantees the global optimality of the results. In this simulation, the CONNOPT solver is used to solve the problem.

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