A Peer-to-Peer Energy Trading Framework for Wind Power Producers With Load Serving Entities in Retailing Layer

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A Peer-to-Peer Energy Trading Framework for Wind Power Producers With Load Serving Entities in Retailing Layer

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***Abstract*—This article proposes a peer-to-peer (P2P) energy trading framework for wind power producer (WPP) in the retailing layer to increase its revenue and to promote wind power utilization. In this framework, the WPP can provide energy consumption of demand response providers (DRPs) in a competitive environment through both the main grid and rival load-serving entities. Also, based on a P2P pricing mechanism, the WPP can choose if to trade energy in a P2P platform or not. The proposed problem is formulated as a stochastic bilevel optimization model, in which in the upper level, the WPP profit is maximized and in the lower level, the DRPs participate in DR programs and tend to choose the fairest supplier among the WPP and LSEs to minimize their energy procurement costs. The proposed method is applied to a realistic case study and the results demonstrate that with P2P, the WPP can schedule the energy transaction with peers to offset part of the energy deviations. Moreover, different values of P2P prices lead to different values of energy transactions due to the relatively diversity pattern of local generation of rival LSEs and their offering prices and demand and generation of the WPP.**

***Index Terms*—Demand response providers (DRPS), peer-to-peer energy trading, stochastic programming, wind power producer (WPP).**

NOMENCLATURE

Sets and indices

t, T	Index (set) of time periods.
ω, N_Ω	Index (set) of scenarios for wind and market prices.
s, N_S	Index (set) of scenarios for rival LSE prices.
LSE, LSE'	Index of load-serving entities.
WPP	Index of the wind power producer.

Parameters

π_ω, π_s	Probability of scenario $\omega(s)$.
β	Risk aversion parameter.
α	Confidence value.
$\rho_{P2P,t,\omega}^{buy/sell}$	P2P buying/selling price (€/MWh).
$Elas_{t,h}$	The elasticity of demand of responsive customers.
$\rho_t^{DA,\text{int}}$	The average of DA market prices (€/MWh).
$\rho_{t,\omega}^{DA,buy/sell}$	DA buying/selling prices (€/MWh).
$\rho_{t,\omega}^{up/dn}$	Up/down regulation prices (€/MWh).
P_t^{int}	Initial demand of responsive loads (MWh).
$P_{t,\omega}^{TD}$	The total demand of customers (MWh).
$\hat{P}_t^{TD}$	The expected required demand of customers (MWh).
$X_{WPP,t,s}^{Di}$	Initial percentage of loads supplied by the WPP.
$X_{LSE,t,s}^{Di}$	Initial percentage of loads supplied by each LSE.
$P_{t,\omega}^{Wind}$	Wind energy production (MWh).
$\overline{P}_t^{buy/sell}$	Limits of buying/selling energy in P2P trading floor (MWh).
$R_{WPP,LSE}^D$	Fictitious cost to model the unwillingness of DRPs to transfer from WPP to LSEs. (€/MWh).
$R_{LSE,LSE'}^D$	Fictitious cost to model the unwillingness of DRPs to transfer among LSEs. (€/MWh).

Variables

$P_{WPP,t,\omega}^D$	The amount of energy under the jurisdiction of the under-study WPP (MWh).
$P_{t,\omega}^{DA,buy/sell}$	Energy bought/sold from/to DA market (MWh).
$P_{P2P,t,\omega}^{buy/sell}$	Energy bought/sold from/to P2P trading floor. (MWh).
$P_{t,\omega}^{up/dn}$	Energy compensation in the regulation market. (MWh).
$\rho_{WPP,t}^D$	The offering price to the DRPs by the under-study. WPP (€/MWh).
ξ	Value at risk (€).
η_ω	Auxiliary positive variable for CVaR calculations.
$X_{WPP,t,s}^D$	Percentage of loads supplied by the WPP.
$X_{LSE,t,s}^D$	Percentage of loads supplied by each LSE.
$Y_{WPP,LSE,t,s}$	Percentage of loads transferred among the WPP and LSEs.
$Y_{LSE,LSE',t,s}$	Percentage of load transferred among the LSEs.

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$u_{P2P,t,\omega}^{buy/sell}$	Binary variable for P2P trading.
U^Y, U^X	Binary variable used in the linear form of the complementary slackness conditions.

I. INTRODUCTION

DURING the last years, the implementation of wind power generation has grown rapidly worldwide [1]. Since the output power of wind turbines has characteristics of randomness and intermittency, it is more important for wind power producers (WPPs) to manage the risk of their participating in the electricity market. In fact, the WPPs are responsible for their energy deviations that are caused by the difference between the scheduled and the actual production, which must be compensated in balancing trading floors provided by expensive resources. To handle WPPs uncertainties, some technologies and facilities such as storage devices [2], pumped-storage hydroplants [3], gas turbines, and compressed air energy storage [4] have been coordinated with WPPs in order to address the randomized characteristics of the wind generation. In addition, in recent years, demand response (DR) resources have been suggested as a flexible and cost-effective option to control the uncertainty of WPPs [5].

Different works have been addressed studying the effect of DR programs on WPPs operation from different aspects [6]–[9]. In this target, the critical peak pricing, which is one of the DR programs has been suggested in [6], in which the optimal value of the critical peak pricing and value of wind energy to sell to the day ahead (DA) market have been investigated.

The influence of market rules and applying DR programs on decreasing the effect of estimating the wind power generation are evaluated in [7]. Moreover, a stochastic bilevel decision-making framework has been investigated in [8] for a WPP in short-term electricity markets to maximize its expected profit. In that study, DR and electric vehicle aggregators were capable to select the most competitive WPP such that their energy procurement costs be minimized in a competitive environment. Moreover, the positive benefits of DR on the WPPs' profit and energy exchange in the DA and intraday markets from the WPPs' viewpoint have been analyzed in [9].

Nowadays, peer-to-peer (P2P) energy trading mechanism has emerged as an impressive method to schedule the distributed energy resources (DERs) that allows energy from one prosumer to transfer to another prosumer or consumer without any direct effect of a central control system [10]. Formal energy exchange is usually unidirectional meaning that energy is transferred from generators to the customers through long distances, while the cash flow is the contrary direction. However, P2P exchanges develops multidirectional trading through a region [11]. Trials of energy trading through the P2P economy have attracted much attention that centralized on making incentive tariffs to the clients from the generators' viewpoint [12]. A P2P energy trading aggregation can make this condition such that a prosumer who requires energy can benefit from purchasing the excess energy at a partly cheaper rate from other prosumers within its community who has surplus energy [13]. Recently, many attempts have been made in designing P2P energy sharing model for prosumers. For example, in [14], an energy sharing method has been presented for a prosumer in a microgrid where each prosumer minimizes its energy costs following the internal dynamic prices based on the energy supply and demand ratio in a microgrid. Furthermore, in [15], a distributed and scalable bilateral contract networks has been presented for P2P energy trading among energy generators and consumers.

Moreover, some of the research works have used P2P energy trading mechanism at the distribution floor. For example, in [16], the coordination between demand side management system and P2P energy exchange in smart grid has been proposed to minimize their energy consumption costs. In [17], an energy sharing scheme with price-based DR has been studied and in [18], a noncooperative game-theoretical framework of the competition among DR aggregators for selling energy stored in energy storage is investigated. However, P2P energy trading mechanism in the retailing floor is neglected in the mentioned literature. Furthermore, the future power system with many integrated smart prosumers requires markets that display the nature of decentralized production and consumption. In comparison with the existing electricity markets, local markets are presumably essential for managing distributed renewable generation and for coordinating decentralized decision models that contents many of self-interested autonomous agents. In this regard, P2P markets provide decentralized, more autonomous, and flexible networks.

In order to cover this research gap, this article presents a method for the optimal scheduling of a WPP in the retailing layer remarking P2P energy trading mechanism. In this model, the WPP can exchange electrical energy with both the main grid and rival load serving entities (LSEs) under a P2P trading floor to attract DRPs in a competitive environment. Also, DRPs are able to choose a fair agent based on the offering price signals and purchase their required energy from the cheapest agent to minimize energy consumption costs. The proposed framework is formulated as a stochastic bilevel optimization problem, in which in the upper level the energy bidding decisions of the WPP to both main grid and rival LSEs as peers are made and the energy offering price to the DRPs is determined. In addition, at the lower level, the energy procurement costs of DRPs are minimized to obtain the energy required by customers and the percentage of loads to be supplied by the WPP and each LSEs.

Compared with previous studies, there are mainly two differences between this article and the existing research works.

First, in the proposed model, the DRPs are able to supply the required demand under their jurisdiction from the WPP and LSEs under competitive conditions and try to minimize their payments by participating in price-based DR programs.

Second, under the P2P energy trading mechanism according, the WPP can exchange energy with rival LSEs and act as a seller or buyer depending on the energy prices, wind generation profile and the required demand of DRPs. This trading framework has not attracted much attention in the previous literature, to the best of our knowledge. Therefore, the main novel contributions of the proposed method are listed as follows.

1) A two-stage bilevel stochastic framework is presented for the WPP decision making strategy in which DRPs can supply their required energy from either the WPP or LSEs with the minimum procurement costs.

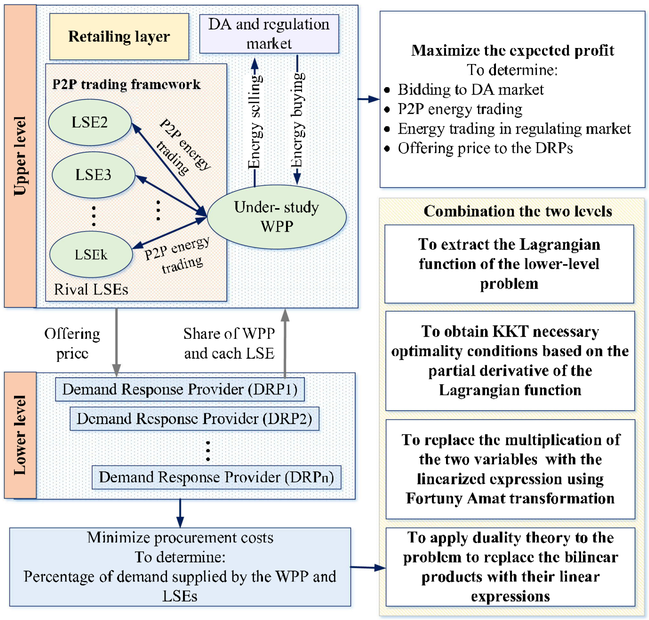


Fig. 1. Schematic of the proposed P2P trading framework.

2) A P2P energy trading platform is introduced in which, from energy trading arrangements in the local retailing layer, the WPP may ensure gaining economic benefits in P2P energy trading from LSEs instead of depending on costly markets.
3) Dynamic price-responsive behavior of DRPs' is modeled through a competitive environment in which the competition among the WPP and the LSEs is explicitly modeled to obtain the impacts of different design parameters of P2P energy sharing on the optimal decision making of the WPP via sensitive analysis.

The rest of the article is organized as follows. In Section II, the P2P energy trading framework for the WPP is described. In Section III, the proposed bilevel framework is formulated mathematically. Case studies and analysis of results are presented in Section IV, and finally, conclusions are given in Section V.

II. PEER-TO-PEER ENERGY TRADING FRAMEWORK

A. Problem Statement

A decision making strategy for WPP with considering P2P energy exchange mechanism is represented in this article. The schematic of the proposed framework is shown in Fig. 1. As observed, the proposed model includes a bilevel problem, in which, in the upper level, the WPP maximizes its profit and so determines its bidding to the DA market and the energy transaction in P2P trading floor as here and now decisions in the first stage. Given the here and now decisions, according to the regulating market prices, wait and see decisions are made in the second stage of the problem to cover the uncertainties. In the lower level, DRPs optimally react to the WPP's and LSEs' offering prices and the amount of their demand to be supplied by the WPP and each LSE is determined such that the DRPs' procurement costs be minimized. Through bidirectional communication and two-way energy flow system, the WPP is able to trade energy with other rival aggregators as LSEs in the retailing layer. The WPP as an agent in the retailing layer should procure electricity from three sources: the main grid, the other LSEs, and from its own wind generation. Then, the WPP resells the procured energy at fixed tariffs to the DRPs that are equipped with smart meters and information tools for local calculation and electrical energy distribution [19].

Here, it is supposed that the DRPs as smart players who have smart energy management systems (EMSs) can serve the loads under their territory. These loads that are responsive can reschedule their consumption to reduce their demands based on the elasticity factor, which is known as demand sensitivity with respect to the price as follows [20]:

$$P^{TD}_{t,\omega} = P^{\text{int}}_{t} \exp \sum_{h\in T} Elas_{t,h} \ln \left[\frac{\rho^{DA,buy}_{t,\omega}}{\rho^{DA,\text{int}}_{t}} + \frac{1}{1+Elas^{-1}_{t,h}} \right]. \tag{1}$$

The consumption information of loads in the territory of each DRP would be provided for the related DRP, which is responsible for serving loads. Given the demand ranges and based on energy price information offered by the WPP and LSEs, the EMS optimally chooses the fairest supplier. The WPP is also connected to the main grid, and thus it can buy/sell energy from/to the main grid and to other LSEs through a P2P contract. Finally, the competition among the WPP and rival LSEs and the DRPs' response to electricity prices offered by WPP and LSEs are both precisely considered via a stochastic bilevel programming framework [21]. In such competitive environment, each of the LSEs and the WPP offers their prices to the DRPs and the DRPs can decide from which supplier to purchase energy to supply their required demand. Therefore, the WPP and the LSEs compete against each other to attract the DRPs and in this case they can augment their share to supply the required demand.

B. P2P Energy Trading Mechanism of the WPP

P2P energy trading mechanism prepares options for the WPP to deal energy within its neighborhood through local exchanges. The collaboration of WPP and LSEs under P2P decreases their dependence on energy trading with the main grid and promotes wind power utilization. In other words, the implementation of P2P trading mechanism by WPP and LSEs causes the energy sold/bought to/from the DA and regulating markets reduces. In this article, a motivational scheme is used to encourage the WPP to take part in P2P trading floor. In this base, the WPP can sell its surplus energy to other LSEs with relatively high prices rather than the DA ones

$$\rho^{sell}_{P2P,t,\omega} = (1+\gamma_{i,j})\rho^{DA}_{t,\omega} \qquad i,j = 1,2,3,\ldots \quad \text{and} \quad i \neq j \tag{2}$$

where, $\gamma_{i,j} \in [0,\infty]$ is a compensating selling price factor that is used to compensate the WPP to sell its extra energy to other LSEs as peers. When $\gamma_{i,j} = 0$, the P2P selling price is equal to the price of electricity bought from the main grid (i.e., $\rho^{sell}_{P2P,t,\omega} = \rho^{DA}_{t,\omega}$). In this condition, WPP *i* may prefer to sell its surplus energy to the LSEs under the P2P mechanism. However, by increasing $\gamma_{i,j}$, the WPP *i* can achieve a higher benefit from selling more energy to the LSE *j* rather than selling it to the main grid. Moreover, to encourage the WPP to participate in P2P trading one day prior to power delivery, it should be able to purchase energy from the LSEs with relatively lower prices rather than the DA ones

$$\rho^{buy}_{P2P,t,\omega} = (1 - \lambda_{i,j})\rho^{DA}_{t,\omega} \quad i, j = 1, 2, 3, \ldots \tag{3}$$

where, $\lambda_{i,j} \in [0, \infty]$ is a compensating buying price factor to encourage the WPP to participate in the P2P energy trading floor. When there is no compensating price (i.e., $\lambda_{i,j} = 0$), the P2P buying price is equal to the DA price, and all or a main part of the required energy is bought from the main grid. By increasing $\lambda_{i,j}$, WPP *i* prefers to provide more energy from LSE *j* to act more economically rather than the case of not taking part in P2P energy trading.

Generally, P2P energy sharing provides options for the participants to trade energy within the neighborhood through local buying and selling energy exchanges. Therefore, through P2P trading, the dependence of the participant on the main grid reduces and consequently, they can supply each other locally. In this regard, the P2P prices should be defined such that to encourage the market players to trade energy with each other. Therefore, in the proposed framework, it is considered that the P2P buying price should not be higher than the price of electricity bought from the grid and the P2P selling price should not be lower than the price of electricity sold to the grid.

III. MATHEMATICAL FORMULATION OF THE PROBLEM

Here, the WPP optimal offering/bidding strategy problem is formulated as a stochastic bilevel optimization framework that the uncertainties lie in the market prices, WPP production, customers' consumption, and rivals' offers. The upper level of the problem deals with WPP profit maximization in the DA, regulation markets, and P2P trading floor, and the lower level represents minimization of DRPs' total costs of supplying customers. In order to combine the upper level and lower level of the problem, the following steps are applied to the problem.

1) For a given vector of upper level variables, the Lagrangian function of the lower level problem is obtained.
2) In addition to the primal feasibility constraints of the lower level, the KKT necessary optimality conditions of the lower level problem would be obtained by partial derivative of the Lagrangian function.
3) It should be noted that the multiplication of the two variables can be replaced with the linearized expression by introducing a new binary variable and large constant as explained in [22]. Then, the nonlinear complementary slackness conditions are equivalently expressed as a set of linear constraints. Then, duality theory is applied to the problem and the bilinear products are replaced with their linear expressions.

A. *Upper Level Problem Formulation*

The objective of the WPP is maximizing its expected profit as follows:

$$Max \sum_{\omega \in N_\Omega} \pi_\omega \sum_{t \in T} \begin{bmatrix} \rho^{D}_{WPP,t} P^{D}_{WPP,t,\omega} \\ +\rho^{DA,sell}_{t,\omega} P^{DA,sell}_{t,\omega} - \rho^{DA,buy}_{t,\omega} P^{DA,buy}_{t,\omega} \\ +\rho^{sell}_{P2P,t,\omega} P^{sell}_{P2P,t,\omega} - \rho^{buy}_{P2P,t,\omega} P^{buy}_{P2P,t,\omega} \\ -\rho^{up}_{t,\omega} P^{up}_{t,\omega} + \rho^{dn}_{t,\omega} P^{dn}_{t,\omega} \end{bmatrix}$$
$$\times \Delta t. + \beta \left(\xi - \frac{1}{1-\alpha} \sum_{\omega \in N_\Omega} \pi_\omega \eta_\omega \right) \tag{4}$$

The expression in (4) includes two different terms, called the expected profit of the WPP and CVaR of the profit weighted by β. The WPP expected profit comprises of the revenue from selling energy to the DRPs and to the DA market minus the energy bought from the DA. Also, the WPP makes benefits from selling energy to the rival LSEs minus the energy purchased from them under the P2P mechanism. Also, the costs of compensating the deviations in the regulation market are brought to the profit term. In addition, the risk associated with the profit variability is explicitly considered in this model through the incorporation of CVaR term as a risk measurement equipment.

The objective function (4) is subjected to the following constraints:

$$P^{Wind}_{t,\omega} + P^{buy}_{P2P,t,\omega} + P^{DA,buy}_{t,\omega} + P^{up}_{t,\omega}$$
$$= P^{D}_{WPP,t,\theta} + P^{sell}_{P2P,t,\omega} + P^{DA,sell}_{t,\omega} + P^{dn}_{t,\omega} \tag{5}$$

$$0 \leq P^{buy}_{P2P,t,\omega} \leq \overline{P}^{buy}_{t} u^{buy}_{P2P,t,\omega} \tag{6}$$

$$0 \leq P^{sell}_{P2P,t,\omega} \leq \overline{P}^{sell}_{t} u^{sell}_{P2P,t,\omega} \tag{7}$$

$$0 \leq u^{buy}_{P2P,t,\omega} + u^{sell}_{P2P,t,\omega} \leq 1 \tag{8}$$

$$\sum_{\omega \in N_\Omega} \pi_\omega \sum_{t \in T} \begin{bmatrix} \rho^{D}_{WPP,t} P^{D}_{WPP,t,\omega} \\ +\rho^{DA,sell}_{t,\omega} P^{DA,sell}_{t,\omega} - \rho^{DA,buy}_{t,\omega} P^{DA,buy}_{t,\omega} \\ +\rho^{sell}_{P2P,t,\omega} P^{sell}_{P2P,t,\omega} - \rho^{buy}_{P2P,t,\omega} P^{buy}_{P2P,t,\omega} \\ -\rho^{up}_{t,\omega} P^{up}_{t,\omega} + \rho^{dn}_{t,\omega} P^{dn}_{t,\omega} \end{bmatrix}$$
$$+ \eta_\omega - \xi \geq 0 \tag{9}$$

$$\eta_\omega \geq 0. \tag{10}$$

Constraint (5) denotes that at each hour and scenario, the summation of the wind power, buying power from the rival LSEs, DA and upregulation markets is equal to the summation of the power consumed by customers under the jurisdiction of the WPP, and selling power to the rival LSEs, DA, and downregulation markets. Constraints (6) and (7) show the limits of buying and selling power in the P2P mechanism, respectively. Constraint (8) states that it is prohibited to purchase power from one peer and sell it back to the same or other peers. Constraints (9) and (10) are the CVaR limits [21].

B. Lower Level Problem Formulation

The objective function of the lower level is minimizing procurement cost of customers that can be formulated as follows:

$$\text{Min}\sum_{t\in T}\overset{\frown}{P}_t^{TD}\left[\begin{array}{c}\rho_{WPP,t}^{D}X_{WPP,t,s}^{D}\\ +\sum_{LSE}\rho_{LSE,t,s}^{D}X_{LSE,t,s}^{D}\\ +\sum_{LSE\neq LSE'}R_{LSE,LSE'}^{D}Y_{LSE',LSE,t,s}^{D}\\ +R_{WPP,LSE}^{D}Y_{WPP,LSE,t,s}^{D}\end{array}\right]. \tag{11}$$

The first two terms of (11) state the consumption costs of customers provided from WPP and the LSEs, respectively. The last two terms explain the costs due to the unwillingness of customers to transfer among the LSEs and the WPP. The above objective function is restricted with the following constraints:

$$\overset{\frown}{P}_t^{TD}X_{WPP,t,s}^{D}=\overset{\frown}{P}_t^{TD}X_{WPP,t,s}^{Di}+\overset{\frown}{P}_t^{TD}Y_{LSE,WPP,t,s}^{D}$$

$$-\overset{\frown}{P}_t^{TD}Y_{WPP,LSE,t,s}^{D}:\varphi_{s,WPP} \tag{12}$$

$$\overset{\frown}{P}_t^{TD}X_{LSE,t,s}^{D}=\overset{\frown}{P}_t^{TD}X_{LSE,t,s}^{Di}+\overset{\frown}{P}_t^{TD}$$

$$\sum_{LSE\neq LSE'}Y_{LSE',LSE,t,s}^{D}$$

$$-\overset{\frown}{P}_t^{TD}\sum_{LSE\neq LSE'}Y_{LSE,LSE',t,s}^{D}:\varphi_{s,LSE} \tag{13}$$

where $X_{WPP,t,s}^{Di}$ and $X_{LSE,t,s}^{Di}$ are the initial percentage of loads supplied by the WPP and rival LSEs. Considering the best response of the consumers, constraints (12) and (13) specify the contribution of the WPP and the LSEs to supply the DRPs' demand, respectively. Moreover, constraint (14) states that the total required demand of customers should be supplied by the WPP and the rival LSEs

$$X_{WPP}^{D}\overset{\frown}{P}_t^{TD}+\sum_{LSE}X_{LSE,t,s}^{D}\overset{\frown}{P}_t^{TD}=\overset{\frown}{P}_t^{TD}\quad:\mu_{s,WPP/LSE} \tag{14}$$

where $\varphi_{s,WPP}$, $\varphi_{s,LSE}$, and $\mu_{s,WPP/LSE}$ are Lagrange multiplier.

C. Combination of Upper and Lower Levels

The bilevel problem is formulated such that the decision-maker WPP as the leader is in the upper level while DRPs in the lower level decide as the follower. To solve the problem, it is changed into a single-level mathematical program with equilibrium constraints (MPEC) by substituting the lower level problem with its Karush–Kuhn–Tucker (KKT) optimality conditions [20]. In addition, the nonlinearities of the derived MPEC are linearized using the strong duality theorem as in [23] and the technique provided in [22]. Therefore, the single-level problem is obtained with the objective function in (4), with the constraints given in both upper and lower level and the complementarity slackness conditions that are linearized using binary variables based on the method given in [24]

$$\overset{\frown}{P}_t^{TD}\rho_{WPP,t}^{D}-\mu_{WPP,s}-\varphi_{s,WPP}\geq 0 \tag{15}$$

$$\overset{\frown}{P}_t^{TD}\rho_{WPP,t}^{D}-\mu_{WPP,s}-\varphi_{s,WPP}\leq M_1U_{WPP,s} \tag{16}$$

$$\overset{\frown}{P}_t^{TD}\rho_{LSE,t,s}^{D}-\mu_{LSE,s}-\varphi_{s,LSE}\geq 0 \tag{17}$$

$$\hat{E}_t^{TD}\rho_{LSE,t}^{D}-\mu_{LSE,s}-\varphi_{s,LSE}\leq M_1U_{LSE,s}^{X} \tag{18}$$

$$X_{WPP,t,s}^{D}\leq M_2[1-U_{WPP,s}^{X}] \tag{19}$$

$$X_{LSE,t,s}^{D}\leq M_2[1-U_{LSE,s}^{X}] \tag{20}$$

$$\overset{\frown}{P}_t^{TD}R_{WPP,LSE}^{D}+\mu_{WPP,s}-\mu_{LSE,s}\geq 0 \tag{21}$$

$$\overset{\frown}{P}_t^{TD}R_{LSE,LSE'}^{D}+\mu_{LSE,s}-\mu_{LSE',s}\geq 0\ :LSE\neq LSE' \tag{22}$$

$$\overset{\frown}{P}_t^{TD}R_{WPP,LSE}^{D}+\mu_{WPP,s}-\mu_{LSE,s}\leq M_1U_{WPP,LSE,s}^{Y} \tag{23}$$

$$\overset{\frown}{P}_t^{TD}R_{LSE,LSE'}^{D}+\mu_{LSE,s}-\mu_{LSE',s}\leq M_1U_{LSE,LSE',s}^{Y}$$

$$:LSE\neq LSE' \tag{24}$$

$$Y_{WPP,LSE,t,s}^{D}\leq M_2[1-U_{WPP,LSE,s}^{Y}] \tag{25}$$

$$Y_{LSE,LSE',t,s}^{D}\leq M_2[1-U_{LSE,LSE',s}^{Y}]\quad:LSE\neq LSE'. \tag{26}$$

In the above expressions, M_1 and M_2 are large constants that should be chosen such that to avoid ill-conditioning. The bilinear production $\rho_{WPP,t}^{D}E_{WPP,t,\omega}^{D}$ is nonlinear and is linearized using the strong duality theory as in [25]. Therefore, this production that implies the revenue that the WPP obtains from selling energy to the customers is obtained as below

$$\rho_{WPP,t}^{D}E_{WPP,t,\omega}^{D}=\frac{P_{t,\omega}^{TD}}{\overset{\frown}{P}_t^{TD}}$$

$$\times\left[\begin{array}{c}-\sum_{s\in N_S}\sum_{LSE}\overset{\frown}{P}_t^{TD}\rho_{LSE,t,s}^{D}X_{LSE,t,s}^{D}\\ -\sum_{s\in N_S}\sum_{LSE}\overset{\frown}{P}_t^{TD}R_{WPP,LSE}Y_{WPP,LSE,t,s}\\ -\sum_{s\in N_S}\sum_{LSE}\overset{\frown}{P}_t^{TD}R_{WPP,LSE}Y_{WPP,LSE,t,s}\\ +\sum_{s\in N_S}X_{WPP,t,s}^{Di}\mu_{WPP,s}+\varphi_{s,WPP}\\ -\sum_{s\in N_S}\sum_{LSE}\overset{\frown}{P}_t^{TD}R_{WPP,LSE}Y_{WPP,LSE,t,s}\end{array}\right]. \tag{27}$$

IV. INPUT DATA AND SIMULATION RESULTS

A. Input Data and Assumptions

The performance of the proposed strategy is assessed on a realistic case study based on the data from the Nordpool electricity market [26]. The DA and balancing market prices are given in Fig. 2. The total requested demand is illustrated in Fig. 3 [27]. Also, it is supposed that the WPP owns a wind farm with the expected wind generation shown in Fig. 3 [28]. Furthermore, this WPP competes against rival LSEs to attract more responsive loads. Here, the WPP acts as decision-maker and LSE$_2$ and LSE$_3$ are rival LSEs. In addition, the financial risk associated with the WPP profit variability is considered in risk aversion parameter

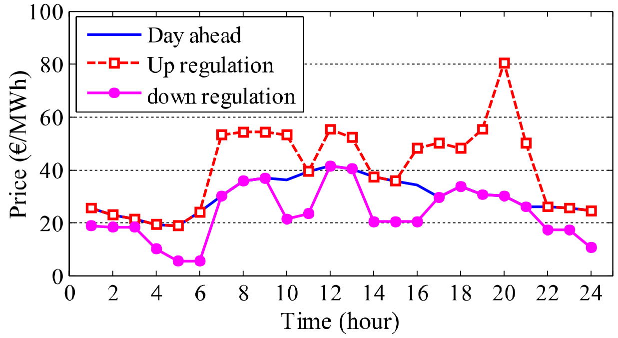


Fig. 2. Electricity market prices.

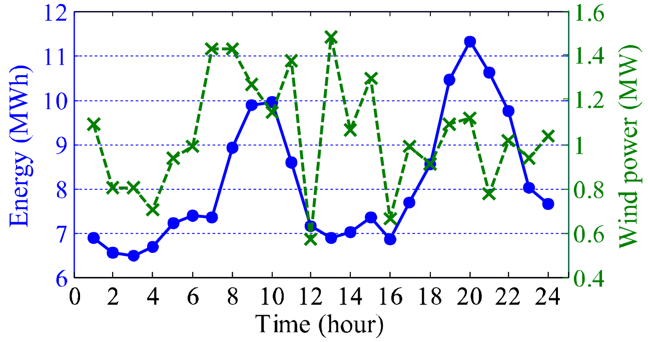


Fig. 3. Total demand of responsive loads and wind energy generated.

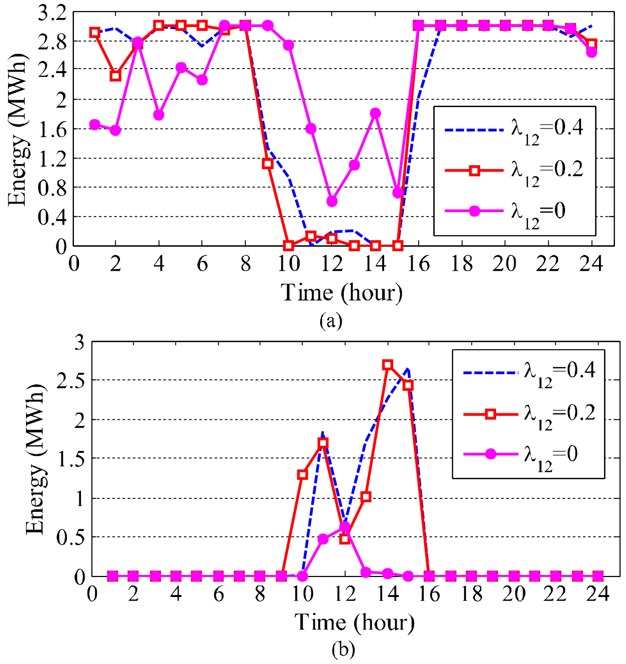


Fig. 4. DA transactions in $\lambda_{13} = 0$ and $\gamma_{12,\,13} = 0$, $\gamma_{13} = 0$. (a) Purchases. (b) Selling.

(β) equal with 1. Also, the P2P energy trading mechanism among the WPP and the LSEs is also considered based on which the WPP can purchase or sell electricity energy with other rival LSEs.

Finally, the optimization problem is carried out by CPLEX solver using GAMS software [29] on a PC with 4 GB of RAM and Intel Core i7 at 2.60 GHz processor. Considering a MIP gap of 0%, the computation time for the studied cases was between 3 and 6 min, with an average of 4 min and 42 s.

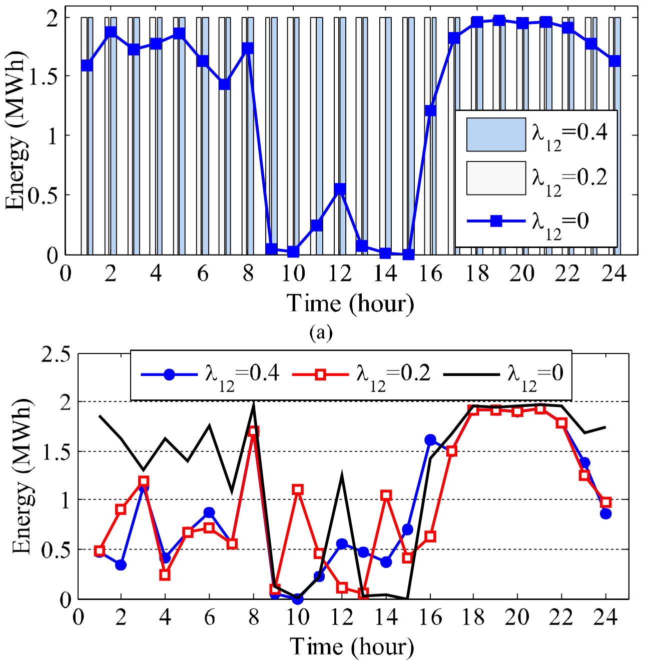
B. Simulation Results

The amount of buying and selling energy from DA market in different buying price factors ($\lambda_{12} = 0.4, 0.2$, and 0) are depicted in Fig. 4. Here, it is assumed that buying price from LSE$_3$ and selling price to the rivals to be equal with the DA price (i.e., $\lambda_{13} = 0$, $\gamma_{12} = 0$ and $\gamma_{13} = 0$). The observations are explained as follows. The main part of DRPs' demand is supplied through the main grid when it is relatively cheap such as early hours in the morning (1:00–8:00) or when it is really necessary like peak hours (16:00–24:00). While, in other hours, when wind generation is high and the required demand is low, the WPP sells its extra energy to the main grid. Moreover, this figure shows how the DA energy trading in different values of λ_{12} changes. In $\lambda_{12} = 0.4$, the P2P buying price is lower than the price of DA market, the WPP purchases a relatively low amount of its required energy from the DA market. In fact, when there is insufficient energy from wind generation, the WPP can purchase its required demand from rival LSEs with lower prices. But, in a lower compensating price factor (i.e., $\lambda_{12} = 0$), the energy purchased from DA market increases.

Fig. 4(b) depicts the energy sold to the DA market in three values of λ_{12}. As observed, with decreasing λ_{12}, the energy sold to the main grid reduces. Because, in higher values of λ_{12}, the WPP supplies its required demand from peers with lower prices. Therefore, it can sell surplus energy to the main grid to obtain more benefits. But, in low values of λ_{12}, the WPP supplies the loads under its jurisdiction through its own wind generation and then reduces its selling to the DA market.

Fig. 5 shows the energy purchased from rival LSE$_2$ and LSE$_3$ in different values of λ_{12}. In high values of λ_{12}, the WPP feeds-in its loads with relatively low prices. Therefore, it purchases from LSE$_2$ with the maximum value. But, when λ_{12} decreases, the WPP reduces its energy procurement from LSE$_2$, specifically during the period with high wind generation (9:00 to 15:00). Moreover, Fig. 5(b) shows in high values of λ_{12}, the WPP buys a low volume of energy from LSE$_3$, because it supplies most of its required demand from rival LSE$_2$ with lower prices. But, when λ_{12} decreases, the WPP reduces energy procurement from both rivals as expensive suppliers. Therefore, the P2P energy trading makes opportunities for the WPP to exchange energy within a neighborhood through local trading to make more benefit.

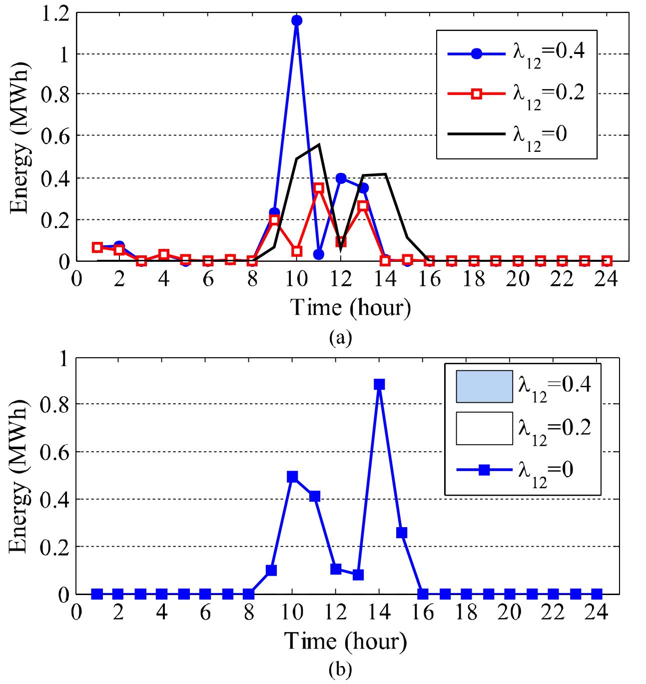
Fig. 6 shows the energy sold to the rival LSEs in different compensating price factors. During the middle hours of the day that the WPP has enough wind generation, it prefers to sell the energy to the rival peers instead of to the DRPs to ensure the WPP can gain economic benefit. In high compensating price factor, selling to both rival LSEs may undermine the revenue of the WPP; however, in lower values of that factor, the WPP sells energy to both rivals to provide revenue. The WPP submits energy deviation bids to the regulation market to request the required



(a)

(b)

Fig. 5. P2P energy buying in $\lambda_{13}=0$ and $\gamma_{12,}=0, \gamma_{13}=0$ from (a) LSE$_2$ and (b) LSE$_3$.



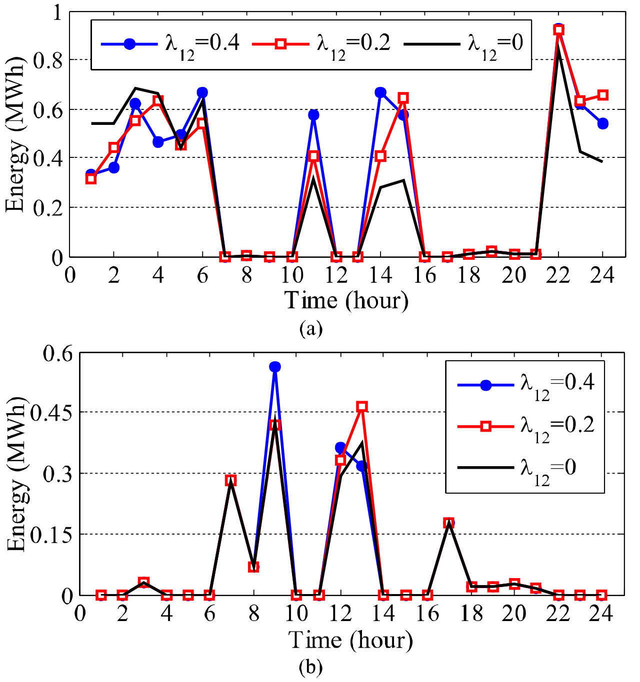
(a)

(b)

Fig. 6. P2P energy selling in $\lambda_{13}=0$ and $\gamma_{12,\ 13}=0, \gamma_{13}=0$ to (a) LSE$_2$ and (b) LSE$_3$.

energy in order to counteract the unplanned deviations. Fig. 7 depicts the energy deviations to be supplied in the regulation market.

The energy deficit is compensated from the costly upregulating market, while the energy surplus is sold to the down-regulating trading floor cheaper than DA market prices. In high



(a)

(b)

Fig. 7. Compensation of energy deviation in $\lambda_{13}=0$ and $\gamma_{12}=0, \gamma_{13}=0$ in (a) up regulation market and (b) down regulation market.

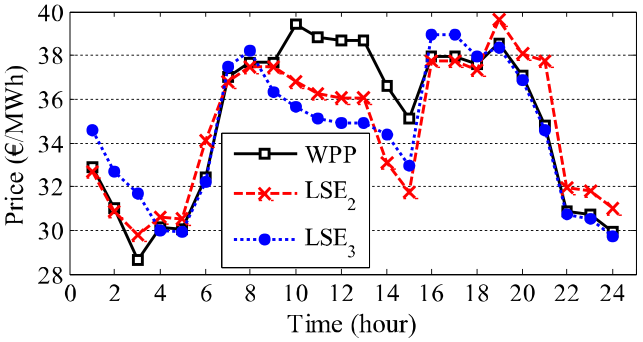


Fig. 8. Offering price to the customers by WPP and rivals in $\lambda_{13}=0.4$, 0.2, and 0, $\lambda_{13}=0$, $\gamma_{12}=0$ and $\gamma_{13}=0$.

λ_{12}, the energy bidding of the WPP in the regulation market increases. In fact, P2P interactions augment the energy transaction in the balancing trading floor, because, in P2P trading, the WPP encounters with uncertainties which originated from the P2P prices. Therefore, the WPP should increase its participation in the regulation market to cover the deviations resulted from the incomplete information of rivals' prices.

The offering price of the WPP and LSEs and the percentage of loads supplied by all of them are given in Figs. 8 and 9, respectively. The price offered by the WPP is usually fair enough to attract responsive loads. However, in some hours specifically from 9:00 to 15:00, the DRPs' load as in Fig. 3 is low and the WPP sells its extra energy to DA and to rivals, it offers higher prices to the DRPs. In this regard, DRPs would go to the rivals and the WPP can sell the extra energy to the market and peers. It is implied from Fig. 9 that the DRPs usually choose the supplier (among the WPP and the LSEs) with a lower price to minimize

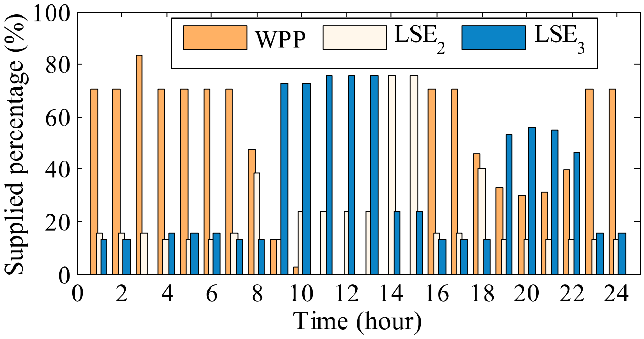


Fig. 9. Percentage of energy supplied by WPP and rivals.

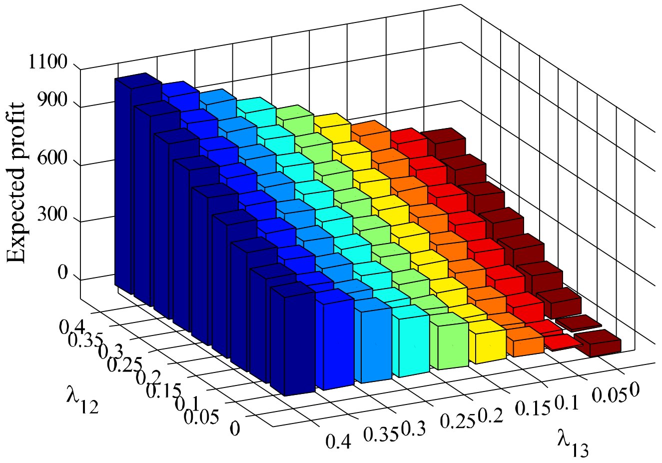


Fig. 10. Expected profit of WPP$_1$ versus different values of $\lambda_,$ in $\gamma_{12} = 0$ and $\gamma_{13} = 0$.

TABLE I
ENERGY TRANSACTION WITH AND WITHOUT P2P TRADING FLOOR

λ_{12}	λ_{13}	**DA selling**	**DA buying**	**Up Regulation**	**Down Regulation**	**Buying LSE$_2$**	**Buying LSE$_3$**	**Selling LSE$_2$**	**Selling LSE$_3$**
0.4	**0.4**	17.1	37.3	5.0	3.2	47.9	47.8	0	0
0.4	**0.2**	16.8	37.7	4.8	3.7	48.0	47.5	0	0
0.4	**0**	9.3	52.6	6.4	1.5	48.0	22.7	2.2	2.2
0.2	**0.4**	17.0	37.7	4.8	3.5	47.5	48.0	0	0
0.2	**0.2**	17.1	37.7	4.8	3.5	47.8	47.7	0	0
0.2	**0**	8.9	50.4	6.6	1.9	48.0	24.1	1.7	1.7
0	**0.4**	8.7	51.9	6.9	1.7	21.7	48.0	0	0
0	**0.2**	8.4	48.7	7.0	1.9	24.5	48.0	0	0
0	**0**	0.86	57.9	6.3	1.6	29.0	30.0	2.2	2.2
No P2P		0.10	58.5	8.7	1.8	-	-	-	-

their procurement costs. Therefore, WPP and rivals compete against each other to attract customers.

Moreover, as observed in Fig. 8, in different values of λ_{12}, the same price is offered to the loads. As expected, purchasing energy from different suppliers such as the main grid or LSEs does not affect the offering price. Because, by changing the offering price to the loads, in such a competitive environment, the WPP may lose its customers. But the effect of supplying loads from rival LSEs in different values of compensating price factors is seen on the expected profit of the WPP that would be explained next.

Fig 10 shows the expected profit of the WPP versus λ_{12} and λ_{13}. When λ_{12} and λ_{13} have higher values, since the WPP purchases energy with lower price from the rival LSEs, it obtains high expected profits, while with increasing the price offered by rivals (i.e., lower values of λ_{12} and λ_{13}), the WPP loses its profit due to high P2P prices. Therefore, the WPP might not have the motivation to supply its required demand through P2P trading and, as a result, it may exit from the P2P contracts. The profile of expected profit versus λ_{12} and λ_{13} is significant that allows the WPP as a decision-maker to decide whether to participate in a P2P trading strategy or supply its loads from the grid, directly.

Table I depicts the energy transaction with the upstream and the peers in the cases with and without the P2P platform. As it can be observed, the cheaper the P2P prices, the more energy purchased from the peers. For example, in a constant λ_{12} and with decreasing λ_{13} (increasing the buying price from LSE$_3$), the WPP tends to purchase less energy from LSE$_3$ and instead to supply its energy requirement from the grid and even the other peer. Therefore, the energy purchased from the DA market and LSE$_2$ augments.

Also, the WPP, as decision-maker, is responsible to compensate the uncertainties in the regulating market. These uncertainties of the problem result in revenue loss for the WPP that should be covered. As seen, in case of with P2P, the WPP purchases more energy from peers with lower prices instead of upregulation market. In other words, with P2P energy trading, the WPP can schedule the energy transaction with peers to offset part of the energy deviations. Therefore, the WPP can ensure the real-time balance between generation and demand by entering P2P trading with cheaper prices. But, in case of without P2P, the WPP should compensate the energy deviation in a costly regulating market.

Moreover, without entering the P2P trading floor, the WPP should purchase the total energy from the DA market while its energy selling to the DA market reduces significantly. But, with P2P, the WPP can purchase the required energy from peers with cheaper prices and sell its excess generation to the DA market to make more revenue. Besides, it is observed from Table I that different values of (λ_{12}, λ_{13}) lead to different results. For instance, the results obtained for (0.4, 0) differ from those achieved with (0, 0.4). That is due to the relatively diversity pattern of the local generation of rival LSEs and their offering prices and the demand and generation of the WPP.

In order to guarantee the effectiveness of the proposed framework, different inputs including the DA prices, regulating market prices as well as the rival LSEs' offering prices are changed. Fig. 11 shows the DA market price and Fig. 12 illustrates the rivals' prices. The offering prices of the WPP are drawn on the offering prices of rivals. Then, the share of the WPP and LSEs to supply the required demand of loads is also provided in Fig. 13. As seen, since the WPP competes against rival LSEs, the trend of its offering price usually follows the prices of rival LSEs. When the DA market prices are low, the WPP offers cheap prices. But,

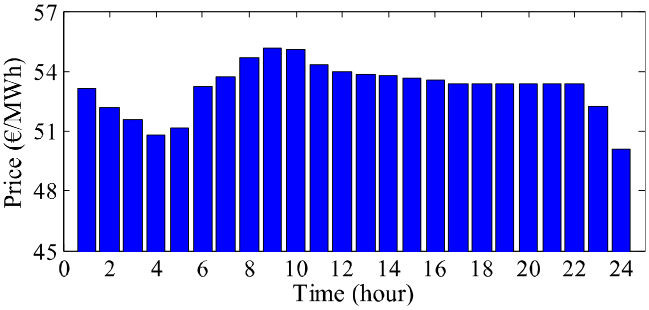


Fig. 11. DA market price.

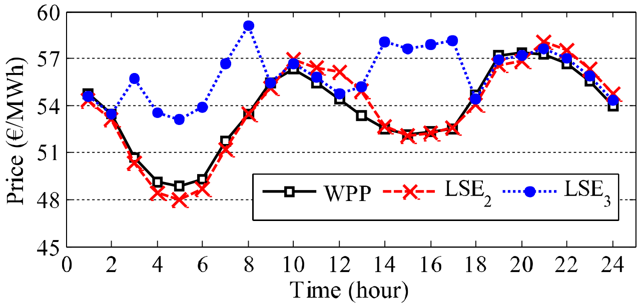


Fig. 12. Offering price to the customers by WPP and rivals in $\lambda_{13} = 0.4$, 0.2 and 0, $\lambda_{13} = 0$, $\gamma_{12} = 0$ and $\gamma_{13} = 0$.

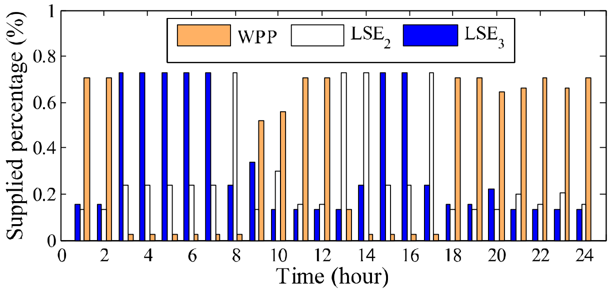


Fig. 13. Percentage of energy supplied by WPP and rivals.

when the DA prices are high, the WPP offers high prices to the customers, else, it may confront with bankruptcy.

Based on the offering prices of the WPP and the LSEs, their contribution to supply the loads is obtained. It is reasonable that the cheaper one attracts more customers. While the more expensive the prices, the less number of customers are supplied by the providers.

Totally, it can be concluded that based on multiple cases including various input data such as market prices and offering prices of rivals, different results would be obtained.

V. CONCLUSION

This article presented a P2P energy trading framework in order to improve the expected profit of the WPP. The proposed framework was implemented on a case study and the results show that collaboration of WPP and LSEs under the P2P trading floor decreases their dependence on the energy trading with the main grid, and consequently, it promotes the local wind power utilization. In fact, through a P2P trading mechanism, the diversity of generation and load profiles of peers facilitates the balance. In the P2P trading floor, if the energy cost of rival LSEs is high, the WPP may have the incentive to exit the P2P contract and seek to trade with the grid directly.

In different prices of energy trading in the P2P platform, the WPP decides not to vary its offering price to the lower level, since, in a competitive environment, it may lose its customers. As a main result, the profile of the expected profit versus different values of prices offered by rivals to the WPP was given, based on which the WPP can decide whether to purchase energy from the rival LSEs or not. Therefore, based on the profile of energy trading with grid and peers, and the expected profit of the WPP, the WPP operator can decide how to react with different values of rivals' prices. Therefore, prior to the construction of the decision making strategy, the WPP can observe its bidding in the DA market, offering to individual customers and purchasing energy through the P2P trading floor. Therefore, the WPP operator can choose its optimal operating point that it prefers. Also, in the presence of P2P trading, the WPP purchases more energy from peers with lower prices instead of that from the upregulation market. In other words, with P2P energy trading, the WPP can schedule the energy transaction with peers to offset part of the energy deviations with cheaper prices than the costly regulating market. Different values of P2P prices lead to different values of energy transactions mainly due to the relatively diversity pattern of the local generation of rival LSEs and their offering prices and the demand and generation of the WPP.

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