Optimal Trading of Plug-in Electric Vehicle Aggregation Agents in a Market Environment for Sustainability

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Abstract

Ever since energy sustainability is an emergent concern, Plug-in Electric Vehicles (PEVs) significantly affect the approaching smart grids. Indeed, Demand Response (DR) brings a positive effect on the uncertainties of renewable energy sources, improving market efficiency and enhancing system reliability. This paper proposes a multi-stage stochastic model of a PEV aggregation agent to participate in day-ahead and intraday electricity markets. The stochastic model reflects several uncertainties such as the behaviour of PEV owners, electricity market prices, and activated quantity of reserve by the system operator. For this purpose, appropriate scenarios are utilized to realize the uncertain feature of the problem. Furthermore, in the proposed model, the PEV aggregation agents can update their bids/offers by taking part in the intraday market. To this end, these aggregation agents take part in Demand Response eXchange (DRX) markets designed in the intraday session by employing DR resources. The numerical results show that DR provides a perfect opportunity for PEV aggregation agents to increase the profit. In addition, the results reveal that the PEV aggregation agent not only can increase its profit by participating in the DRX market, but also can become an important player in the mentioned market.

Keywords: Intraday demand response exchange; Offering/bidding strategy; Plug-in electric vehicle aggregation.

Nomenclature

Indices (Sets)

d	demand response provider
k	block of price-quantity offer
i	plug-in electric vehicle
t	time
ω (Ω)	scenario

Parameters and Variables

$Act_{t,\omega}^{Res}$	activated amount of reserve by system operator
$C^{battery}$	battery investment cost

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$C^{\deg}$	degradation cost
$c_{d,t}^{k}$	offered price of demand response provider
$Cost_{t,\omega}^{Charge}$	cost of purchasing energy to charge PEVs
$Cost_{t,\omega}^{Obl}$	cost of purchasing energy to meet the aggregation agent obligations
$Cost_{t,\omega}^{Imb}$	cost of imbalance penalties
$Cost_{t,\omega}^{Intra}$	cost of purchasing from the intraday electricity market
$Cost_{t,\omega}^{DRX}$	cost of purchasing DR from intraday DRX market
$Cost_{\omega}^{Res}$	payment cost to PEV owners for taking part in the reserve market
$Cost^{Infra}$	annualized infrastructure cost
$Cost^{Wiring}$	wiring upgrade cost
$Cost^{On-board}$	on-board incremental cost
$CDRP_{d,t}$	cost of demand response provider
dr	yearly discount rate
$DR_{d,t}$	traded amount of DR in DRX
$DR_{d,t}^{\max}$	maximum offered capacity of DRP d
E_{Ω}	expected value resulted from set of scenarios
FOR^{Agg}	probability of inability to generate energy
$Income_{t,\omega}^{Res}$	income resulted from taking part in the reserve market
$Income_{t,\omega}^{Call}$	income resulted from delivering the delegated amount of reserve
$Income_{t,\omega}^{Energy}$	income resulted from participation in the electricity market
$Income_{t,\omega}^{Intra}$	income resulted from selling to intraday electricity market
$Income_{t,\omega}^{DRX}$	income resulted from selling DR to intraday DRX market
$Income_{\omega}^{Charge}$	income of charging the PEVs
$L^{battery}$	battery lifetime
N^{y}	life expectancy of device

$Offer_{t,\omega}^{Res}$ quantity of offer to reserve market

$Offer_{t,\omega}^{En}$ quantity of offer to energy market

$P_{t,\omega}^{del}$ probability of delivering the delegated amount of reserve

$P_{i,t,\omega}^{\mathrm{G2V}}$ injection from grid to PEV i

$P_{t,\omega}^{Intra,buy}$ buying power in intraday market

$P_{t,\omega}^{Intra,sell}$ selling power in intraday market

$P_{i}^{\max}$ maximum power of PEV to participate in electricity markets

$P_{t,\omega}^{Sch}$ scheduled generation of the PEV aggregation agent

$P_{i,t,\omega}^{\mathrm{V2G}}$ injection from PEV i to grid

$q_{d,t}^{k}$ offered quantity of demand response provider

r_t^{+}, r_t^{-} positive and negative imbalance ratios

$SOC_{i,t,\omega}^{Disconnect}$ state of charge when disconnecting from the grid

$\Delta_{t,\omega}^{+}, \Delta_{t,\omega}^{-}$ positive and negative deviations

η_i^{C}, η_i^{D} charging and discharging efficiencies

γ maximum modification level in intraday markets

$\pi_{t,\omega}$ occurrence probability of scenario ω

$\lambda_{t,\omega}^{DA}$ price of day-ahead energy market

$\lambda_{t,\omega}^{Intra}$ price of intraday market

$\lambda_{t,\omega}^{Bal}$ price of balancing market

$\lambda_{t,\omega}^{Res}$ price of spinning reserve market

$\lambda_{t,\omega}^{DRX}$ price of DRX market

$\lambda_{t}^{ContRes}$ price of spinning reserve contract

λ_{t}^{ContEn} price of energy contract

1. Introduction

1.1. Motivation

Electrification of transportation is a key element to enhance energy security by varying resources of energy, to support economic growth by forming advanced industries and, to conserve the environment by reducing pollutions [1]. Electric Vehicle Initiative (EVI) and International Energy Agency (IEA) reported that the global Electric Vehicle (EV) stock was more than 180,000 at the end of 2012 [2]. The market share of EVs can be significantly increased in most of countries, since some national targets for EV developments have been considered in the near future. On this basis, several policies have been implemented, such as incentives/subsidies for the purchase cost of EVs and infrastructure requirements [1].

Moreover, according to the growth of energy sustainability concerns, Plug-in Electric Vehicles (PEVs) are a key element in the sustainable energy systems [3]-[4]. Researches on the driving patterns reveal that the overwhelming majority of the EVs can be connected to the grid and trade energy with the electricity markets, while an ample part of the stored energy is eventually remained [5]-[6]. Currently, development of technologies of EVs causes an increase of the market share of these vehicles. Therefore, a massive amount of PEVs jeopardizes the power system's quality and stability [7]-[8] and as a result the management of this new resource have become unavoidable [9]-[10]. Depending on the level of deregulation of the market, some of the market players (e.g., Demand Response Providers (DRPs) and retailers) can manage the operation of PEVs [11]. In this paper, it is supposed that the market player's activities are totally disaggregated from each other.

On this basis, the PEV aggregation agent as a new player in the market is considered to manage the PEVs and control the discharge/charge of their batteries. The assumption is because PEV owners prefer to separate their PEV contracts from the other household consumptions for three reasons. First, the expenses of vehicles have always been separated from households' costs. Second, the PEV may have a major role in current expenditure of the household, since it can increase residential electricity consumption by approximately 50% [12]. Third, the PEV has a different nature compared to common electricity end-users due to its ability of charging/discharging, and consequently it can easily participate in different electricity markets [13].

The PEV owners' uncertain behaviour causes that the PEV aggregation agent should confront numerous challenges in order to contribute in electricity markets. The uncertain feature of this new market player can cause that its primary bids/offers have various deviations from the actual amounts and it consequently poses undesirable costs for the PEV aggregation agent. This is because of the inequity between the scheduled and actual consumption/production. Nevertheless, from the day-ahead session to the balancing one, the PEV aggregation agent is able to gather a number of new data in order to modify its primary bids/offers in an intraday market. Due to the high level of uncertainty of PEV owners' behaviour, the PEV aggregation agent requires to take part in short-time session markets, e.g., intraday market. It should be mentioned that, regarding the participation in the intraday markets, there are three major differences between the PEV aggregation agent and other market players:

- First, the main source of the thermal and especially renewable energy units to obtain profit is generally the electricity market. Therefore, these market players can directly achieve benefit from participating in the intraday markets because the mentioned markets enable them to cover their uncertainties of electricity generation in the electricity market. On the contrary, the main source of the PEV aggregation agent to obtain profit is the spinning reserve market. On this basis, the PEV aggregation agent can indirectly achieve benefit from the intraday markets. This means that, the aggregation agent should manage the strategic behaviour of participating in different markets.
- Second, unlike the mentioned above units, the PEV aggregation agent can behave as both consumer and generator. Based on this, the PEV aggregation agent can contribute in the intraday markets as both a seller and a buyer player. In addition to the aggregation agent's own benefit, the intraday markets can achieve benefit from the improvement of the competition level.
- Third, in comparison with the other market participants that supply the spinning reserve (e.g., hydro, thermal and energy storage units), the PEV aggregation agent has the highest uncertainty.

1.2. Literature review and background

According to the restructuring in the power system, the PEV aggregation agents take part in the electricity markets with the aim of maximizing their profit. In other words, the aggregation agent is considered as a private entity who wants to maximize its own profit. From the PEV aggregation agent's point of view, several frameworks have been proposed to improve the participation of PEV aggregation agents in the electricity market. Controlling PEVs to maximize the revenue from frequency regulation is presented in [14] and [15]. In [16], a business model has been described where the aggregation agent is a common load aggregator that buys energy from the electricity market and has no control over the PEV charging rates. In [17], a framework has been described to integrate the PEVs within the power system planning and operation tasks. In [18], a heuristic charging strategy has been presented to provide the regulation service. Moreover, a heuristic algorithm has been developed to arrange the PEV charge in response to market prices in a traditional power system [19].

In the mentioned studies, it has been assumed that the PEV variables are deterministic; therefore, uncertainties have not been considered. In [13], an optimization algorithm has been proposed to manage the individual charging of PEVs to decrease the deviation costs and to ensure a reliable supply of manual reserve. In [20], an optimization method has been proposed to support the participation of the PEV aggregation agent in the day-ahead spot and secondary reserve market.

In competitive electricity markets, DR plays a notable role in enhancing market efficiency, improving system reliability, and mitigating the uncertainty of renewables [21]. For this purpose, the regulatory bodies are changing market rules and regulations to support implementation of DR programs in electricity markets [22]. However, in order to implement DR in real applications, the Advanced Metering Infrastructure (AMI) developments as well as Information and Communication Technologies (ICT) are required [11]. In the U.S., penetration of AMI is growing, so that it reached approximately 23% in 2011. Moreover, as reported by FERC [23], in the U.S., the yearly potential contribution of DR resources was approximately 72 GW during 2012. Currently, DR programs are offered by many ISOs/RTOs such as Pennsylvania–New Jersey–Maryland (PJM), California ISO (CAISO), ISO New England (ISO-NE) and ERCOT as well as a large number of utilities such as Pacific Gas & Electric (PG&E) and Southern California Edison (SCE). An overview of present status of DR in the U.S. RTOs and ISOs is presented in Table 1 [24].

Nevertheless, two main challenges negatively affect the potential of demand-side resources compared with the supply-side ones. First, most of the consumers have no sense about the value of electricity to consider in order to submit appropriate price-quantity offers to the electricity market [25]. Second, there is not a proper mechanism as an alternative for the consumers to response to motivate signals [25].

In order to overcome the first challenge, the DR aggregator concept is developed to manage the response of a group of consumers and participate in the electricity market on their behalf. The second challenge can be overcome by developing Demand Response eXchange (DRX) mechanism. In the DRX market, DR can be traded in a market that is separated from the electricity market. Therefore, in the DRX market, market players are categorized into two sets: DR buyers and DR sellers. DR buyers, such as retailers and distributors, need DR to enhance their profit and system reliability, whereas DR sellers have the ability to considerably change the demand and sell DR to increase their profit [22].

DR sellers consist of large consumers or other market participants such as Distribution System Operators (DSOs), Load Service Entities (LSEs), aggregators and DRPs, which have the responsibility of managing customer responses. As there are a large number of buyers and sellers in DRX markets, a DRX operator is required to collect both the aggregated demand of DR (from DR buyers) and the individualized supply curves of DR (from DR sellers), then, it clears the DRX market [22].

Although, it may seem that a new DRX market requires high investment costs, as presented in [26], "Even the DRX operator could be represented by a dedicated computer, which solves the market clearing optimization using automatically collected data from DR buyers and DR sellers". On this basis, even forming a physical marketplace for DRX is not required. This advantage simplifies the cost of forming the proposed market and can accelerate its real-world realization.

1.3. Aims and contribution

Demand Response Resources (DRRs) are technically able to take part in intraday sessions. Thus, this paper proposes that the PEV aggregation agent contributes as DR buyer/seller in an intraday DRX market. Therefore, the PEV aggregation agent can utilize DRRs to modify the offers/bids.

In the propose approach, the PEV aggregation agent confronts the uncertainties of the electricity market and PEV owners' behaviour, and takes part in the intraday DRX market in order to cover the mentioned uncertainties. Although in some studies (e.g., [27]-[30]), optimization of bidding/offering strategy of PEV aggregation agents has been reported, participation of these agents in the intraday electricity market has been rarely addressed. Furthermore, the literature has not modelled the impacts of DRX market on the PEV aggregation. To the best of the authors' knowledge, participation of PEV aggregation agents in the intraday DRX markets has not been addressed.

Hence, the novel contribution of this paper is to analyse the influences of the PEV aggregation agent taking part in the intraday DRX market. To this end, a new model is developed to enhance the aggregation agents' offering/bidding strategy by means of DRRs. In the proposed model, the PEVs are operated in both G2V and V2G modes considering several types of uncertainties. Moreover, minimum connection duration (MCD) of PEVs is considered as an operation constraint. Furthermore, the effect of integrated PEVs on the loading of distribution transformers has been taken into account.

1.4. Paper organization

The rest of the paper is organized as follows: Section 2 presents the proposed intraday DRX market with the presence of the PEV aggregation agent. Section 3 models the uncertainty characteristics related to PEV owners' behaviour and market prices. Section 4 describes the formulation of the proposed framework of the PEV aggregation agent. Numerical studies are presented in section 5. Section 6 determines the paper remarks.

2. Proposed Intraday DRX Market

2.1. DRX market

Positive impacts of implementation of DR programs on the electricity market have been reported in [31]-[33]. In order to benefit from DR advantages, DRPs are in charge to manage the responsive demands and participate in the electricity markets. Since DR can be traded among DR sellers and DR buyers as a virtual quantity, Nguyen et al. firstly proposed the concept of DRX market [22], [34]. The DRX market is an independent market of the energy and ancillary services markets. As it mentioned, participants in the DRX market can be categorized into two groups; namely, DR sellers and DR buyers.

DR buyers purchase generation reserves from the ancillary services market or purchase load curtailments from the DRX market, or a mixture of these two markets. DR buyers purchase load curtailments to enhance the system reliability, control network constraints, and decrease the risks of price volatility. In order to reduce financial risks arisen from volatility of electricity market prices, retailers as DR buyers can also purchase load curtailments from the DRX market.

DR sellers offer load curtailments to the DRX market to obtain higher economic benefits. DR sellers consist of customers who are willing to participate in the electricity market. Since, small loads do not directly participate in the DRX market, LSEs, DRPs and aggregators generally participate in the markets on behalf of the small customers.

Although the DRX concept is not a contribution of this paper, considering a DRX market that is formed in intraday sessions is a new issue. Since the intraday market is closer to the balancing time, the estimated DR is associated with a lower error and consumers can estimate the amount of their DRs more precisely. Hence, the consumers incur in less financial losses because of penalty payment prevention due to a more accurate DR estimation, and they will be more and more encouraged to participate in DR programs. The most important motivations for the establishment of an intraday DRX market, besides the conventional intraday market, are summarized as follows:

1) Since the DRX market can be a local market, its rules and regulations can depend on regions. Moreover, they can be less strict than the regular intraday market. For instance, the minimum required capacity for the market participants can be much less than the regular markets. On this basis, the number of participants in the DRX market can be increased; thus, competition between aggregation agents can be improved. This competitive situation causes the aggregation agents to propose diverse incentive mechanisms and attractive programs for consumers in order to retain in competition with other participants. Thus, market performance and overall efficiency under DRX market are increased.
2) The consumers can sell their DR capacity with higher rates, because they are faced with more various DR buyers (i.e., aggregation agents). In other words, the DRX market can create an appropriate opportunity for small consumers to confront other DR-involved players. Therefore, the DRX market can attract the small consumers by making a competitive environment; consequently, it can motivate them to take part in DR programs more actively. Moreover, it is proven in [26], [34] that trading DR in the DRX context leads to allocate payments among all the players fairly, with the aim of ensuring the maximum market efficiency.

2.2. Modelling the DRPs' behaviour in the DRX market

The PEV aggregation agent participates in DRX market as a buyer, who purchases DR from the mentioned market. In addition, the aggregation agent can also attend the market as a seller, who sells DR to the market. In the DRX market, DRPs aggregate their customers' response, and then they submit their price-quantity offers to the market. The DRP offered price-quantity in the DRX market is illustrated in Fig. 1. In this paper, it is assumed that the demand is reduced if the price increases; therefore, it is constrained to increase monotonically. The discrete DRP quantities in hour t and scenario ω are labelled as $q_{d,t,\omega}^{k}$ with the associated cost of $c_{d,t}^{k}$. Equations (1)-(4) represent the behaviour of DRPs in the DRX market.

$$DR_{d,t,\omega} = \sum_{k=1}^{NQ_d} q_{d,t,\omega}^{k} \tag{1}$$

$$CDRP_{d,t,\omega} = \sum_{k=1}^{NQ_d} c_{d,t}^{k} q_{d,t,\omega}^{k} \tag{2}$$

$$q_{d,t,\omega}^{k} \leq q_{d,t}^{k,\max} \tag{3}$$

$$DR_{d,t,\omega} \leq DR_{d,t}{}^{\max} \tag{4}$$

where NQ_d is the number of blocks of d-th DRP. Inequality (3) denotes the maximum amount of DR in k-th block. Inequality (4) represents the highest level of DR that can be provided.

3. Uncertainty Characterization

3.1. Modelling the uncertainties

In this paper, three groups of uncertainty are taken into account; namely, regarding uncertainty of market prices, uncertainty of activated amount of reserve by ISO and uncertainty of PEV owners' behaviour. In order to offer in day-ahead market, PEV aggregation agent not only should forecast the day-ahead market price but also needs to estimate its PEVs variables. Then, the PEV aggregation agent can obtain new information and hence update its day-ahead scheduling between the closures of day-ahead and intraday market. In this regard, it needs to forecast the price of intraday market and update its estimation in terms of PEV owners' behaviour due to the latest gained information. Afterwards, according to the actual PEVs variables in real time, the balancing market mechanism is implemented. Modelling these uncertainties is expressed as follows.

3.1.1. Market prices

The current paper considers four uncertain prices including day-ahead energy and reserve, intraday energy as well as intraday DRX. The lognormal distribution is employed to characterize these prices in each hour [35]. On this basis, the PDF of market prices can be formulated by (5):

$$f(\lambda,\mu,\sigma)=\frac{1}{\lambda\sigma\sqrt{2\pi}}\exp\left[-\frac{(\ln\lambda-\mu)^2}{2\sigma^2}\right] \tag{5}$$

where μ denotes the mean value and σ represents the standard-deviation of the price series.

By considering the mentioned PDF, different scenarios of markets' behaviour are generated by Roulette Wheel Mechanism (RWM) [36].

3.1.2. Activated quantity of reserve

The uncertainties of calling to deliver the offered reserve and the quantity of activated reserve by the system operator are modelled by Poisson (6) and uniform distributions (7), respectively.

$$f(k,\mu)=\frac{\mu^k.\exp(-\mu)}{k!} \quad , \quad \mu>0 \quad , \quad k=0,1,2,... \tag{6}$$

$$f(x)=\begin{cases}\dfrac{1}{Offer_{t,\omega}^{Res}} & , \quad 0\le x\le Offer_{t,\omega}^{Res} \\ 0 & , \quad Otherwise\end{cases} \tag{7}$$

where μ denotes the expected value and k represents the number of calls.

Considering (6) and (7), several outcomes of delivering the offered reserve are taken into account by the RWM-based scenario generation process [36].

3.1.3. PEV owners' behaviour

Behaviour of PEV aggregation agents relies on the behaviour of PEV owners. Due to the uncertain behaviour of PEV the aggregation agent has to face with diverse uncertain parameters including the number of PEVs in each hour, arrival state of charge (SOC) of each PEV and the time duration which the vehicle stays plugged-in.

The pattern of available PEVs is extracted from real data in [37]. This pattern is employed for scenario generation by using RWM. It should be noted that, since a nearer time to the market closure implies a more accurate prediction of the PEVs, the utilized standard deviations for generated scenarios in the intraday session are assumed to be lower if compared to the day-ahead session. In other words, in the intraday stage, the PEV aggregation agent can predict the customers' behaviour with lower deviation from the actual value.

Total stored energy relies on the number of PEVs as well as their driven distance. In order to consider the daily travelled distance, the lognormal distribution is employed [38]-[39] as presented in (8)-(10).

$$M_d = \exp(\mu_m + \sigma_m . N) \tag{8}$$

$$m_m = \ln\left(m_{md}^2 \Big/ \sqrt{m_{md}^2 + s_{md}^2} \right) \tag{9}$$

$$\sigma_m = \sqrt{\ln\left(1 + \sigma_{md}^2 / \mu_{md}^2\right)} \tag{10}$$

where M_d is the daily driven distance, μ_{md} and σ_{md} are respectively the mean and standard variation of daily driven distance, calculated from the historical data.

3.2. Stochastic programming approach

In order to study the influences of the mentioned uncertainty resources on the behaviour of the PEV aggregation agent, a stochastic procedure is utilized based on a multi-stage stochastic programming. This procedure for modelling the market players' behaviour by considering the day-ahead, intraday and balancing sessions has been addressed in [40]. In the mentioned approach, each stage denotes a market session as indicated in Fig. 2. Description of the stages is presented as below:

- Ω1: In the first stage (*here-and-now*), the PEV aggregation agent designs its bidding/offering strategy for the day-ahead markets. Then, it submits the resulting bids and offers to the markets for each hour of the market horizon. In this stage, decision making are carried out according to plausible realizations of the uncertain variables, namely, market prices (in day ahead, intraday energy and DRX, and balancing sessions), activated quantity of reserve and PEV owners' behaviour. $Offer_{t,\omega}^{En}$, $Offer_{t,\omega}^{Res}$, $P_{i,t,\omega}^{Res}$, $\lambda_{t,\omega}^{DA}$ and $\lambda_{t,\omega}^{Res}$ are the variables of the first stage.
- Ω2: When the hourly prices of day-ahead market are known, the amounts of energy and DR to sell/buy to/from the intraday energy and DRX markets are decided. In the second stage (*wait-and-see*), the hourly prices of day-ahead market and the PEV owners' behaviour in the hours between the closures of the day-ahead and intraday markets are supposed to be known. However, the intraday and balancing market prices, the amount of activated reserve, and the PEV owners' behaviour for the remainder of the market horizon are still uncertain. Consequently, in the second stage, and for every day-ahead market price realization, decisions are made based on plausible scenarios of intraday and balancing prices, activated quantity of reserve and PEV owners' behaviour. $CDRP_{d,t,\omega}$, $DR_{d,t,\omega}$, $DR_{t,\omega}^{Agg}$, $q_{d,t,\omega}^{k}$, $P_{t,\omega}^{Intra,buy}$, $P_{t,\omega}^{Intra,sell}$, $\lambda_{t,\omega}^{DRX}$ and $\lambda_{t,\omega}^{Intra}$ are the variables of the second stage stochastic programming.

- Ω3: The third stage of the stochastic programming approach is determined by the materialization of the imbalance prices, activated quantity of reserve and the PEV owners' behaviour in the hours spanning the whole market horizon. Therefore, the deviation incurred by the PEVs in each hour is known and the consequent cost for imbalance can be computed. The stochastic decision variables are $SOC_{i,t,\omega}^{Disconnect}$, $SOC_{i,t,\omega}$, $P_{t,\omega}^{del}$, $Act_{t,\omega}^{Res}$, $P_{i,t,\omega}^{G2V}$, $P_{i,t,\omega}^{V2G}$, $r_{i,t,\omega}^{charge}$, $r_{i,t,\omega}^{discharge}$, $U_{i,\omega}$, $\alpha_{i,t,\omega}$, $\beta_{i,t,\omega}$, $\Delta_{t,\omega}^{+}$, $\Delta_{t,\omega}^{-}$ and $\lambda_{t,\omega}^{Bal}$.

4. Proposed Model of PEV Aggregation Agent

Each PEV owner is able to charge its PEV batteries with or without control of its aggregation agent. The PEV owner takes advantage of contracting with the aggregation agent, although it allows the agent operating the PEV's battery. Based on the contract between the owner and the aggregation agent, the agent can apply some rules and limitations.

One of the constraints of the aggregation agent is the MCD. Based on this rule, the PEV owner cannot disconnect its vehicle earlier than MCD, in order to benefit from this type of charging. Based on this type of contract, the aggregation agent has to ensure a desired amount of SOC for each PEV that is called Minimum Charge of Battery (MCB). The objective of the PEV aggregation agent is to maximize the profit as formulated in (11).

$$\begin{aligned}\max_{\pi_{t,\omega}} \sum_{t} \Big\{ & -Cost^{Infra} + \mathrm{E}_{\Omega 1}\Big[Income_{t,\omega}^{Res} + Income_{t,\omega}^{Energy} \\ & + \mathrm{E}_{\Omega 2|\Omega 1}\Big[Income_{t,\omega}^{Intra} + Income_{t,\omega}^{DRX} - Cost_{t,\omega}^{Intra} - Cost_{t,\omega}^{DRX} \\ & + \mathrm{E}_{\Omega 3|\Omega 2,\Omega 1}\Big[Income_{\omega}^{Charge} + Income_{t,\omega}^{Call} + Income_{t,\omega}^{Imb} \\ & - Cost_{t,\omega}^{Imb} - Cost_{t,\omega}^{Charge} - Cost_{t,\omega}^{Obl} - Cost_{\omega}^{Res} - Cost_{\omega}^{Deg.} \Big]\Big]\Big]\Big\}\end{aligned} \tag{11.a}$$

$$Cost^{Infra} = \frac{1}{365} \sum_{i \in PIEV_{tot}} \left[\frac{dr.\left(Cost_{i}^{Wiring} + Cost_{i}^{On-board}\right)}{1-(1+dr)^{-N^{y}}} \right] \tag{11.b}$$

$$Income_{t,\omega}^{Res} = Offer_{t,\omega}^{Res}.\lambda_{t,\omega}^{Res} \tag{11.c}$$

$$Income_{t,\omega}^{Energy} = Offer_{t,\omega}^{En}.\lambda_{t,\omega}^{DA} \tag{11.d}$$

$$Income_{t,\omega}^{Intra} = \lambda_{t,\omega}^{Intra}.P_{t,\omega}^{Intra,sell} \tag{11.e}$$

$$Income_{t,\omega}^{DRX} = DR_{t,\omega}^{Agg}.\lambda_{t,\omega}^{DRX} \tag{11.f}$$

$$Cost_{t,\omega}^{Intra} = \lambda_{t,\omega}^{Intra}.P_{t,\omega}^{Intra,buy} \tag{11.g}$$

$$Cost_{t,\omega}^{DRX} = \sum_{d} CDRP_{d,t,\omega} \tag{11.h}$$

$$Cost_{t,\omega}^{Charge} = \sum_{i \in PIEV_{tot}} P_{i,t,\omega}^{G2V}.\lambda_{t,\omega}^{DA} \tag{11.i}$$

$$Cost_{t,\omega}^{Obl} = FOR^{Agg}.Act_{t,\omega}^{Res}.P_{t,\omega}^{del}.\lambda_{t,\omega}^{Bal} \tag{11.j}$$

$$Cost_{t,\omega}^{Imb} = \lambda_{t,\omega}^{DA}.r_t^{-}.\Delta_{t,\omega}^{-} \tag{11.k}$$

$$Income_{t,\omega}^{Call} = Act_{t,\omega}^{Res}.\lambda_{t,\omega}^{Bal}.P_{t,\omega}^{del} \tag{11.l}$$

$$Income_{t,\omega}^{Imb} = \lambda_{t,\omega}^{DA}.r_t^{+}.\Delta_{t,\omega}^{+} \tag{11.m}$$

$$Cost_{\omega}^{Res} = \sum_{i \in PIEV_{tot}} \left[\sum_{t=t_{Connect(i,\omega)}}^{t_{Full(i,\omega)}} P_{i,t,\omega}^{\mathrm{G2V}}.\lambda_t^{ContRes} \right] U_{i,\omega} \tag{11.n}$$

$$Income_{\omega}^{Charge} = \sum_{i \in PIEV_{tot}} \left[\sum_{t=t_{Connect(i,\omega)}}^{t_{Full(i,\omega)}} P_{i,t,\omega}^{\mathrm{G2V}}.\lambda_t^{ContEn} \right] U_{i,\omega} \tag{11.o}$$

$$Cost_{\omega}^{Deg.} = \sum_{i \in PIEV_{tot}} \left[\sum_{t \in t_{Connect(i,\omega)}} P_i^{\max}.C_d \right] U_{i,\omega} \tag{11.p}$$

Eq. (11.a) indicates the different terms of the aggregation agent's profit. The profit is dependent on the behaviour of the aggregation agent in the different electricity markets, and consequently, it relies on the uncertain variables associated with the market sessions. Therefore, the aggregation agent faces with a multi-stage stochastic model resulted from the set of uncertain variables that are mentioned in Section 3. The term $Cost_{Infra}$ in (11.b) represents the infrastructure expenditure including on-board and wiring costs [41]. The aggregation agent's income resulted from taking part in the spinning reserve market is presented in (11.c). The agent's income obtained from taking part in the day-ahead energy, intraday energy and intraday DRX markets are respectively formulated in (11.d)-(11.f). Eqs. (11.g) and (11.h) represent the agent's costs resulted from purchasing energy and DR from the intraday energy and intraday DRX markets, respectively, to compensate the lack of generation. Eq. (11.i) represents the cost of purchasing from the day-ahead market to charge the batteries. The inability of the PEV aggregation agent to deliver the offered amount of reserve causes a cost that is represented in (11.j). The impact of distribution network reliability is modelled by FOR^{Agg}. According to (11.j), if the PEV aggregation agent cannot deliver the offered reserve, it has to supply it by purchasing from the energy market to meet its obligation. Eq. (11.k) denotes the imbalance cost resulted from lack of injection compared to the day-ahead offer. Eq. (11.l) considers the aggregation agent's income obtained from delivering the offered amount of reserve to the spinning reserve market. Eq. (11.m) formulates the imbalance income due to surplus of injection in comparison with the primary offer. Eq. (11.n) is related to the aggregation agent's cost resulted from the owners' contracts to motivate them to take part in the reserve market. $U_{i,\omega}$ is a binary number equal to 1, if the owner of a PEV respects the MCD, and 0 otherwise. π^{ContEn} and $\pi^{ContRes}$ are respectively the agreed tariffs between PEV owner and the aggregation agent to contribute in the energy and reserve markets. Eq. (11.o) shows the agent's income from charging tariff of each PEV owner who respects the MCD. Eq. (11.p) denotes the cost of battery degradation due to the participation in the electricity market in V2G mode [41]. Battery degradation cost relies on the investment cost and the lifetime of battery, as formulated in (12):

$$C^{\deg} = C^{battery} \big/ L^{battery} \tag{12}$$

The constraints of the PEV aggregation agent are presented as following:

$$[SOC_{i,t,\omega}^{Disconnect} \geq MCB\,]U_{i,\omega} \tag{13}$$

$$0 < SOC^{\min} \leq SOC_{i,t,\omega} \leq SOC^{\max} < 1 \tag{14}$$

$$SOC_{i,t,\omega} = SOC_{i,t-1,\omega} + \alpha_{i,t,\omega}.\eta_i^C.P_{i,t,\omega}^{\text{G2V}} - \beta_{i,t,\omega}.P_{i,t,\omega}^{\text{V2G}} \tag{15}$$

$$\alpha_{i,t,\omega} + \beta_{i,t,\omega} = 1 \tag{16}$$

The constraint of MCB is presented in (13). Eq. (14) ensures the level of SOC of PEVs. Eqs. (15) and (16) calculate the PEVs' SOC. α and β are binary variables to guaranty that each PEV does not receive and inject energy simultaneously.

The constraints of charging and discharging rates can be presented as follows:

$$r_{i,t,\omega}^{charge} = \left(SOC_{i,t,\omega} - SOC_{i,t-1,\omega}\right) \big/ \eta_i^C \tag{17}$$

$$r_{i,t,\omega}^{discharge} = \left(SOC_{i,t-1,\omega} - SOC_{i,t,\omega}\right).\eta_i^D \tag{18}$$

$$r_{i,t,\omega}^{charge} \leq r_i^{charge,\max} \quad , \quad r_{i,t,\omega}^{discharge} \leq r_i^{discharge,\max} \tag{19}$$

The scheduled energy of the PEV aggregation agent in electricity markets is formulated in (20). Eq. (21) makes the PEV aggregation agent offer to the electricity market based on the PEVs' power in V2G mode.

$$\begin{aligned} P_{t,\omega}^{Sch} + \Delta_{t,\omega}^{+} - \Delta_{t,\omega}^{-} &= Offer_{t,\omega}^{En} + P_{t,\omega}^{Intra,sell} \\ &- P_{t,\omega}^{Intra,buy} + DR_{t,\omega}^{Agg} - \sum_{d=1}^{ND} DR_{d,t,\omega} \end{aligned} \tag{20}$$

$$Offer_{t,\omega}^{En} + P_{t,\omega}^{Intra,sell} + DR_{t,\omega}^{Agg} \leq \sum_{i \in PIEV_{tot}} \left[\eta_i^D.P_{i,t,\omega}^{\text{V2G}}\right] U_{i,\omega} \tag{21}$$

Since the distribution transformers may be overloaded because of PEV integration into the electrical distribution network, the aggregation agent should manage the charging and discharging of its customers' PEVs to avoid overloading the mentioned transformers [11], [42]-[43]. On this basis, the loading of transformers with considering the PEVs is presented in (22). Eq. (23) ensures that the transformers are not overloaded in any scenario.

$$Load_{Tr,t,\omega}^{withPIEVs} = Load_{Tr,t,\omega}^{withoutPIEVs} + \sum_{i \in Tr}\left[\frac{P_{i,t,\omega}^{\mathrm{G2V}}/PF_i}{\eta_i^C}\right] - \sum_{i \in Tr}\left[\eta_i^D . P_{i,t,\omega}^{\mathrm{V2G}}/PF_i\right] . U_{i,\omega} \quad (22)$$

$$Load_{Tr,t,\omega}^{withPIEVs} \leq S_{Tr}^{\max} \quad (23)$$

where $Load_{Tr,t,\omega}^{withPIEVs}$ and $Load_{Tr,t,\omega}^{withoutPIEVs}$ are the loads of transformer Tr with and without considering the PEVs, respectively. PF_i is the power factor of each PEV and $S_{Tr}^{\max}$ is the maximum loading of the transformer. Fig. 3 illustrates a scheme of the proposed model.

5. Numerical Studies

5.1. Case studies and input data

A case study including a PEV aggregation agent and 50,000 PEVs is considered, in order to analyse the effectiveness of the proposed model. The detailed information of the PEV aggregation agent is presented in Appendix. The generated scenarios for PEV owners' behaviour are based on some general assumptions extracted from driving and parking patterns of Spanish vehicle drivers [37]. On this basis, the average number of trips per day is considered equal to 2.4. According to the driving patterns, 75 km and 1.5 hours are the average amount of daily driving distance and daily driving time, respectively. Moreover, an EV takes about 0.22 kWh to charge for 1 km travelled. Based on the mentioned description in Section II, scenarios of the number of PEVs are generated for both day-ahead and intraday sessions as illustrated in Figs. 4 and 5, respectively. By considering a smaller standard deviation for the PEVs number in the intraday market, the more accurate prediction of the PEV aggregation agent due to a time closer to the balancing market has been taken into account. Additionally, the uncertain amounts of total available SOC in the day-ahead session are generated as indicated in Fig. 6.

Price data used for the scenario generation process for day-ahead, intraday and balancing markets are obtained from the hourly data of Iberian electricity market in November 2010 [44]. As mentioned in Section II, the market prices have been considered stationary stochastic parameters. Therefore, in order to generate the related scenarios, the intraday prices of each hour for all days of November 2010 have been used to find the parameters of the lognormal distribution explained in Section

II. Furthermore, the imbalance ratios, i.e., the ratios between the balancing market prices and the day-ahead market prices, are considered by using the mean of historical data. The graphical illustration of the amount of imbalance price ratios is shown in Fig. 7.

Moreover, in order to model the proposed DRX market, three DRPs are considered that collect local customers and offer to the intraday DRX market. A three-step pair of price-quantity is offered from each DRP. In the interest of a fair comparison between conventional intraday and DRX markets, the mentioned pairs are considered associated with the prices of intraday energy market. Accordingly, the offered prices of DRPs to the pool-based intraday DRX market are a ratio of the prices of conventional intraday energy market, as presented in Table A.3 in Appendix.

5.2. Impact of operation in V2G mode

In this paper, in order to consider the effect of operation in V2G mode on the behaviour of PEV aggregation agents, two scenarios have been taken into account. In Scenario 1, all PEV owners allow their vehicles supplying electricity back to the grid. Instead, in Scenario 2, 50% of owners allow their vehicles operating in V2G mode and it has been assumed that the remainder only participates in G2V mode due to the battery warrantee issue, the requirement to reserve battery SOC, etc.

PEV owners require some incentives to allow aggregation agents operating their PEVs in V2G mode. On this basis, in this paper, the charging tariff for PEVs that participate in electricity markets is assumed 10% less than that for participants in only G2V mode. In addition, as mentioned in Section IV, the aggregation agent pays the cost of battery degradation to each PEV owner who participates in V2G mode.

The obtained SOC of PEVs in both the mentioned scenarios has been indicated in Fig. 8 and 9. By comparing these figures with Fig. 4, it can be seen that the PEV aggregation agent prefers to charge the PEVs and use their battery capacity between hours 3 to 6 AM. Indeed, the market price in these hours is low and these hours are the last ones before the peak of midday when the PEVs are available to be charged. According to Fig. 4, after the mentioned hours, most of PEVs start traveling. When these PEVs reach their destinations, the peak period of midday starts. On the other hand, a major part of them will not be available to be plugged-in in their destination during the day. Moreover, it can be seen that, the obtained SOC between hours 3 to 6 in Scenario 1 is higher than that in Scenario 2. This is because in Scenario 1 the PEV aggregation agent prefers to store more electricity in order to have a reserve to participate in the electricity markets during the day.

5.3. Impact of transformer loading

In order to study the effect of different transformer loading, a typical 500 kVA distribution transformer with two different initial loading patterns has been considered. The first type is related to a transformer having its loading peak during the night, which represents a distribution transformer in a residential area. The loading peak of the second type occurs in the middle of the day. Moreover, it is assumed that each transformer serves 50 PEVs in addition to its mentioned loading.

The transformers loading with/without considering the PEVs have been illustrated in Figs. 10 and 11. It is noteworthy that, in these figures, the transformer constraints (Eq. (23)) have not been considered to show the effects of PEVs on the loading. It can be seen that, the connection of PEVs can increase the loading of distribution transformers and even can cause them to be overloaded based on the initial loading pattern of the transformer. For instance, the transformer in the first type of loading can be overloaded at 9 PM, whereas, in the second type of loading, the transformer loading at 9 PM is less than 500 kVA.

It should be mentioned that the growth of transformer loading has been dispersed over the 24 hours. In other words, charging of PEVs has not concentrated in a specific period, because the high number of PEVs connected to each transformer (i.e., 50) causes the load pattern to be smooth.

5.4. Impact of intraday DRX market

Fig. 12 shows the effect of DRPs' offered prices on the amount of DR traded between DRPs and the PEV aggregation agent in DRX market. The positive values signify the purchased amount of DR and the negative values indicate the sold amount of DR. The maximum of DRPs' offer in the DRX market is assumed equal to 10% of the load value in each hour. Indeed, the traded DR is affected by different hours of the day. On this basis, the aggregation agent prefers to buy DR from the intraday DRX market in the peak hours of energy market as well as on the hours with high demand of charging the PEVs because of insufficient SOCs. In addition, changes in the offered prices can affect the amount of DR purchased by the aggregation agent. On this basis, in some hours, an increase in the offered prices pushes the aggregation agent to decrease its purchase from the DRX market. As can be seen, in some hours, the sensitivity of the traded DR with respect to the offered prices is dramatically high. The sensitivity is related to the prices of intraday market.

In order to study the impact of DRX market on the PEV aggregation agent's profit, two cases are considered. In the first case, the PEV aggregation agent does not take part in intraday DRX markets. In the second case, the PEV aggregation agent takes part in the mentioned market. The hourly profits of the aggregation agent in both cases are indicated in Fig. 13. In addition, in this case all PEVs are available to be operated in V2G mode. Fig. 13 indicates that, in most of the hours, the profit of the PEV aggregation agent participating in the DRX market is higher if compared to its profit when it does not take part in the DRX market.

In order to analyse the influences of the contribution of DRPs, similar simulations carry out by assuming that the maximum of DRPs' offer in the DRX market is equal to 20% of the load value in each hour. In these simulations, the effect of conventional intraday energy market is also investigated. The results have been presented in Table 2 for Scenario 1 (i.e., participation of all PEVs in V2G mode) and in Table 3 for Scenario 2 (i.e., participation of half of the PEVs in V2G mode).

As it can be seen in Table 2, the higher amounts of participation level of DRPs causes a higher interest of the PEV aggregation agent to take part in the DRX market. On this basis, the aggregation agent employs DRRs to confront the imbalance costs belonging to the uncertain behaviour of PEVs. If the DRX market has appropriate potential, PEV aggregation agent maximizes the profits by taking part in the mentioned market instead of taking the risk of higher prices in the balancing market. Furthermore, Table 3 indicates that, if participation of responsive demands in DRX market increases to 20% of the load value, the PEV aggregation agent benefits more than 40% if compared to the case without participation of DRPs, which is significant. According to Table 3, since the most important part of the PEV aggregation agent's income is the revenue from the reserve market, its profit is decreased without fifty percent of its capacity in Scenario 2.

In order to consider the behaviour of the PEV aggregation agent in more detail, Fig. 14 is presented. In the figure, the expected traded DRs and the expected value of the reserve market price have been illustrated in each hour. In addition, the difference between the aggregation agent's offers in the spinning reserve market with and without DRX market has been indicated. This difference is calculated by subtracting the expected won offers without DRX market from the ones with the mentioned market in each hour.

Fig. 14 shows that, the amount of DR traded between the aggregation agent and the DRX market follows the pattern of the reserve market prices in many hours. Furthermore, it should be noted that the behaviour pattern of the PEV aggregation agent to participate in the reserve market is very similar to its pattern to buy/sell DR. On this basis, all of the traded DRs are not only applied to compensate the inaccurate offers/bids in the day-ahead market. As can be inferred from Fig. 14, most of the purchased DRs in peak hours have been utilized to improve the ability of the aggregation agent for taking part in the reserve market. By using the DRX market, before and during peak hours, the aggregation agent can supply the energy for charging the PEVs in lower price and participate in the reserve market with higher capacity. Therefore, unlike most of the participants in the intraday DRX market, the PEV aggregation agent can achieve benefit from managing its strategy to take part in both the DRX and the reserve markets, due to its ability for storing energy.

According to previously mentioned results, the PEV aggregation agent takes considerable advantages by participating in the DRX market. This agent plays a very important role in the mentioned market. Because, on one hand, the player can participate as both DR buyer and DR seller, on the other hand, it can become a linking player between the DRX and the reserve markets.

On this basis and with the increasing number of PEVs in the near future, the DRX market can have a significant effect on the prices of the reserve market, in addition to the well-known effects on the electricity market. An applicable DRX market can indeed encourage a PEV aggregation agent to offer more quantities to day-ahead electricity markets, since the player expects to compensate uncertainties of PEVs. Therefore, utilization of DRRs to incorporate PEVs brings advantages for the power systems.

6. Conclusion

This paper addressed the effects of DRX market on the optimum performance of PEV aggregation agents. The aggregation agent participated in the intraday DRX market to mitigate the imbalance cost. The uncertain behaviour of PEVs and different market prices were modelled through a multi-stage stochastic programming. Several numerical studies were accomplished and various aspects of the problem were analysed in detail. The results showed that forming an adjustment DRX market would definitively present additional opportunity for the PEV aggregation agent, even for participating in the spinning reserve market. Furthermore, influences of the DR on the behaviour of PEV aggregation agents were analysed. It was confirmed that DR presents a significant opportunity for PEV aggregation agents to reinforce their profits. Although it was expected that the intraday markets would not directly affect the aggregation agent's behaviour in the spinning reserve market, they effectively stimulated the aggregation agent to improve its participation strategy in the energy and reserve markets, which is an important outcome for future papers in the field.

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Figure captions

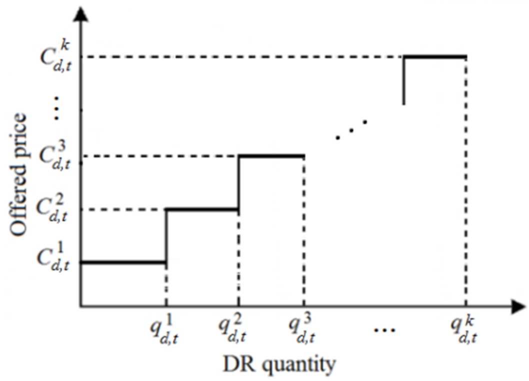

Fig. 1. Typical price-quantity offer of a DRP.

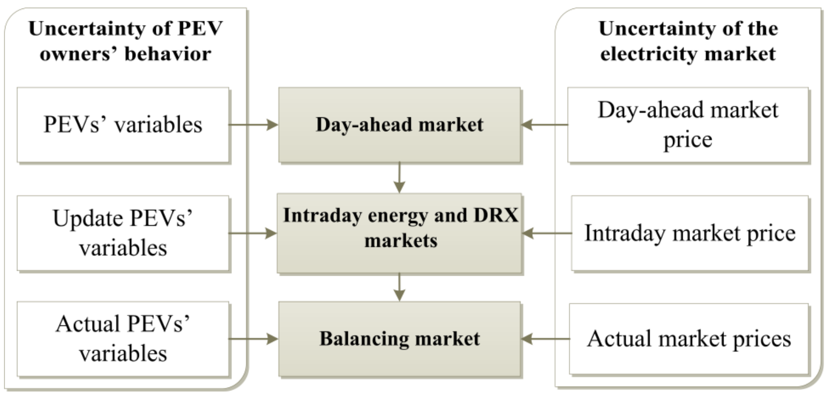

Fig. 2. The proposed multi-stage stochastic model.

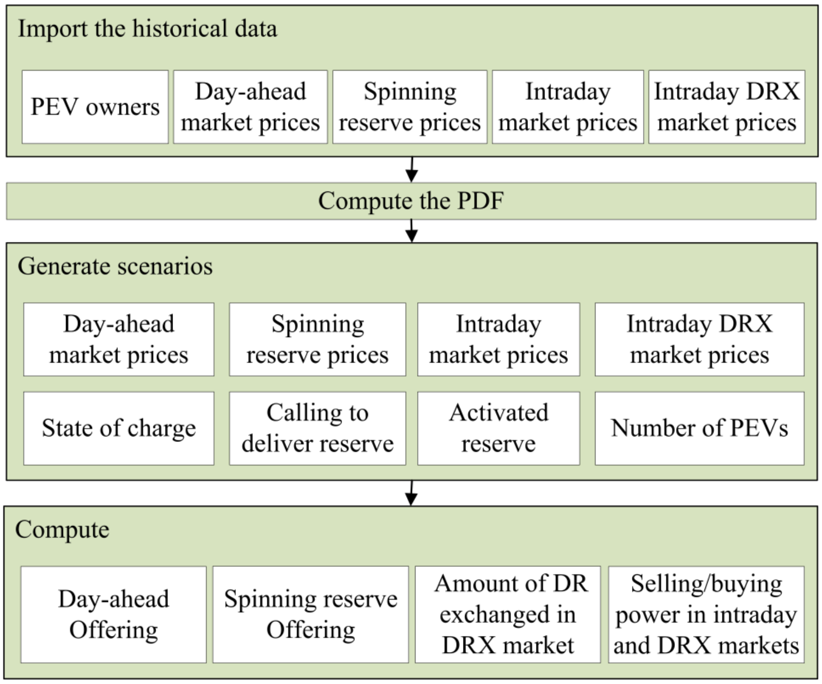

Fig. 3. The proposed model for offering and biding strategy of PEV aggregation agent.

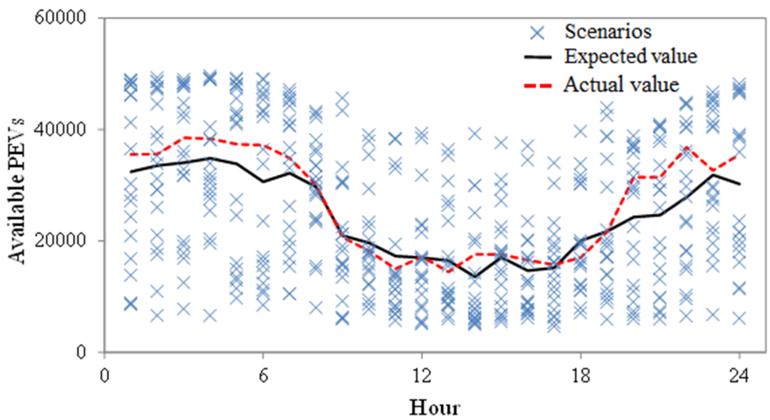

Fig. 4. Available number of PEVs in the day-ahead session (the first stage).

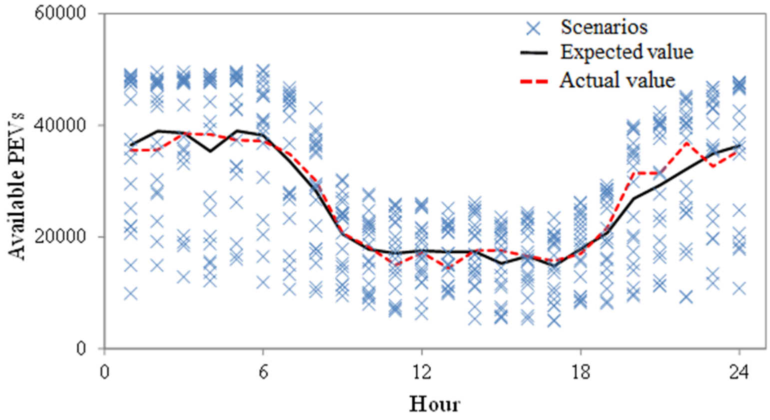

Fig. 5. Available number of PEVs in the intraday session (the second stage).

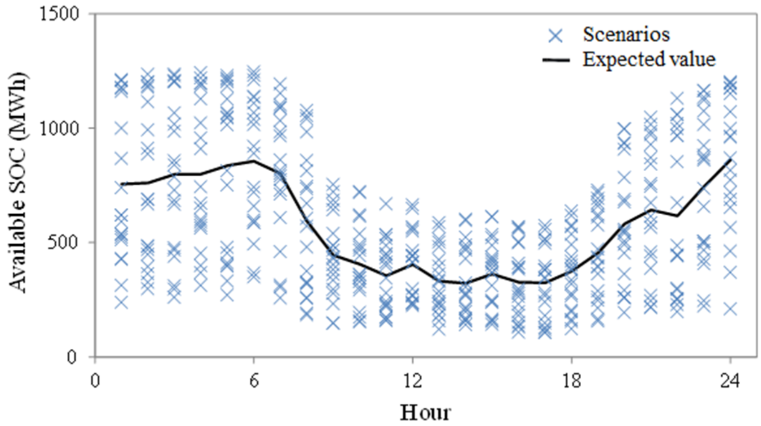

Fig. 6. Available SOC of PEVs in the day-ahead session.

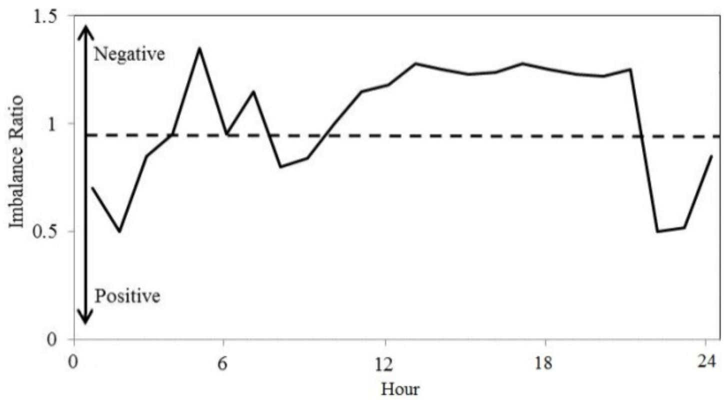

Fig. 7. Graphical representation of imbalance ratios.

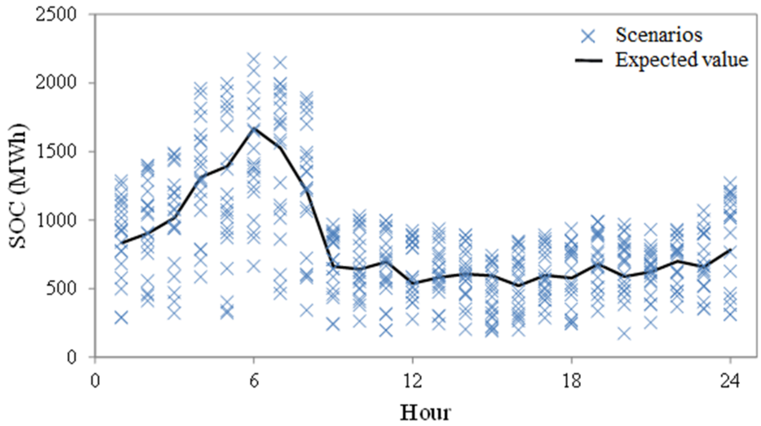

Fig. 8. The obtained SOC of PEVs in Scenario 1 (participation of all the available PEVs in V2G mode).

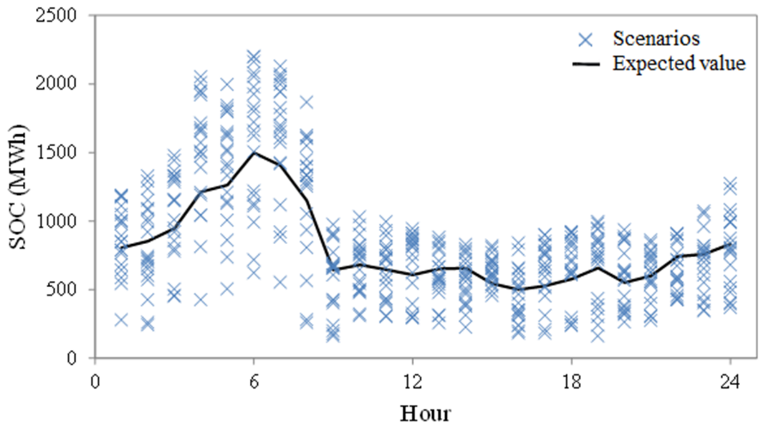

Fig. 9. The obtained SOC of PEVs in Scenario 2 (participation of half of the available PEVs in V2G mode).

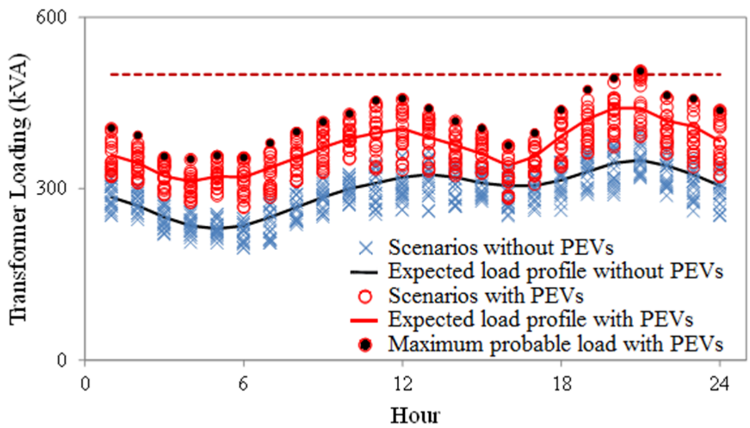

Fig. 10. The loading of 500 kVA distribution transformer serving PEVs- Type 1.

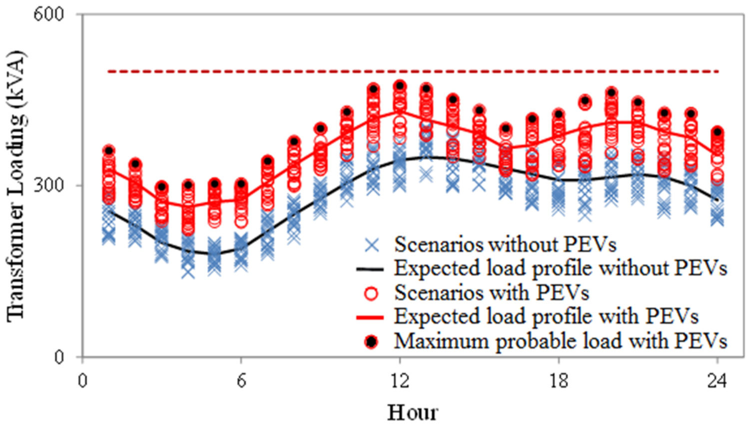

Fig. 11. The loading of 500 kVA distribution transformer serving PEVs- Type 2.

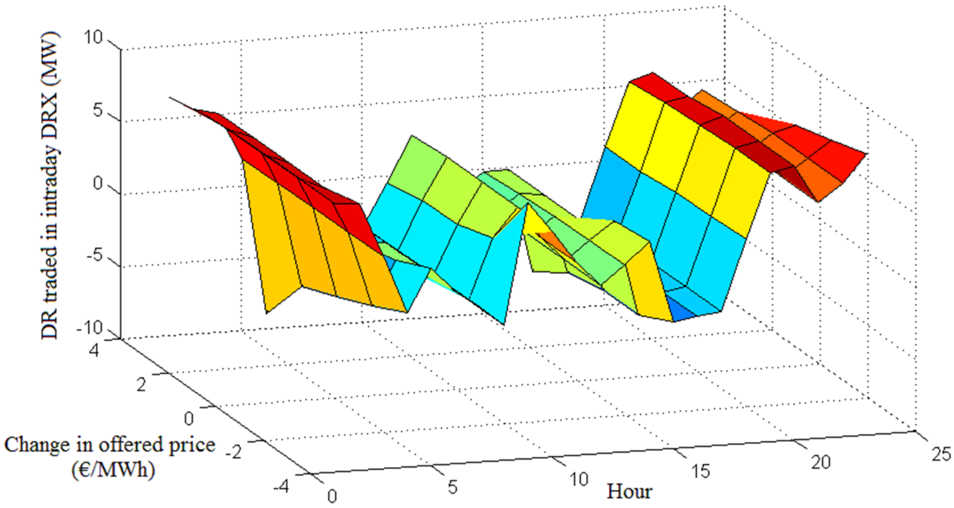

Fig. 12. The effect of DRPs' offered prices on the traded DR.

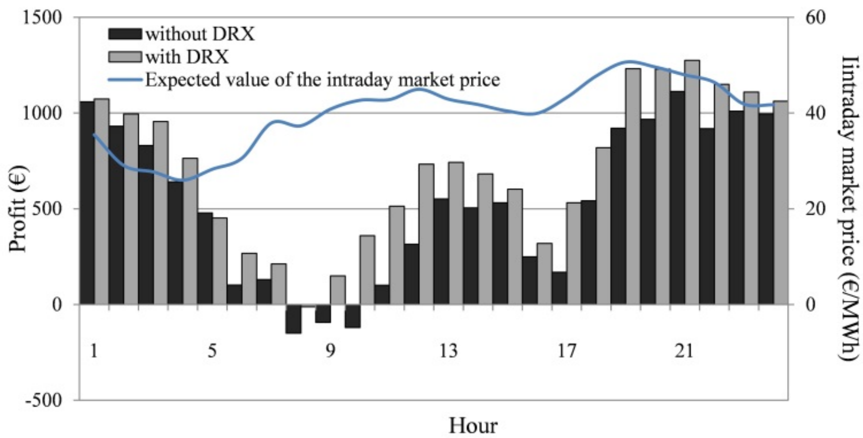

Fig. 13. PEV aggregation agent's profit with and without the intraday DRX market.

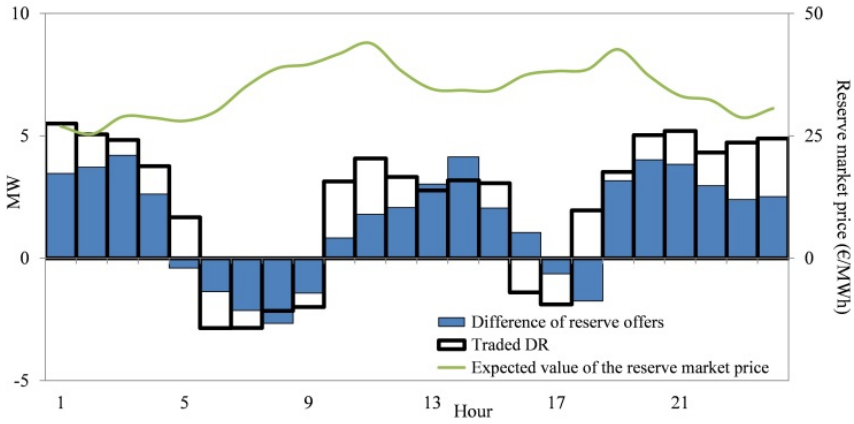

Fig. 14. Difference between won offers in the spinning reserve market with and without DRX.

Tables

Table 1. DR status in the U.S. ISOs and RTOs [24]

DR program type	NYISO	ISO-NE	PJM	CAISO	MISO	ERCOT
Emergency DR program	✓	✓	✓			✓
Real-time DR bids	✓	✓	✓	✓	✓	✓
Day-ahead DR	✓	✓	✓			✓
Capacity market DR participation	✓	✓	✓			✓
Ancillary services	✓	✓	✓	✓		✓

Table 2. Impact of DRP participation level on PEV aggregation agent's costs and incomes – scenario 1

	Without intraday market			With intraday market		
DRP participation	0%	10%	20%	0%	10%	20%
Revenue from day-ahead market (€)	6,309	6,665	6,681	6,511	6,693	6,700
Revenue from spinning reserve market (€)	165,997	167,228	168,676	162,843	166,388	167,452
Revenue from charging (€)	51,983	52,899	52,632	52,821	53,034	53,044
Revenue from intraday market (€)	0	0	0	165	91	24
Revenue from DRX market (€)	0	752	931	0	719	967
Imbalance cost (€)	1,052	164	75	535	174	63
Cost of DRX market (€)	0	1,549	1,637	0	1,211	1,487
Cost of intraday market (€)	0	0	0	303.0	132.2	120.3
Cost of battery degradation (€)	4,904	4,951	4,998	4,823	4,927	4,960
Cost of energy market (€)	528	496	532	507	524	536
Cost of charging (€)	50,733	49,034	48,373	48,775	48,369	47,700
Fixed costs (€)	154,374	154,374	154,374	154,374	154,374	154,374
Expected profit (€)	12,698	16,976	18,930	13,021	17,215	18,946

Table 3. Impact of DRP participation level on PEV aggregation agent's costs and incomes – scenario 2

	Without intraday market			With intraday market		
DRP participation	0%	10%	20%	0%	10%	20%
Revenue from day-ahead market (€)	3,219	3,245	3,257	3,217	3,249	3,265
Revenue from spinning reserve market (€)	84,032	85,028	85,059	84,200	85,313	85,325
Revenue from charging (€)	51,872	52,107	52,005	51,920	52,104	51,950
Revenue from intraday market (€)	0	0	0	83	44	10
Revenue from DRX market (€)	0	591	673	0	524	673
Imbalance cost (€)	527	41	33	280	37	27
Cost of DRX market (€)	0	1,368	1,561	0	1,305	1,498
Cost of intraday market (€)	0	0	0	299.7	118.4	114.7
Cost of battery degradation (€)	2,443	2,482	2,491	2,449	2,475	2,484
Cost of energy market (€)	253	256	257	253	256	256
Cost of charging (€)	46,348	46,251	46,086	46,383	46,468	46,257
Fixed costs (€)	77,187	77,187	77,187	77,187	77,187	77,187
Expected profit (€)	12,365	13,386	13,379	12,568	13,387	13,398

Appendix

Table A.1. Technical data for the PEV aggregation agent

P^* (kW)	CPEV (kWh)	η^D (%)	η^C (%)	FOR^{Agg}	$Ramp^{C/D}$ (pu/h)
10	50	82	90	0.05	0.2
SOC^{min} (pu)	SOC^{max} (pu)	L_{ET} (kWh)	PF	MCD (h)	MBC (pu)
0.3	0.9	43840**	0.95	5	0.5

* It is assumed that $P=P_{Res}=P_{Energy}=P_{line}$, P_{line} affected by wiring cost

** A deep depth of discharge (DoD) is assumed [36]

Table A.2. Economic data for the PEV aggregation agent

$C^{battery}$ (€)	$Cost^{Wiring}$ (€)	$Cost^{On\text{-}board}$ (€)	N^y (year)	dr (%)
15300*	500	300	10	10

* 300 (€/kWh) × 50(kWh) + 10 h replacement labor × 30 (€/h)

Table A.3. Price-quantity offer of DRPs in intraday DRX market

k	1	2	3	4
q_{dt}^{k}	25% of response	50% of response	75% of response	100% of response
c_{1t}^{k}	40% of the intraday market price	70% of the intraday market price	100% of the intraday market price	130% of the intraday market price
c_{2t}^{k}	50% of the intraday market price	80% of the intraday market price	110% of the intraday market price	140% of the intraday market price
c_{3t}^{k}	60% of the intraday market price	90% of the intraday market price	120% of the intraday market price	150% of the intraday market price