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Stochastic Multiperiod Decision Making Framework of an Electricity Retailer Considering Aggregated Optimal Charging and Discharging of Electric Vehicles

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ABSTRACT
This paper proposes a novel decision making framework for an electricity retailer to procure its electric demand in a bilateral-pool market in presence of charging and discharging of electric vehicles (EVs). The operational framework is a two-stage programming model in which at the first stage, the retailer and EV aggregator do their medium-term planning. Determination of retailer's optimum selling price and the amount of energy that should be purchased from bilateral contracts are medium-term decisions that are made one month prior to real-time market. At the second stage, market agents deal with their activities in the short-term period. In this stage the retailer may modify its preliminary strategy by means of pool market option, interruptible loads (ILs), self-scheduling and EVs charging and discharging (V2G). Thus, a bi-level programming is introduced in which the upper sub-problem maximizes retailer profit, whereas the lower sub-problem minimizes the aggregated EVs charging and discharging costs. Final decision making is obtained in this stage that may be considered as a day-ahead market, keeping in mind the medium-term decisions. Due to the volatility of pool price and uncertainties associated with the consumers and EVs demand, the proposed framework is a mixed integer nonlinear stochastic optimization problem; therefore, Monte Carlo Simulation (MCS) is applied to solve it. Furthermore, a market quota curve is utilized to model the uncertainty of the rivals and obtaining retailer's actual market share. Finally, a case study is presented in order to show the capability and accuracy of the proposed framework.

KEYWORDS: Aggregator, Bilateral, Decision making, Electric vehicle, Interruptible load, Retailer, Self-production.

1. INTRODUCTION

Role of retailer in electricity market is highlighted more, because a large number of consumers due to lack of familiarity with the market rules, cannot play active role in that. Retailers take part in power markets by procuring energy from the bilateral and the pool markets and by selling energy to their consumers at fixed prices during a specific medium-term period. Because of volatility of pool price, the retailer is exposed to the uncertainties of the pool price and demand of consumers. On the other hand, the costs of multiple options at the medium-term period are generally greater than the average pool price. Therefore, the retailer faces a trade-off between different purchasing options of electricity [1].

There are noticeable literatures describing retailer role in the electricity markets. In [2] a stochastic based decision-making framework for an electricity retailer is proposed in which the retailer determines the sale price of electricity to the consumers based on TOU rates. The proposed framework in [3] is modeled in the form of a multi-objective framework to simultaneously maximize retailers' profit and minimize selling prices to clients. The work addressed in [4] includes a stochastic medium-term planning for an electricity retailer considering objective functions of expected profit and downside risk for determining the selling price offered to the

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consumers and the optimal quantity of forward contracts. Reference [5] provides a novel technique based on Information Gap Decision Theory (IGDT) to assess different strategies for a retailer under unstructured pool price uncertainty. All of above mentioned models in [3-6] have focused on retailers' medium-term planning that may be inaccurate. In [6], a Non-dominated Sorting Genetic Algorithm-II (NSGA-II) based approach is presented for conversion of multi-objective function into an equivalent single objective function; however impacts of bilateral contracts and pool price volatilities are not taken into account. A reliability assessment model in presence of micro grids is represented in [7]. Although the model considers distribution load uncertainties but it mostly investigates system reliability enhancement. Electricity procurement for a large consumer from the pool market and forward contracts is reported in [8,9] and [11]. Although, a mixed pool-forward market is represented in [8-10]; however the problem is discussed from electricity consumers and retailers' perspectives are not considered.

Recently due to environmental issues and customer preferences a great attention has been paid to electric vehicles (EVs). Thus, increasing deployment of the EVs in the power system needs an agent responsible for aggregating of large EV fleets and controlling their charging and discharging process. In the electricity market environment, this agent is popularly referred to as EV aggregation agent [11], or in short, EV aggregator.

In this paper, a stochastic programming approach [11] is presented for an electricity retailer who procures its demand in a mixed bilateral-pool market. The retailer load consists of conventional loads and flexible EV loads. In fact, EV aggregator is in charge of controlling EVs charging and discharging process and the retailer supplies its flexible demand as well as other conventional consumers. Accordingly, a two stage operational framework is presented in which at the first stage, the retailer and aggregator do their medium-term planning that is made one month prior to real-time market.

At the second stage, the retailer and EV aggregator deal with their activities in the short-term period. In this stage, the retailer may modify its preliminary strategy by means of different sources such as pool market, interruptible loads, self-scheduling and EVs charging and discharging (entitled, vehicle to grid (V2G)) strategies, keeping in mind the medium-term decisions. Subsequently, a bi-level programming approach is adopted to solve the decision-making problem in which the upper sub-problem maximizes retailer profit, whereas the lower sub-problem minimizes the aggregated EVs charging and discharging costs. Due to the volatility of pool price and uncertainties associated with the consumers and EVs demand, the proposed framework is a mixed integer nonlinear stochastic optimization problem; therefore, Monte Carlo Simulation (MCS) is applied to solve it;. Furthermore, a market-quota curve is utilized to model the uncertainty of the rivals and obtaining retailer's actual market share.

The rest of this paper is organized as follows: the proposed market framework in terms of retailer's medium-term and short-term strategies in pool and bilateral markets as well as EV aggregator model are presented in Section 2. The case study is provided in Section 3 and finally Section 4 represents the conclusion.

2. FORMULATION OF PROPOSED MARKET FRAMEWORK

It is assumed the retailer buys electricity from the wholesale market and sells it back to conventional consumers and EV aggregator based on TOU rates for a specified period. Following, a detailed structure of the proposed multi-period decision making model is presented that allows a retailer and EV aggregator to determine the optimal strategy in the medium and short-term programming.

2.1. Medium-term planning framework

The medium-term program is a stochastic program in which uncertain parameters are modeled through scenario generation. The retailer's medium-term program is to determine the selling price and the quantity of power that should be purchased from bilateral contract as well as an approximate estimate of EVs aggregated demand.

2.1.1. Scenario generation

As previously mentioned, the pool price and consumer's demand are uncertainties in the medium-term program. The pool price uncertainty is modeled by mean–variance model of historical data, and it is assumed that the pool price distribution around the expected value is normal. We assume that the retailer has a forecast of the expected demand of conventional consumers, $\bar{\lambda}^{P}_{tj}$. Also, we consider that the amount of load demand is highly dependent on pool prices; therefore, after generating each pool price scenario $\lambda^{P}_{tj}(\omega)$, conventional load demands can be generated as a function of pool market prices that is calculated as below [12]:

$$d_{tj}(\omega) = \bar{d}_{tj}(1 + \xi \frac{\lambda^{P}_{tj}(\omega) - \bar{\lambda}^{P}_{tj}}{\bar{\lambda}^{P}_{tj}}) \quad (1)$$
$$\forall \omega \in \Omega_{\omega}, \forall t \in \{v, s, p\}, \forall j = j1, \ldots, j7$$

where, ξ is a parameter that depends on the relationship between the pool price and the demand of conventional consumers. In this paper, we assume ξ = -0.1. It is notable that advanced methods for forecasting such as scenario generation, scenario reduction and model building could be easily used for medium-term planning strategy. Afterwards, the retailer generates scenarios for EVs load demand as well. The most effective factors on the EVs load demand are home departure time, daily travelled distance and home arrival time. Besides, road traffic condition, driving habits, battery capacity and its charger efficiency should also be considered. In medium-term, in order to generate MCS random samples, some of EVs related data are used to obtain corresponding probability density functions (PDFs). Non-Gaussian PDFs are suggested to create EVs random variables due to the better approximation of these functions. The Weibull PDF has been selected as the most appropriate function for departure time (d_k) of EVs as bellow:

$$f_{d_h}(\mathrm{h}) = \frac{\beta}{\alpha}(\frac{h}{\alpha})^{(\beta-1)} e^{-(\frac{h}{\alpha})^{\beta}} \qquad h > 0 \quad (2)$$

Also, to model daily travelled distance (tr_d) and arrival time (a_k), a type III Generalized expected value (Gev) PDF is selected. These functions are presented in Eqs. (3) and (4):

$$f_{tr_d}(\mathrm{t}) = \frac{1}{\sigma_{tr_d}}(1 + \mathrm{k}_{tr_d}\frac{(\mathrm{d}-\mu_{tr_d})}{\sigma_{tr_d}})^{-(1+\frac{1}{k_{tr_d}})} e^{-(1+\mathrm{k}_{tr_d}\frac{(\mathrm{d}-\mu_{tr_d})}{\sigma_{tr_d}})^{\frac{1}{k_{tr_d}}}} \quad (3)$$

$$f_{a_h}(\mathrm{t}) = \frac{1}{\sigma_{a_h}}(1 + \mathrm{k}_{a_h}\frac{(\mathrm{d}-\mu_{a_h})}{\sigma_{a_h}})^{-(1+\frac{1}{k_{a_h}})} e^{-(1+\mathrm{k}_{a_h}\frac{(\mathrm{d}-\mu_{a_h})}{\sigma_{a_h}})^{\frac{1}{k_{a_h}}}} \quad (4)$$

Required power for full-charge of EV battery in each day, is equal to the difference between its battery capacity and initial state of charge, when EV comes back from its last daily trip. This statement can be expressed as follows:

$$charge^{EV}_{j} = Cap_{bat} - SOC^{EV}_{0} \quad (5)$$

The SOC^{EV}_{0} of EVs depends on several factors such as daily travelled distance and battery capacity. Hence, SOC^{EV}_{0} can be derived as:

$$SOC^{EV}_{0} = 100 - \frac{tr_d}{C_{eff} \times Cap_{bat}} \times 100 \quad (6)$$

where, C_{eff} is the efficiency coefficient of the EV which depends on the traffic conditions and driving patterns as well as converter efficiency.

Here, EV aggregator generates total EVs demand scenarios. Subsequently, it estimates EVs aggregated power in the valley, shoulder and peak hours of EVs fleet using the following model:

$$Min: \sum_{EV=1}^{N'_{EV}} \sum_{j} \sum_{h=a_h}^{d_h} (P^{P}_{hj,EV}(\omega) \,.\, (1 + \xi \frac{\lambda^{P}_{hj}(\omega) - \bar{\lambda}^{P}_{hj}}{\bar{\lambda}^{P}_{hj}})) \quad (7)$$

s.t.

$$P_{hj,EV}(\omega) = \frac{CH_{hj,\mathrm{EV}}(\omega)}{\eta} \qquad \forall \omega, \forall EV, \forall h, \forall j \quad (8)$$

$$\sum_{h=a_h}^{d_h}(CH_{hj,\mathrm{EV}}(\omega)) + SOC^{EV}_{0}(\omega) = Cap_{bat} \quad \forall \omega, \forall EV, \forall h, \forall j \quad (9)$$

$$SOC^{EV}_{h,j}(\omega) = SOC^{EV}_{h-1,j}(\omega) + CH_{hj,\mathrm{EV}}(\omega) \quad \forall \omega, \forall EV, \forall h, \forall j (10)$$

$$CH_{\min} \le CH_{hj,\mathrm{EV}}(\omega) \le CH_{\max} \qquad \forall \omega, \forall EV, \forall h, \forall j (11)$$

$$SOC_{\min} \le SOC^{EV}_{h,j}(\omega) \le SOC_{\max} \qquad \forall \omega, \forall EV, \forall h, \forall j (12)$$

$$P^{P}_{hj,EV}(\omega) = P_{hj,EV}(\omega) \qquad \forall \omega, \forall EV, \forall h, \forall j (13)$$

In which, Eq. (8) represents the amount of required power for charging EVs battery in ωth scenario during hour h in day j. Based on Eq. (9) EVs battery should be fully charged within charging time [a_k d_k]. The charging state of the battery at the end of interval h considering charging power at that interval is given in Eq. (10). Moreover, constraints associated with variables of optimization problem are represented in the Eqs. (11)- (12). The power balance for each EV in ωth scenario during hour h in day j can be expressed as Eq. (13).

After implementation of the above mentioned optimization problem, the aggregated EVs fleet required power during valley, shoulder and peak hours can be derived as follows:

$$d_{tj}^{Fleet}(\omega) = \sum_{EV=1}^{N_{EV}} \sum_{h \in t} \mathrm{P}_{hj,EV}(\omega) \quad \forall \omega, \forall t \in \{v,s,p\}, \forall j \quad (14)$$

By means of market-quote curve which will be explained in the next subsection, retailer's selling price and the percentage of consumers demand supplied by the retailer can be obtained.

2.1.2. Formulation of medium-term strategy

The profit objective function of the retailer in this stage can be formulated as follows:

$$Max: Exp\left(\sum_{j=1}^{7}\sum_{t}\begin{pmatrix}\mathrm{Rev}_{tj}^{mid-term}(\omega) \\ -COST_{tj}^{B,mid-term}(\omega) - COST_{tj}^{P,mid-term}(\omega))\end{pmatrix}\right) \quad (15)$$

$$\forall \omega \in \Omega_{\omega}, \forall t \in \{v,s,p\}, \forall j = j1,...,j7$$

where, the first term is the retailer's revenue from selling to the consumers while the second and third terms are the cost of purchasing from bilateral contract and pool market, respectively. The individual parts of the above function can be explained as follows:

2.1.2.1. Setting retailer selling price

The relationship between the actual demand supplied to the consumers and the price offered by the retailer is proposed through a step wise market-quota curve. This curve represents retailer's market share among its other rivals.

A market-quota curve with three blocks is shown in Fig. 1. From mathematical perspective, the market-quota curve for consumers during period t in day j and ωth scenario of MCS can be formulated as follows:

$$D_{tj}(\omega) = \sum_{i=1}^{N_i} (\overline{D}_{tj,\mathrm{i}}^{D}(\omega) + \overline{D}_{tj,\mathrm{i}}^{Fleet}(\omega)).\nu_{\mathrm{t,i}} \quad (16)$$
$$\forall \omega, \forall t, \forall j, i = 1,...,N_i$$

$$\lambda_t^R = \sum_{i=1}^{N_i} \lambda_{t,i}^R \qquad \forall t \quad (17)$$

$$\overline{\lambda}_{\mathrm{t,i-1}}^R \nu_{\mathrm{t,i}} \le \lambda_{\mathrm{t,i}}^R \le \overline{\lambda}_{\mathrm{t,i}}^R \nu_{\mathrm{t,i}} \qquad \forall t, \forall i \quad (18)$$

$$\sum_{i=1}^{N_i} \nu_{\mathrm{t,i}} = 1 \qquad \nu_{\mathrm{t,i}} \in \{0,1\} \quad (19)$$

Where, $\overline{D}_{tj,\mathrm{i}}^{D}(\omega)$ and $\overline{D}_{tj,\mathrm{i}}^{Fleet}(\omega)$ are percentage of $d_{tj}(\omega)$ and $d_{tj}^{Fleet}(\omega)$, respectively.

The revenue obtained from selling to the consumers (conventional consumers and EVs loads) is equal to the product of the selling price and power supplied by the retailer.

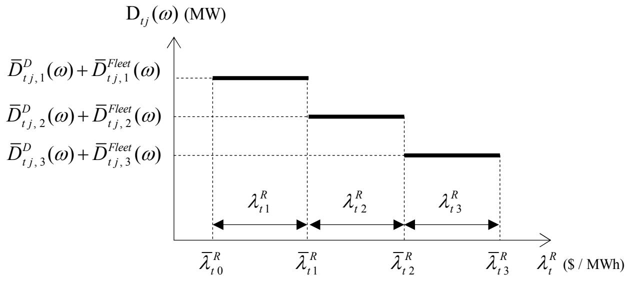

Fig. 1. Retailer market-quota curve [13].

Due to the stochastic behavior of consumer demands, the retailer's obtained revenue would be a random variable; Thus, the corresponding medium-term revenue from selling to the consumers during period t in day j and in ωth scenario can be formulated as:

$$\mathrm{Rev}_{tj}^{mid-term}(\omega) = D_{tj}(\omega)\,\lambda_t^R \qquad \forall \omega, \forall t, \forall j \quad (20)$$

$$\mathrm{Rev}_{tj}^{mid-term}(\omega) = \sum_{i=1}^{N_i} (\overline{D}_{tj,\mathrm{i}}^{D}(\omega) + \overline{D}_{tj,\mathrm{i}}^{Fleet}(\omega)).\nu_{\mathrm{t,i}}.\lambda_{\mathrm{t,i}}^R \quad (21)$$
$$\forall \omega, \forall t, \forall j$$

2.1.2.2. The cost of bilateral contracts

In bilateral contracts a maximum and a minimum bound of the purchased power is defined for each period. In the maturity period, if consumed power violates from these bounds, the retailer incurs a penalty. In the medium-term program, the quantity of power that is procured from bilateral contract during valley, shoulder and peak hours for a week is defined. Accordingly, the cost of bilateral contract throughout the time horizon of one week in ωth scenario during period t in day j is given as:

$$COST_{tj}^{\mathrm{B,mid-term}}(\omega) = P_{tj}^B(\omega)\lambda_{tj}^B \qquad \forall \omega, \forall t, \forall j \quad (22)$$

2.1.2.3. The cost of pool market

Besides the bilateral contract, the retailer may also procure its demand from the pool market. Due to the volatility of pool prices, the retailer faces uncertainty while offering in the medium-term market. In order to consider this uncertainty, a stochastic programming should be considered for retailer's medium-term planning. Therefore, purchasing cost from the pool market in ωth scenario can be formulated as:

$$COST_{tj}^{P,mid-term}(\omega) = P_{tj}^{P}(\omega)\lambda_{tj}^{P}(\omega) \qquad \forall\, \omega, \forall\, t, \forall\, j \qquad (23)$$

The medium-term model is a stochastic mixed integer non-linear problem (MINLP) due to the randomness of pool prices and consumer demands.

2.2. Short-term planning framework

A bi-level programming approach is proposed to solve the decision making problem faced by the retailer and EV aggregator in the short-term problem; the upper sub-problem maximizes retailer profit whereas the lower sub-problem minimizes aggregator charging cost. On the other hand, in the lower level, the EV aggregator agent is responsible for optimal scheduling of its EVs battery charging and discharging process. In this way EV owners would pay less and also the retailer can adhere its plan thereby reduces its imbalance costs. Following the lower and upper levels of short-term optimization problem are addressed.

2.2.1. EVs aggregator model in the lower sub-problem

In this stage, aggregator should supply EVs charging loads. Furthermore, aggregator may set up bilateral contracts with retailer in order to supply a part of its required demand through V2G concept, when the price of pool market and other options are high. It is assumed that the EVs demand is responsive to the selling price offered by the retailer and is scheduled by the aggregator. In the lower level of short-term optimization problem, the objective function of the aggregator is to minimize the total cost over the scheduling time horizon. Mathematically, this objective function in day *j* can be formulated as:

$$Min: \sum_{EV=1}^{N_{EV}} \sum_{h\in t=a_h}^{d_h} (p_{hj,EV}^{S} \cdot \lambda_t^{R} - p_{hj,EV}^{P} \cdot \lambda_t^{Pei}) \qquad \forall j \quad (24)$$

s.t.

$$p_{hj,EV}^{S} = \frac{ch_{hj,\mathrm{EV}}}{\eta} \qquad \forall EV, \forall h, \forall j \quad (25)$$

$$p_{hj,EV}^{P} = dch_{hj,\mathrm{EV}} \cdot \eta \qquad \forall EV, \forall h, \forall j \quad (26)$$

$$\sum_{h=a_t}^{d_t} (\mathrm{ch}_{hj,\mathrm{EV}} - \mathrm{dch}_{hj,\mathrm{EV}}) + soc_0^{EV} = Cap_{bat} \quad \forall EV, \forall h, \forall j \quad (27)$$

$$soc_{h,j}^{EV} = soc_{h-1,j}^{EV} + ch_{hj,\mathrm{EV}} - dch_{hj,\mathrm{EV}} \qquad \forall EV, \forall h, \forall j \quad (28)$$

$$ch_{\min} \le ch_{hj,\mathrm{EV}} \le ch_{\max} \qquad \forall EV, \forall h, \forall j \quad (29)$$

$$dch_{\min} \le dch_{hj,\mathrm{EV}} \le dch_{\max} \qquad \forall EV, \forall h, \forall j \quad (30)$$

$$soc_{\min} \le soc_{h,j}^{EV} \le soc_{\max} \qquad \forall EV, \forall h, \forall j \quad (31)$$

Where all mentioned constraints are previously described except for Eq. (26) that shows useful power for discharging EV batteries.

2.2.2. Retailer profit model in the upper sub-problem

In the upper level of short-term optimization problem, the retailer seeks to maximize its short-term profit during each day keeping in mind the medium-term decisions. The complete formulation of the upper level is given as:

$$\begin{aligned} Max: \ & \mathrm{Rev}_j^{Selling} + \mathrm{Rev}_j^{Fleet} + \mathrm{Rev}_j^{IL} - COST_j^{\mathrm{B,short-term}} \\ & - COST_j^{\mathrm{B,penalty}} - COST_j^{P,short-term} - COST_{hj}^{G} - COST_j^{Fleet} \end{aligned} \quad (32)$$

This objective function consists of two main parts, the revenue obtained by the retailer from selling to both consumers and the pool market as well as the cost of buying from various options. Different parts of the objective function can be explained as follows:

2.2.2.1. Cost of bilateral contract

It is assumed that in the medium-term a Contract for Difference (CFD) agreement is signed between wholesale market and the retailer in such a way that the difference between the bilateral contract price and actual pool price is equally split between two sides. The proportion of the difference could be changed by negotiating between two sides. Based on CFD, in the short-term program the bilateral contract cost can be formulated as:

$$\begin{aligned} COST_j^{\mathrm{B,short-term}} &= \sum_t \sum_{h\in t} (\lambda_{tj}^{B} + \frac{\lambda_{tj}^{P} - \lambda_{tj}^{B}}{2}) \mathrm{p}_{hj}^{B} \\ &= \sum_t \sum_{h\in t} \frac{1}{2} \lambda_{tj}^{B} p_{hj}^{B} + \sum_{h=1}^{24} \frac{1}{2} \lambda_{hj}^{P,est} p_{hj}^{B} \qquad \forall j \end{aligned} \quad (33)$$

On the other hand, in the short-term period, retailer should pay penalties due to under or over-consumption of bilateral contracts that are signed in the medium-term. The total power consumed from bilateral contract during period *t* in day *j* is:

$$\sum_{h\in t} p_{hj}^{B} = \sum_{m=1}^{5} x_{\mathrm{m,t}j} \qquad \forall t, \forall j \quad (34)$$

where, $X_{m,tj}$ is an auxiliary variable for penalty calculations of bilateral contracts in the short-term stage. Fig. 2 shows the penalties that are incurred for under or over-consumption of a bilateral contract related to period t in day j.

The penalty constraints can be expressed mathematically as:

$$0 \le x_{1,tj} \le 0.8\,\bar{P}^{\mathrm{B}}_{tj} \qquad \forall t, \forall j \quad (35)$$

$$0 \le x_{2,tj} \le 0.1\,\bar{P}^{\mathrm{B}}_{tj} \qquad \forall t, \forall j \quad (36)$$

$$0 \le x_{3,tj} \le 0.2\,\bar{P}^{\mathrm{B}}_{tj} \qquad \forall t, \forall j \quad (37)$$

$$0 \le x_{4,tj} \le 0.1\,\bar{P}^{\mathrm{B}}_{tj} \qquad \forall t, \forall j \quad (38)$$

$$0 \le x_{5,tj} \le M \qquad \forall t, \forall j \quad (39)$$

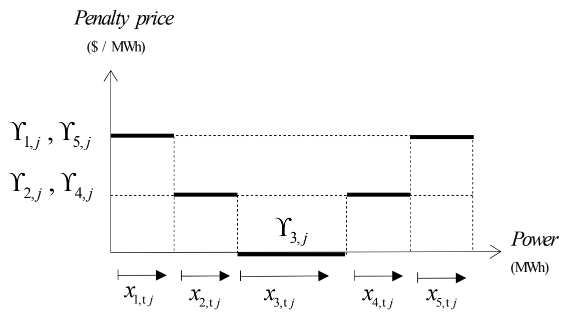

Fig. 2. Penalty function for under or over-consumption of bilateral contracts.

In the above constraints, $X_{m,tj}$ (m=1 … 5) is a variable representing the power consumed within block m. With this approach under or over-consumption penalties can be expressed in cumulative blocks and formulated as follows:

$$COST^{\mathrm{B,Penalty}}_{tj} = \begin{pmatrix} \Upsilon_{1,t}\,(0.8\,\bar{\mathrm{P}}^{\mathrm{B}}_{tj} - x_{1,tj}) \\ +\Upsilon_{2,t}\,(0.1\,\bar{\mathrm{P}}^{\mathrm{B}}_{tj} - x_{2,tj}) \\ +\sum_{m=3}^{5} \Upsilon_{\mathrm{m,t}}\, x_{\mathrm{m,tj}} \end{pmatrix} \qquad \forall t, \forall j \quad (40)$$

Note that, $\bar{P}^{B}_{tj}$ is computed in the medium-term program and is a sufficiently large constant, e.g. $2\bar{P}^{B}_{tj}$.

Finally, total penalty cost considering all bilateral contracts throughout the time horizon of day j is:

$$COST^{\mathrm{B,penalty}}_{j} = \sum_{t} COST^{B,penalty}_{tj} \qquad \forall j \quad (41)$$

2.2.2.2. Retailer self-production

Some retailers hedge against risk of pool market by owning some self-production utilities such as distributed generators. It is considered that self-production facility can only supply a part of the retailer's demand, which is a realistic assumption. Thus, the retailers face a trade-off between the cost of self-production and the cost of other options. In the short-term program the self-produced power at hour h of day j, P^{G}_{hj} is given as:

$$P^{G}_{hj} = u_{hj}\, P^{\mathrm{G,min}} + \sum_{f=1}^{F} P_{fhj} \qquad \forall h, \forall j \quad (42)$$

$$0 \le P_{fhj} \le u_{hj}\, P^{\max}_{f} \qquad \forall h, \forall j, \forall f \quad (43)$$

The retailer production cost may be implemented using an approximate piecewise linear function curve as shown in Fig. 3. Considering DG corresponding costs, the aggregated self-production cost during hour h in day j is thus obtained as:

$$COST^{G}_{hj} = u_{hj} C^{fix} + y_{hj} C^{su} + z_{hj} C^{shd} + \sum_{f=1}^{F} \ell_f\, P_{fhj} \qquad \forall h, \forall j \quad (44)$$

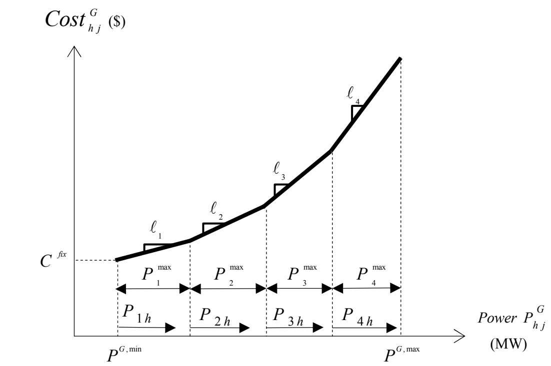

Fig. 3. Piecewise linear convex production cost using four blocks [9].

Subsequently, self-production constraints in terms of minimum up time and down time as well as ramp-up and ramp-down constraints are expressed as Eqs. (45)- (48):

$$\left[X^{on}_{(\mathrm{h}-1)} - T^{on}\right].\left[u_{(\mathrm{h}-1)\mathrm{j}} - u_{\mathrm{h}j}\right] \ge 0 \qquad \forall h, \forall j \quad (45)$$

$$\left[X^{off}_{(\mathrm{h}-1)} - T^{off}\right].\left[u_{\mathrm{hj}} - u_{(\mathrm{h}-1)\mathrm{j}}\right] \ge 0 \qquad \forall h, \forall j \quad (46)$$

$$P^{G}_{h+1,j} - P^{G}_{h,j} \le R^{UP} \qquad \forall h, \forall j \quad (47)$$

$$P^{G}_{h,j} - P^{G}_{h+1,j} \le R^{DN} \qquad \forall h, \forall j \quad (48)$$

The relationship between binary variables used to model the ON and OFF status of the self-production facility should meet the following constraints to avoid conflicting situations:

$$u_{hj} - u_{(h-1)j} = y_{hj} - z_{hj} \;,\; \mathrm{y}_{hj} + z_{hj} \le 1 \qquad \forall h, \forall j \quad (49)$$

On the other hand, self-produced power can be locally consumed or sold to the pool in the short-term program during hour h in day j as shown in Eq. (50):

$$P^{G}_{hj} = P^{consume}_{hj} + P^{Sell}_{hj} \qquad \forall h, \forall j \quad (50)$$

In order to avoid simultaneous buying and selling power during hour h in day j at an identical price, the following constraints can be used in the content of short-term program:

$$p_{hj}^{P} \le k_{hj} L_{hj} \quad , \quad k_{hj} \in \{0,1\} \qquad \forall h, \forall j \qquad (51)$$

$$P_{hj}^{Sell} \le (1-k_{hj}) P^{G,\max} \qquad \forall h, \forall j \qquad (52)$$

Where $L_{k,j}$ is total load of consumers during hour h in day j with interrupted load. It is notable that based on Eq. (51), retailer can consume the obtaining power of self-production facility, but the output power should be less than or equal to the actual demand of consumers. On the other hand, based on Eq. (52) retailer can sell the obtaining power of self-production facility to the pool, however, the output power should be less than or equal to the maximum power output of the self-production.

2.2.2.3. Retailer strategy with EV aggregator agent

In the short-term program, the revenue of retailer from selling to EVs fleet during hours h of type t in day j is:

$$\mathrm{Re}v_{j}^{Fleet} = \sum_{EV=1}^{N_{EV}} \sum_{h \in t} p_{hj,\mathrm{EV}}^{S} \, \lambda_{t}^{R} \qquad \forall j \qquad (53)$$

On the other hand, the cost of purchasing from the EVs fleet through V2G capability can be formulated as:

$$COST_{j}^{Fleet} = \sum_{EV=1}^{N_{EV}} \sum_{h \in t} p_{hj,\mathrm{EV}}^{P} \, \lambda_{t}^{Pei} \qquad \forall j \qquad (54)$$

where, $p_{hj,EV}^{S}$ and $p_{hj,\mathrm{EV}}^{P}$ are obtained by EV aggregator through short-term lower sub-problem.

2.2.2.4. Participating in the pool market

As the medium-term stage, in the short-term program the retailer may also procure its residual demand from the pool market. Thus, purchasing cost from the pool in the short-term program for each day j is computed as:

$$COST_{j}^{P,short-term} = \sum_{h=1}^{24} p_{hj}^{P} \lambda_{hj}^{P,est} \qquad \forall j \qquad (55)$$

Also, it is assumed that the retailer can sell back its excess self-produced power to the pool market. Therefore, selling revenue from the pool for each day j is computed as:

$$\mathrm{Re}v_{j}^{Selling} = \sum_{h=1}^{24} \lambda_{hj}^{P,est} P_{hj}^{Sell} \qquad \forall j \qquad (56)$$

2.2.2.5. Presence of IL contracts

In addition to the self-production and V2G capabilities of EVs, ILs can be utilized by retailers as a risk management tool against volatility of pool prices. In this paper, two types of IL contracts are considered. In the first case the consumers pay λ_{t}^{R} for their loads; but if in case of emergency, the retailer is forced to interrupt the consumers loads, a penalty λ_{t}^{Fine} ($\lambda_{t}^{Fine} \rangle \lambda_{t}^{R}$) should be paid to the consumers. In the second case, an IL contract has been signed between two sides and consumers pay a reduced price for their loads, $\lambda_{t}^{\mathrm{Re}duce}$ but do not receive any additional pecuniary compensation in case of interruption. For this type of consumers $\lambda_{t}^{Fine} = 0$ [13]. Mathematically, the revenue of retailer from selling to the conventional consumers considering IL contract in the short-term program can be formulated as:

$$\mathrm{Re}v_{j}^{IL} = \begin{pmatrix} \sum_{h \in t} (D_{1,hj} - p_{1,hj}^{IL}) \,.\, \lambda_{t}^{R} \\ + \sum_{h \in t} (D_{2,hj} - p_{2,hj}^{IL}) \,.\, \lambda_{t}^{\mathrm{Re}duce} \\ - \sum_{h \in t} p_{1,hj}^{IL} \,.\, \lambda_{t}^{Fine} \end{pmatrix} \qquad \forall j \qquad (57)$$

where, the first and second terms are associated with the net revenue of retailer from selling to consumers of type 1 and 2, respectively. Also, the cost of interrupting consumers of type 1 is given in the third term. Eventually, the short-term power balance at hour h in day j can be expressed as:

$$\begin{pmatrix} \sum_{EV=1}^{N_{EV}} p_{hj,EV}^{P} + P_{hj}^{consume} \\ + p_{hj}^{P} + p_{hj}^{B} \end{pmatrix} = \begin{pmatrix} \sum_{EV=1}^{N_{EV}} p_{hj,EV}^{S} + D_{1,hj} \\ + D_{2,hj} - p_{1,hj}^{IL} - p_{2,hj}^{IL} \end{pmatrix} \forall h, \forall j \quad (58)$$

It is notable that, self-production facility, V2G and IL options, not only meet a part of the retailer's demand, but also their implementation in the short-term program is more realistic. The short-term framework is a bi-level optimization problem. EMP (Extended Mathematical Programming) solver in the GAMS software is used to solve this model. Here, in order to simulate the uncertainty of the mathematical model a large number of parameters related to uncertainties of the spot market price $\lambda_{tj}^{P}(\omega)$, the conventional consumers demand $d_{tj}(\omega)$ and EVs fleet demand $d_{tj}^{Fleet}(\omega)$ are randomly produced by MCS. Subsequently, for each of these uncertainties, the optimization problem is solved to get $P_{tj}^{B}(\omega)$, $P_{tj}^{P}(\omega)$ *and* λ_t^R. Finally, the expected values of all allocation schemes are computed for the decision variables. These decisions are imposed as boundary constraints in the short-term program.

3. CASE STUDY

To show the efficiency of the proposed framework, a case study is performed based on a typical electricity retailer data in Nord Pool Market [14]. Decision making time horizon is one month prior to real-time market for medium-term and one day prior to real-time market for short-term. In this paper, one week time horizon is considered for numerical analysis. According to employed TOU pricing, the valley period is defined at hours 1-7, hours 11-13 and 17-21 are peak periods and the remaining hours are considered as shoulder period. It is assumed that the selling price at each hour is fixed. Moreover, the retailer pays a fine $\lambda_t^{Fine} = 1.15\,\lambda_t^R$ per unit of interruption to conventional consumers of type 1 and offers a 7% discount in the selling price, $\lambda_t^{\mathrm{Re}duce} = 0.93\,\lambda_t^R$ for consumers of type 2. Also, it is supposed that, 80% and 20% of consumers are type 1 and type 2, respectively, and the retailer can interrupt maximum 30% of each customer's load. Fig. 4 shows expected demand data of conventional consumers, $\bar{d}_{tj}$, for valley, shoulder and peak hours of a sample week days. Subsequently, Fig. 5 illustrates retailer's market-quota curve with 100 points (100 steps) for each valley, shoulder and peak periods.

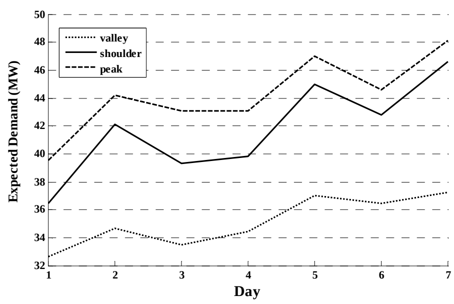

Fig. 4. Expected demand data during each hour of period *t* (MW)

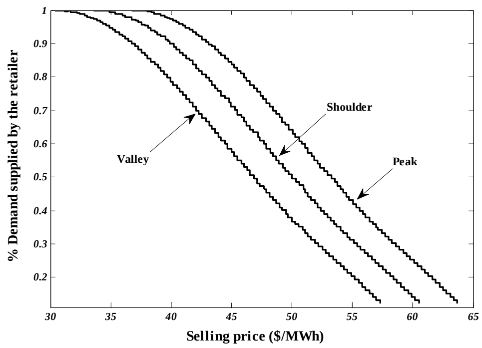

Fig. 5. Market-quota curves data with 100 intervals

Table 1, provides the mean and standard deviation of existing pool prices for one week time horizon that are obtained from historical data of Nord Pool spot market. Penalty data of bilateral contracts for under-consumption and over-consumption is given in Table 2.

Table 1. Mean and standard deviation of pool price data

	valley	shoulder	peak
Mean (μ)	40.86	44.68	48.08
Standard deviation (δ)	1.20	4.33	6.68

Data associated with self-production unit in terms of unit technical data and cost coefficients is also represented in Tables 3-5.

Table 2. Penalty data of bilateral contracts($\Upsilon_{3,t} = 0$) $/MWh

Penalty slope	Valley	Shoulder	Peak
$\Upsilon_{1,t}$	3	4	5
$\Upsilon_{2,t}$	1.5	2	3
$\Upsilon_{4,t}$	1.5	2	3
$\Upsilon_{5,t}$	3	4	5

Table 3. Technical characteristics of the self-production facility

$P^{G,\min}$ (MW)	$P^{G,\max}$ (MW)	Ramp-up limit, (MW/h)	Ramp-down limit (MW/h)	Minimum up/down time (h)
3	12	3	3	2

Table 4. Fixed, shut-down and start-up costs ($).

Fixed	Shut-down	Start-up
200	100	150

Table 5. Piecewise linear cost for self-production unit.

Block	Block size (MW)	Cost ($/MWh)
1	2.5	29
2	2.5	38
3	2.5	45
4	1.5	55

In this paper considering 10% penetration level an introduction of 6000 EVs has been estimated in the retailer area. The parameters of the non-Gaussian fitted PDFs associated with EVs random parameters are given in Table 6.

Table 6. Parameters of the fitted PDFs.

Datasets	The suggested PDF
d_t	$\alpha = 7.67$ $\beta = 21.38$
tr_d	$k_{tr_d} = -0.05$ $\mu_{tr_d} = 17.65$ $\sigma_{Ntr_d} = 7.12$
a_t	$k_{tr_d} = -0.06$ $\mu_{tr_d} = 17.27$ $\sigma_{Ntr_d} = 0.84$

EV battery parameters such as Cap_{bat}, η and C_{eff} are 24 kW, 90% and 2km/kWh, respectively. Also, it is assumed that, maximum charging and discharging power in each hour is equal to the 10% of EV battery capacity. Price and conventional demand forecasting data during the time horizon of one week are given in [15].

In the medium-term problem MCS with 200 iterations is employed to obtain the expected values of pool and bilateral procurement levels, as well as optimal selling prices. Based on the market-quota curve the percentage of total demand supplied by the retailer for both conventional and aggregated EVs load in the valley, shoulder and peak hours are 34%, 38% and 40%, respectively. Consequently, expected retail selling prices for valley, shoulder and peak hours are 50.732, 52.899 and 55.673 (\$/MWh), respectively.

Expected weekly power procurement from bilateral contract, $\overline{P}_{tj}^{B}$ (MW), is represented in Table 7. Also, in Fig. 6 the probability distribution function of expected profit in the medium-term problem is shown that is obtained from 200 MCS scenarios. As shown in Fig. 6, the expected value and standard deviation of the profit in the medium-term problem are 28364.5 \$ and 2078.27 \$, respectively. As it is obvious from Fig. 6, the probability density function of expected profit is approximately close to the normal distribution function.

To analyze the impact of each option on the retailer's optimal bidding strategy in the short-term problem, five cases are considered as follows:

- Case 1: The retailer procures its demand only from pool market.
- Case 2: The retailer procures its demand from both pool market and bilateral contract. Also, in this case retailer will sign IL contracts with conventional consumers.
- Case 3: Same as case 2; however, in this case a contract is signed between retailer and EV aggregator for buying its own V2G contribution.
- Case 4: Same as case 3; however, in this case the retailer utilizes its self-production unit just for self-consumption.
- Case 5: Same as case 4; however, in this case the retailer can also sell its excess self-production power to the pool market.

Table 7. Expected power procurement from bilateral contract $\overline{P}_{tj}^{B}$ (MW).

Day	Valley	Shoulder	Peak
j1	51.61	61.75	63.56
j2	59.36	73.19	79.01
j3	54.93	69.84	72.78
j4	58.93	65.58	70.41
j5	61.49	76.70	64.48
j6	59.00	69.14	76.26
j7	57.79	84.95	67.94

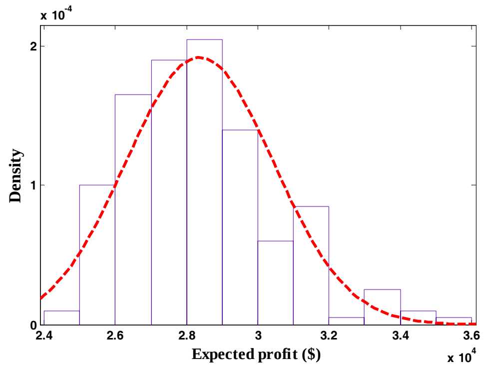

Fig. 6. The probability distribution function of expected profit in the medium-term program

Retailer's profits in individual days of the week are represented in Table 8. As shown increases in pool prices in seventh day, causes a profound reduction in all cases and as indicated in the first case it is noticeable due to its force to buy just from the pool market. However, in other cases the considered options will prevent loss of reduction, nevertheless, the total profit is drastically reduced. In cases 3, 4 and 5, the retailer hedges against the risk of pool market with self-production facility and uses a part of its self-production power for self-consumption. Moreover, the retailer has IL contracts and can also procure some of its demand from V2G capability of EVs in hours that pool price is high. In these cases retailer's strategy within these hours would be beneficial.

Table 8. Retailer's profit in different cases in days of the week ($).

Day	Case 1	Case 2	Case 3	Case 4	Case 5
1	3782.38	3691.82	3691.82	3691.82	3685.17
2	2000.13	2178.75	2218.99	2280.23	2444.27
3	3899.97	3743.24	3743.24	3743.24	3733.33
4	3725.76	3585.72	3585.72	3585.72	3582.53
5	2651.76	2694.16	2712.10	2641.89	2753.50
6	3758.51	3619.73	3619.73	3394.52	3389.06
7	-1528.4	-24.17	294.44	2073.01	3542.85
Sum	18290.09	19489.28	19866.08	21410.47	23130.73

Percentages of various power source contributions to meet retailer's weekly demand for cases 4 and 5 are illustrated in Fig. 7. As indicated in case 5 the self-production quota in final demand is reduced in comparison to case 4. This is due to retailer incentive to sell back its excess self-production to the pool market considering corresponding high prices. As a result more percentage of the demand would be provided by other options. It is noticeable that despite existing high pool prices the retailer still prefers to sell its power while repurchasing from the pool market.

The amount of interrupted loads and penalties that are incurred for under or over-consumption of bilateral contracts are represented in Table 9. As it is obvious, penalty of bilateral contract in case 3 is less than case 2; however in case 4, the use of various options such as self-production, ILs and V2G capability of EVs, prevents over-consumption of bilateral contracts, thus reduces penalties incurred for these contracts. Also, use of self-production facility for self-consumption, causes profound reductions in interrupted loads and bilateral contract penalties in cases 4 and 5. Note that in case 5, due to selling power the retailer may be obligated to over-consume from bilateral contracts. Consequently, incurred penalty due to over-consumption of bilateral contracts as well as IL contracts are relatively increased.

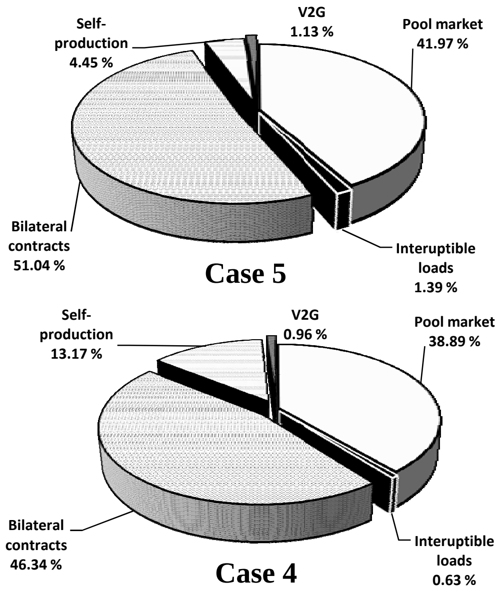

Fig. 7. Percentages of various power source contributions during whole week for cases 4 and 5 (MW).

Table 10 represents the detailed status of the retailer in terms of generation, demand, revenue and cost in case 5. Note that in this Table, the net profit is calculated as the total revenue obtained from selling power to the pool, conventional loads and EVs minus the costs of all options. Fig. 8 provides the optimal sharing of retailer's procurement options to meet the corresponding demand in Case 5 for a representative day. It can be observed that the retailer employs its self-production facility for self-consumption within hours 11,13 and 21-22, while benefits from selling power to the pool during hours 11,12 and 14-20. Note that in these periods retailer prefers to procure its demand from bilateral contracts as well as V2G capability of EVs rather than participating in the pool market. It is notable that the retailer has employed IL contracts in these hours since the amount of pool price is drastically high.

Table 9. the amount of interrupted load and penalties associated with bilateral contracts in different cases ($).

CASE	1	2	3	4	5
Penalty of bilateral contracts ($)	-	229.18	148.73	0	286.68
IL (MW)	-	36.38	36.38	18.17	40.40

Table 10. Numerical results of the case 5.

Gen.	Total power generated Percentage self-consumed Percentage sold	396.5 MW 32.5 % 67.5 %
Demand	Demand supplied Percentage of self-production and consumption Percentage of purchased power from pool Percentage of procured power from bilateral contracts Percentage of procured power from V2G capability of EVs percentage of interrupted loads (ILs)	2897.0 MW 4.45 % 51.04 % 41.97 % 1.13 % 1.39 %
Revenue	selling to the pool selling to the conventional consumers selling to the EVs Total revenue	16689.3 $ 138371.6 $ 12041.1 $ 167102.0 $

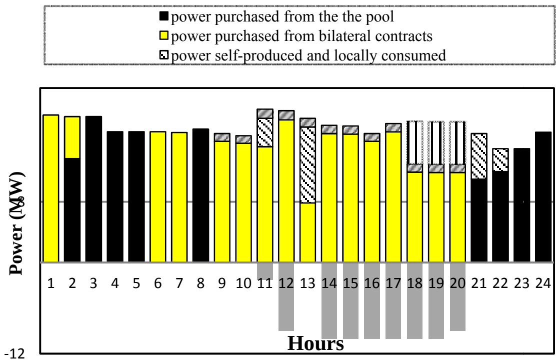

Fig. 8. Mix of electricity sources for a typical working day.

Furthermore, during hours 1,6,7 and 9-10 pool prices are much higher than corresponding bilateral prices; thus within these hours power can be bought exclusively from bilateral contracts. Nevertheless, the retailer provides its required power just from pool market during hours 3-5, 8 and 23-24 due to its relatively cheap prices. On the other hand, during hours 2 and 21-22, the pool prices are greater than other options. Nonetheless, the retailer procures a part of its demand from the pool. The penalties incurred for over-consumption of bilateral contracts are the main reason of this behavior.

The role of aggregator is to coordinate EVs charging in order to minimize corresponding charging costs. This in turn reduces retailer's aggregated cost due to shifting a part of demand to off-peak periods. Furthermore, V2G capability of EVs may affect retailer's profit.

Totally one can conclude that the retailer does not rely heavily on single electric power resource and procures its demand from different resources. Among which pool and bilateral markets are usually considered as the most reliable markets due to their relatively high certainty and firm structure. Subsequently, self-production, IL and some other options are in the next priority. Also, due to the flexible power procurement framework, penalties of bilateral contract associated with under-consumptions or over-consumptions are comparatively very small (see Table 10). Moreover, without self-production facility, the net profit of retailer would be decreased by 14.10 %. As a result the self-production is a tool that acts as a hedge against the volatility of pool prices. Finally, it is worth to note if neither the self-production facility, nor other options (e.g. IL, bilateral contracts and V2G capability of EVs) are available, the net profit would be drastically decreased by 20.92 % that is noticeable from the retailer's point of view.

4. CONCLUSIONS

In this paper, a multi-stage and multi-period framework for the decision making of an electricity retailer and EV aggregator is proposed. A bi-level programming approach is adopted to solve the decision making problem in the short-term problem; in which the upper sub-problem maximizes retailer revenue whereas the lower sub-problem minimizes the EVs charging costs. This paper provides a model that allows a retailer to procure optimally its power using different power supply options such as bilateral contracts, ILs programs, V2G capabilities of EVs and self-production facility in order to hedge against market risks. The appropriate use of these options allows significant increment in retailer's profit in comparison with buying exclusively from the pool. Due to the volatility of pool price and uncertainties associated with the consumers and EVs demand, a mixed integer nonlinear stochastic optimization problem is utilized to solve the problem. Numerical results show the capability and economic advantages of the proposed model for the retailer.

NOMENCLATURE

Sets and numbers:

t	Set of periods in the valley (v), shoulder (s) and peak (p) hours
h	Set of hours
j	Set of days

ω	Index for scenarios of MCS
Ω_{ω}	Set of scenarios in MCS
EV	Index for each EV
N'_{EV}	Total number of EVs in the aggregator's area
N_{EV}	Number of EVs supplied by EV aggregator
f	Number of blocks in the self-production function
i	Index of blocks in market-quote curve
N_i	Number of blocks in market-quote curve

Parameters:

$\lambda_{tj}^{P}(\omega)$	Pool price in ωth scenario during period t in day j
$\bar{\lambda}_{tj}^{P}$	Mean value of pool prices during period t in day j
$\lambda_{hj}^{P}(\omega)$	Hourly pool price in ωth scenario during hour h in day j
$\lambda_{t,i}^{R}$	Selling price associated with ith block of market-quote curve in period t
$\bar{\lambda}_{t,i}^{R}$	Upper bound of the ith interval of market-quote curve in period t
λ_{tj}^{B}	Bilateral contract price during period t in day j
λ_{hj}^{B}	Hourly bilateral contract price during hour h in day j
λ_{t}^{Pei}	Payment price to the EV aggregator by the retailer due to V2G capability during period t
$\lambda_{hj}^{P,est}$	Short-term pool market price forecast during hour h in day j
ℓ_f	Price of fth block of self-production function
$d_{tj}(\omega)$	Consumer's demand in ωth scenario during period t in day j
$\bar{d}_{tj}$	Expected demand of consumers during period t in day j
$\mathrm{SOC}_{0}^{EV}(\omega)$	Initial state of charge of EV battery in ωth scenario
soc_{0}^{EV}	Initial state of charge of EV battery
$P^{\mathrm{G,min}}, P^{\mathrm{G,max}}$	Minimum and maximum output power of self-production unit
$P_{f}^{\max}$	Maximum output power of fth block of self-production function
$\Upsilon_{m,\mathrm{t}}$	Slope of mth block during period t associated with penalty function of bilateral contract
C^{fix}, C^{su}, C^{shd}	Fixed start-up and shut-down costs of self-production facility
T^{on}, T^{off}	Up-time and down-time of the self-production facility
R^{UP}, R^{DN}	Ramp-up and ramp-down rates of self-production facility
$D_{1,hj}$, $D_{2,hj}$	Short-term forecasted demands of consumer types 1 and 2 during hour h in day j

Variables:

$P_{hj,EV}^{P}(\omega)$	Required power of EV that would be traded in the pool market in ωth scenario during hour h in day j
$P_{hj,EV}(\omega)$	Required power for charging EVs batteries in ωth scenario during hour h in day j
$CH_{hj,\mathrm{EV}}(\omega)$	Useful charging power for each EV in ωth scenario during hour h in day j
$\mathrm{SOC}_{h,j}^{EV}(\omega)$	State of charge of EV battery at the end of interval h in day j in ωth scenario
$d_{tj}^{Fleet}(\omega)$	Total EVs fleet required power in ωth scenario during period t in day j
$D_{tj}(\omega)$	Total demand supplied by the retailer to the consumers in ωth scenario during period t in day j
$\bar{D}_{tj,\mathrm{i}}^{D}(\omega), \bar{D}_{tj,\mathrm{i}}^{Fleet}(\omega)$	Power associated with ith block of the market-quote curve during period t in day j and in ωth scenario for conventional consumers and EVs fleet, respectively
$P_{tj}^{B}(\omega)$	Medium-term power purchased from bilateral contracts during period t in day j and in ωth scenario
$P_{tj}^{P}(\omega)$	Medium-term power purchased from the pool market during period t in day j and in ωth scenario
$p_{hj,EV}^{S}$	Short-term EVs required charging power during hour h of type t in day j
$p_{hj,\mathrm{EV}}^{P}$	Short-term power purchased from the EVs during hour h in day j
$ch_{hj,\mathrm{EV}}$	Short-term useful charging power of EVs batteries during hour h in day j
$dch_{hj,\mathrm{EV}}$	Short-term discharging power of EVs batteries during hour h in day j
$soc_{h,j}^{EV}$	State of charge of EV battery at the end of interval h in day j
p_{hj}^{B}	Short-term power purchased from bilateral contract during hour h in day j
p_{hj}^{P}	Short-term power purchased from pool market during hour h in day j
$\bar{P}_{tj}^{B}$	The expected value of purchasing power from bilateral contract during period tin day j
P_{hj}^{G}	Power self-produced at hour h of day j
P_{fhj}	Self-produced power associated with fth block of self-production function during hour h in day j
P_{hj}^{Sell}	Power self-produced and sold to the pool during hour h in day j
$P_{hj}^{consume}$	Power self-produced and locally consumed at hour h in day j
$p_{1,hj}^{IL}$, $p_{2,hj}^{IL}$	Interrupted load from consumer types 1 and 2 in the short-term stage during hour h in day j
λ_{t}^{R}	Selling price offered by the retailer to the conventional consumers and EV aggregator in period t
$v_{\mathrm{t,i}}$	Binary variable that is equal to 1 if the selling price offered by the retailer to consumers belongs to block i of the market-quota curve, and 0 otherwise
u_{hj}	Binary variable that is equal to 1 if unit is committed during hour h and 0 otherwise
y_{hj}	Binary variable that is equal to 1 if the unit starts up at the beginning of hour h in day j and 0 otherwise
z_{hj}	Binary variable that is equal to 1 if the unit shuts down at the beginning of hour h in day j and 0 otherwise
k_{hj}	Binary variable that is equal to 1 if power is bought from the pool and 0 if it is sold to the pool during hour h in day j
X_{h}^{on}, X_{h}^{off}	Number of continuously on (off) time

hours of self-production unit up to the hour h

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