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Optimal Bidding/Offering Strategy for EV Aggregators under a Novel Business Model

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Abstract: Realizing the full potential of plug-in electric vehicle (PEVs) in power systems requires the development of business models for PEV owners and electric vehicle aggregators (EVAs). Most business models neglect the significant economic potential of PEV demand response. This paper addresses this challenge by proposing a novel business model to optimize the charging energy of PEVs for maximizing the owners' profits. The proposed business model aims to overcome the opportunity cost neglect for PEV owners, whose charging energy and charging profiles are optimized with full consideration of the demand curves and market conditions. Lagrangian relaxation technology is used for the relaxation of the constraint of satisfying the charging demand, and as a result, the optimization potential becomes greater. The bidding/offering strategy is formulated as a two-stage stochastic optimization problem, considering the different market prices and initial and target state of energy (SOE) of the PEVs. By case studies and analyses, we demonstrate that the proposed business model can effectively overcome the opportunity cost neglect and increase the PEV owners' profits. Furthermore, we demonstrate that the proposed business model is incentive-compatible. The PEV owners will be attracted by the proposed business model.

Keywords: aggregator; business model; bidding strategy; plug-in electric vehicle (PEV); stochastic optimization

1. Introduction

As a new type of load, the large-scale penetration of plug-in electric vehicles (PEVs) challenges secure system operation and energy delivery [1–4]. However, PEV devices are a promising ancillary service resource under the vehicle-to-grid (V2G) mode [5–8]. PEV owners purchase energy from the energy market to satisfy their transportation usage. Meanwhile, they can make a healthy profit via participation in ancillary service markets. Since the capacity of an individual PEV is limited, an electric vehicle (EV) aggregator (EVA) is expected to combine and dispatch a large group of PEVs [9].

An efficient business model is vital for an EVA to attract new PEV owners and maintain existing PEV owners under contract. In addition, the government and industry need innovative EVA business models to incentivize new technologies and attract investments [10]. Plenty of studies have identified such business models and quantified the associated economic benefits for PEV owners and EVAs. In [11], the EVA controls the charging rates of PEVs, offering ancillary services and peak shaving services to the power grid for cost saving. A package deal business model is proposed in [12]. The EVA provides discount rates for charging and parking PEVs if the owners plug their PEVs during the periods determined by EVA to participate in the electricity market. In [13], a novel modeling framework is proposed to optimize the provision of multiple interdependent services in the wholesale market, balancing market and local distribution peak management for revenue maximization. In [14], a novel peer-to-peer energy trading system is presented between two sets of PEVs in local distribution to reduce the impact of the charging process on the power system during business hours.

Given charging energy during the charging period, the charging power can generally be flexibly controlled, and thus various charging strategies are proposed to optimize PEVs' charging profiles. While the flexibility of charging power (kW) are taken into account in many papers, the flexibility of the charging energy (kWh), however, is ill-considered. In the previous business model [11–19], the EVA optimizes the charging profiles for PEVs on the premise of satisfying the charging demands determined by PEV owners but ignoring the elasticity of charging demands. In fact, if the energy prices are sufficiently high, PEV owners may reduce their charging demands. Few works consider the elasticity of charging demands in the bidding/offering strategy. Reference [20] allows the EVA to optimize the charging energy of PEVs in response to energy prices, without considering the provision of regulation services. Due to limited charging power, an increased quantity of energy demand results in the lower regulation capacity as well as less regulation revenue during the charging periods. Therefore, the regulation revenues are the opportunity costs of the charging energy. Although normative decision-making models suggest that customers should always consider opportunity costs, they often fail to do so, resulting in so-called opportunity cost neglect [21,22]. In other words, calculating opportunity costs and determining the optimal charging energy for PEVs are difficult for their owners. Hence, the EVA is supposed to provide such services.

Although PEVs can provide several kinds of ancillary services to the power grid, their highest value is expected from the provision of regulation [23]. To participate in the regulation market, EVAs have to reserve the available regulation capacity, which has an impact on the charging profiles of PEVs. The optimal charging scheduling strategies considering the regulation participation are investigated in [5,24–26]. The objectives of the strategies mentioned above are to maximize the energy and regulation revenue, the latter of which is influenced by the regulation compensation schemes. Recently, a new performance-based compensation scheme has been introduced in some regulation markets [27–30]. Under this scheme, the more closely the resources follow the regulation signals, the higher compensation for regulation service they can get. Due to the fast response characteristic of the battery systems, PEVs can get a high regulation performance score and earn a considerable amount of money [31,32]. Meanwhile, the EVAs' strategies in the regulation market become more important and complex. However, few studies concentrate on the strategy to simultaneously optimize the energy and regulation bids under this new scheme. Moreover, PEVs can make a considerable profit under the new compensation scheme, and thus the opportunity costs of the charging energy become more significant.

In this paper, the EVA is assumed to participate in the energy and regulation markets simultaneously. The new performance-based compensation scheme is considered, which is designed to facilitate the market participation of fast-response resources such as batteries.

The main contributions of this paper can be summarized as follows:

- A novel business model is proposed for the EVA, distinguished by the idea that the PEV owners' charging demands are considered to be elastic. Instead of being a binding constraint, the charging demands of PEVs are optimized according to the owners' demand curves and marketing conditions.
- We demonstrate that (1) the optimization potential under this business model is greater than that under the traditional one; (2) the proposed business model can realize the full potential of the PEVs as a demand-response resource; (3) the proposed business model is incentive-compatible.
- The optimal bidding/offering strategy is proposed for the EVA in the energy and regulation market, formulated as a two-stage stochastic optimization model. A risk-constrained profit term is added in the objective function to regularize the expected profits and optimize the charging schedules of PEVs.

The rest of this paper is organized as follows. In Section 2, the novel business model for EVA is proposed. The bidding/offering strategies under the traditional and proposed novel business model are proposed in Section 3, respectively. Section 4 details the case studies. Finally, conclusions are drawn in Section 5. For convenience, the notations used in this paper are provided in Table 1.

Table 1. List of notations and variables used in this paper.

Abbreviations	
SOE	State of energy.
ENC	Energy not charged, defined as the part of charging demands that are not satisfied.
Indices	
i	Index of PEVs, running from 1 to N.
k	Index of segments of demand curves, running from 1 to K.
s	Index of scenarios of uncertain factors, running from 1 to S.
t	Index of time intervals, running from 1 to T.
Parameters	
A	Accuracy performance in the regulation market.
$E^{\mathrm{d}}_{i,s,k}$	Charging demand of segment k of PEV i in scenario s.
$\overline{E}_i$	Maximum SOE of PEV i.
$\underline{E}_i$	Minimum SOE of PEV i.
$E^{0}_{i,s}$	Initial SOE of PEV i in scenario s.
$E^{\mathrm{tar}}_{i,s}$	Target SOE of PEV i in scenario s.
M^{r}	Historic mileage ratio (historical mileage per unit capacity)
P_0	Daily demand bid limit.
$\overline{P}^{+}_{i}$	Maximum charging power of PEV i.
$\overline{P}^{-}_{i}$	Maximum discharging power of PEV i.
p^{c}_{i}	Unit degradation cost of PEV i.
$p^{\mathrm{da}}_{s,t}$	Forecast day-ahead (DA) LMP in scenario s at period t.
$p^{\mathrm{rt}}_{s,t}$	Forecast real-time (RT) LMP in scenario s at period t.
$p^{\mathrm{rc}}_{s,t}$	Forecast price of regulation capacity in scenario s at period t.
$p^{\mathrm{rm}}_{s,t}$	Forecast price of regulation mileage in scenario s at period t.
$r^{\mathrm{up/down}}_{s,t}$	Regulation dispatch ratio of up (/down) capacity in scenario s at period t.
Δt	Time-step duration.
$\eta^{\mathrm{c}}_{i}/\eta^{\mathrm{d}}_{i}$	Charging/Discharging efficiency of PEV i.
$\lambda_{0,s}$	System marginal benefit in scenario s, defined as the highest marginal benefit among all ENC.
$\lambda_{i,s,k}$	Marginal benefit of segment k of the demand curve of PEV i in scenario s.
π_s	Probability of scenario s.
γ^{C}	Weight factor for the risk position.
β	Confidence level for risk calculation.
Variables	
$C^{\mathrm{d}}_{s,t}$	Discharging cost in scenario s at period t.
C^{reg}_{t}	Regulation bids at period t.
$C^{\mathrm{cap}}_{i,s,t}$	Available regulation capacity of PEV i in scenario s at period t.
$E_{i,s,t}$	SOE of PEV i in scenario s at period t.
$E^{\mathrm{dev}}_{i,s,t}$	Energy deviation due to regulation service of PEV i in scenario s at period t.
$E^{\mathrm{enc}}_{i,s,k}$	ENC of charging demands in segment k of PEV i in scenario s.
$E^{\mathrm{down}}_{i,s,t}$	Down regulation deployment in real time of PEV i in scenario s at period t.
$E^{\mathrm{up}}_{i,s,t}$	Up regulation deployment in real time of PEV i in scenario s at period t.
P^{da}_{t}	DA bid power of the EVA at period t.
$P^{\mathrm{ch}}_{i,s,t}$	RT charging power of PEV i in scenario s at period t.
$P^{\mathrm{dc}}_{i,s,t}$	RT discharging power of PEV i in scenario s at period t.
$R^{\mathrm{e}}_{s,t}$	Energy revenue in the energy market in scenario s at period t.
$R^{\mathrm{reg}}_{s,t}$	Regulation revenue in scenario s at period t.
$x^{\mathrm{c/d}}_{i,s,t}$	Binary variables (1 if PEV i is charged/discharged at period t in scenario s and 0 otherwise).
V^{C}	Conditional value-at-risk (CVaR) of the expected profits.
V	Value-at-risk of the expected profits.
L_s	Auxiliary variables to compute V^{C}.
Π_s	Net profit in scenario s.

2. A Novel Business Model for EVA

2.1. Business Model Structure

The proposed business model is illustrated in terms of three aspects commonly used to describe business models: target customers, service provision and revenue streams [10]. First, as shown in Figure 1, the target customers are the private PEVs that stay in parking lots for a long time. For example, many PEVs stay at workplaces or residential areas during the daytime or nighttime, and they are very suitable to be used for regulation services. Second, the EVA acts as a middleman between PEV owners and the electricity market. As the EVA combines PEVs to participate in the energy and regulation markets, providing peak-shaving and regulation services to the power grid, the EVA also optimizes the market bids, charging energy and profiles for PEVs based on the information submitted for profit maximization. Third, the EVA leverages fixed brokerage fees for the services for PEVs. All the revenue from the electricity market will be allocated to PEV owners. Given the nascence of the new business model and the difficulties in predicting individual PEV savings, such brokerage fees have no connection to savings or earnings of PEVs.

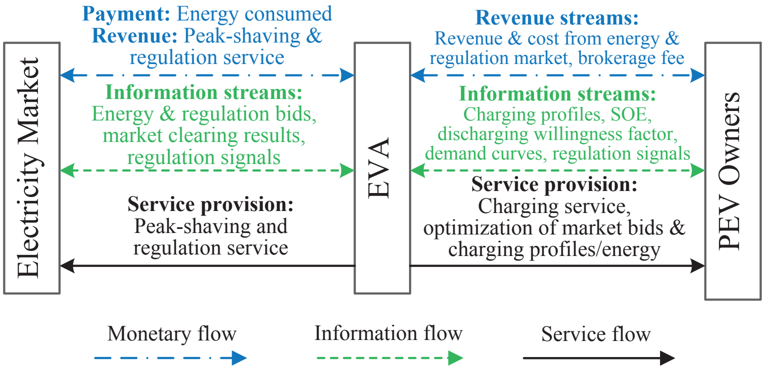


Figure 1. Structure of the proposed business model.

2.2. The Improvement of the Proposed Business Model

The charging energy constrains the available regulation capacity of a PEV during the charging period. As shown in Figure 2, the sum of the charging power and regulation-down capacity cannot exceed the maximum charging power. In the PJM market, the regulation-up capacity equals the regulation-down capacity. Therefore, given the maximum charging power, the available regulation capacity of a PEV is constrained by the charging power. During a certain period, the charging energy equals the integral of charging power and time. Therefore, the available regulation capacity of a PEV is constrained by the charging energy during the charging period. The increased charging energy entails decreased available regulation capacity and regulation revenue. For profit maximization, the charging energy of PEVs should be optimized with full consideration of the opportunity costs, which become more significant under the performance-based compensation scheme.

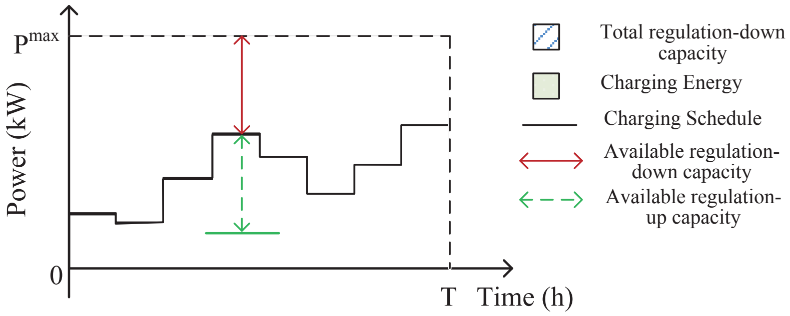


Figure 2. The relationship between the charging energy and total regulation capacity during the charging period.

From a mathematical perspective, the improvement of the proposed business model lies in the expansion of the solution space. Figure 3 illustrates the optimization potential with or without considering the elasticity of charging demands (the dotted trapezoid and rhomboid, respectively). The black line represents the state of energy (SOE) of PEV i. The slope of the dotted line l represents the maximum charging power. It takes at least $(T-t)$ hours to satisfy the charging demands of PEV i at the maximum charging power. Under the traditional model, the PEV has to be charged no later than time t, and the SOE is within the dotted trapezoid. However, under the proposed business model, since the charging demands do not have to be fully satisfied, the PEV can be charged after time t, and the SOE is within the dotted rhomboid. Therefore, the potential for optimization under the proposed business model is greater.

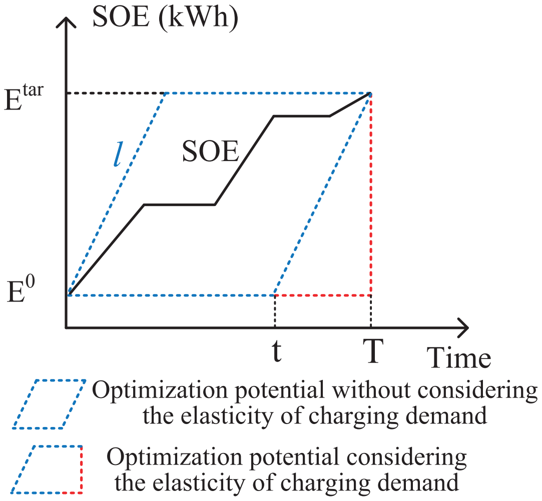


Figure 3. Potential for optimization with or without considering the elasticity of charging demands.

2.3. Practicability of the Proposed Business Model

The charging energy of PEVs can be optimized by introducing the demand curves to quantify the charging benefits [20,33]. Therefore, PEV owners can reduce their charging demands in response to high energy prices. To this end, stepwise demand curves are used in this paper, as shown in Figure 4. When arriving at the parking lot, PEV owners will provide the EVA with the initial SOE and target SOE. The charging demands are defined as the differences between the initial and target SOE. The marginal benefits are used to quantify the importances of the charging demands to PEV owners. The marginal benefits of the energy segments are defined as the minimum amount of money that the owner would take instead of charging the PEVs.

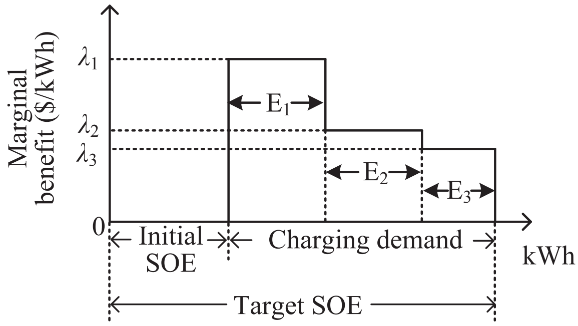


Figure 4. Demand curves of plug-in electric vehicle (PEVs).

Under the proposed business model, PEV owners must submit the demand curves and accept that their charging demands may be not satisfied before the time specified. If the charging demands are not satisfied, PEV owners will get compensation according to the demand curves, and they can satisfy their driving needs in other ways. For example, owners with hybrid PEVs can drive the vehicles consuming fuel. Besides, PEV owners can delay leaving to have their PEVs fully charged.

In fact, the charging energy that PEV owners plan to buy depends in part on the prices of substitutes. Therefore, the marginal benefits of the charging demands can be simply set at the price of the next best alternative to fulfill vehicle demand for mobility. For example, for a hybrid PEV, the marginal benefit can be set at the price of secondary fuel. For a PEV owner that delay leaving, the marginal benefit can be regarded as the compensation price for the delay. One can set high enough marginal benefit to ensure that the charging demands of his or her PEV will be satisfied, which leads to the same results as those under the traditional business model. In general, the marginal benefits of the charging demands vary from a PEV owner to another.

3. Optimal Bidding/Offering Strategy under the Traditional and Proposed Business Model

For comparison, the optimal bidding/offering strategy is proposed under the traditional and the novel business model, respectively, based on the PJM market.

The traditional business model: the PEVs' charging demands are considered to be inelastic, and the satisfaction of the charging demands is one of the constraints.

The proposed novel business model: the PEVs' charging demands are considered to be elastic. The charging energy is optimized by EVA according to the demand curves and market conditions.

3.1. Regulation Revenue Modeling

The regulation revenue is dependent on the market rules. In this paper, we model the regulation revenue based on the PJM market.

A performance-based compensation scheme has been introduced in the PJM regulation market [27]. Compared with the traditional compensation schemes, this new scheme has two main improvements. Firstly, the mileage compensation is introduced to compensate for the resources' actual amount of up/down operation in real time. Secondly, the compensation for regulation capacity/mileage will be affected by the resources' performance of following the regulation signals. Generally, the more closely the resources follow the regulation signals, the more compensation for regulation capacity and mileage they can get. The settlement rules of the capacity and mileage revenues can be summarized as [31,34]

$$r^{\text{cap}} = C^{\text{cap}} \cdot p^{\text{rc}} \cdot A \tag{1}$$

$$r^{\text{mil}} = M^{\text{mil}} \cdot p^{\text{rm}} \cdot A, \tag{2}$$

where r^{cap} and r^{mil} are the regulation capacity and mileage revenue, respectively. C^{reg} and M^{mil} are the regulation capacity and mileage, respectively.

The mileage is calculated as the sum of the absolute differences between the two consequent regulation signals at a certain period. The overall performance score is expressed as a weighted average of the scores of precision, correlation, and delay. It is determined by the ISO according to the performance of the resources in following the AGC signals in past hours. Under the performance-based compensation scheme, PEV as a fast response resource can get more compensation than traditional regulation resources.

3.2. The Proposed Strategy under the Traditional Business Model

The decisions at the first stage, including the hourly day-ahead (DA) energy and regulation bids (P_t^{da} and C_t^{reg}), must be made before uncertainties are realized at the second stage. Depending on the first-stage decisions, the decisions at the second stage are made after the uncertainties are unveiled. The second-stage decisions include the charging profiles of the PEVs. In the following analysis, all the second-stage decision variables are denoted with a superscript representing scenario s. The objective function maximizes the total profit and is formulated as follows

$$\max\ \gamma^C V^C + \left(1-\gamma^C\right)\sum_{s=1}^{S}\pi_s\Pi_s \tag{3}$$

s.t.

$$V^C = V - \frac{1}{1-\beta}\sum_{s=1}^{S}\left(\pi_s L_s\right) \tag{4}$$

$$L_s \geq V - \Pi_s;\ \ L_s \geq 0\ \forall s \tag{5}$$

$$\Pi_s = \sum_{t=1}^{T}\left(R_{s,t}^{\text{reg}} + R_{s,t}^{\text{e}} - C_{s,t}^{\text{d}}\right) \tag{6}$$

$$R_{s,t}^{\text{reg}} = \left(C_t^{\text{reg}} p_{s,t}^{\text{rc}} + M^r C_t^{\text{reg}} p_{s,t}^{\text{rm}}\right) A\ \forall s,\ \forall t \tag{7}$$

$$R_{s,t}^{\text{e}} = \left(P_t^{\text{da}} - \sum_{i=1}^{N}\left(P_{i,s,t}^{\text{ch}} - P_{i,s,t}^{\text{dc}}\right)\right) p_{s,t}^{\text{rt}}\Delta t - P_t^{\text{da}} p_{s,t}^{\text{da}}\Delta t\ \forall s,\ \forall t \tag{8}$$

$$C_{s,t}^{\text{d}} = \sum_{i=1}^{N}\left(P_{i,s,t}^{\text{dc}} p_i^{\text{c}}\Delta t\right)\ \forall t. \tag{9}$$

The objective function defines the profit regularization term with expected profits from Π_s and risk V^C and determines the optimized risk trade-off based on a given risk-aversion attitude. Constraints (4) and (5) define the risk conditional value-at-risk (CVaR), which is a function of the value-at-risk (VaR). By introducing the auxiliary variable L_s, we can calculate the values of CVaR and VaR simultaneously [35–37]. Parameter γ^C is used to control the risk positions of EVA due to the forecast uncertainty, which is determined by the decision maker. A larger γ^C indicates a more risk-averse position. In (6), the expected profit Π_s consists of the regulation revenues, energy costs, and discharging costs, which are explained in Equations (7)–(9), respectively. Under the performance-based compensation scheme, the revenue from the regulation market consists of the capacity and mileage revenue, as shown in (7). Since the regulation mileage depends on the real-time (RT) response, in the DA market, the total regulation mileage during period Δt is estimated as the product of the mileage ratio and the regulation capacity. The two-settlement rule [34,38] is adopted in the PJM energy market, and thus the EVA can get revenue by price arbitrage in the DA and RT markets, as shown in (8). The discharging costs of the PEVs are shown in (9).

The objective function is subjected to the following constraints:

(1) The satisfaction of charging demand

The PEVs' charging demands must be satisfied. The charging energy plus the energy deviations due to regulation service should be equal to charing demands of PEVs.

$$E_{i,s}^{\mathrm{tar}} = \sum_{t=1}^{T} \left(\left(P_{i,s,t}^{\mathrm{ch}} \eta_i^{\mathrm{c}} - P_{i,s,t}^{\mathrm{dc}} / \eta_i^{\mathrm{d}} \right) \Delta t + E_{i,s,t}^{\mathrm{dev}} \right) + E_{i,s}^{0} \; \forall i, \forall s, \forall t \tag{10}$$

The PEVs respond to the regulation signals by changing their charging/discharging power, which may lead to unexpected energy deviation from the schedules [26]. A regulation-up signal indicates that the power generation is lower than the load. In this case, PEVs decrease the charging power (or increase the discharging power) to provide regulation up service. A regulation-down signal indicates that the power generation is higher than the load and PEVs should increase the charging power (or decrease the discharging power). The energy deviation consists of 'up' and 'down' components, as shown in (11)–(13).

$$E_{i,s,t}^{\mathrm{dev}} = E_{i,s,t}^{\mathrm{down}} - E_{i,s,t}^{\mathrm{up}} \tag{11}$$

$$E_{i,s,t}^{\mathrm{down}} = r_{s,t}^{\mathrm{down}} \cdot C_{i,s,t}^{\mathrm{cap}} \cdot \Delta t \tag{12}$$

$$E_{i,s,t}^{\mathrm{up}} = r_{s,t}^{\mathrm{up}} \cdot C_{i,s,t}^{\mathrm{cap}} \cdot \Delta t. \tag{13}$$

(2) The limitation of battery capacity

The SOE of the battery is limited by the maximum and minimum SOE limitation. The SOE of the PEVs has to be within the maximum and minimum limitation, which in fact limits the charging and discharging power of the PEVs.

$$E_{i,s,t-1} + \left(P_{i,s,t}^{\mathrm{ch}} \eta_i^{\mathrm{c}} - P_{i,s,t}^{\mathrm{dc}} / \eta_i^{\mathrm{d}} \right) \Delta t + E_{i,s,t}^{\mathrm{dev}} \geq \underline{E}_i \; \forall i, \forall s, \forall t \tag{14}$$

$$E_{i,s,t-1} + \left(P_{i,s,t}^{\mathrm{ch}} \eta_i^{\mathrm{c}} - P_{i,s,t}^{\mathrm{dc}} / \eta_i^{\mathrm{d}} \right) \Delta t + E_{i,s,t}^{\mathrm{dev}} \leq \overline{E}_i \; \forall i, \forall s, \forall t \quad . \tag{15}$$

(3) The limitation of charging/discharging power

The charging/discharging power of the PEVs would be limited in its normal range. The binary variables $x_{i,s,t}^{\mathrm{c}}$ and $x_{i,s,t}^{\mathrm{d}}$ are used to preclude PEVs from simultaneously charging and discharging.

$$0 \leq P_{i,s,t}^{\mathrm{ch}} \leq x_{i,s,t}^{\mathrm{c}} \overline{P}_i^{+} \; \forall i, \forall s, \forall t \tag{16}$$

$$0 \leq P_{i,s,t}^{\mathrm{dc}} \leq x_{i,s,t}^{\mathrm{d}} \overline{P}_i^{-} \; \forall i, \forall s, \forall t \tag{17}$$

$$x_{i,s,t}^{\mathrm{c}} + x_{i,s,t}^{\mathrm{d}} \leq 1 \; \forall i, \forall s, \forall t. \tag{18}$$

(4) The constraints of energy and regulation bids

In the PJM market, the total quantity of demand bids submitted by the EVA for a given operating day must not exceed the daily demand bid limit [38], as shown in (19). With respect to the regulation offer, the maximum regulation capacity of the EVA is limited by the available power capacity of the battery. The regulation-up and regulation-down capacity are set to be symmetric. Hence, the maximum regulation capacity of PEV i is the smaller one between the available regulation-up and regulation-down capacity, as shown in (20). The offered regulation capacity is limited by the total available regulation capacity of the PEVs, as shown in (21).

$$\sum_{t=1}^{T} P_t^{\mathrm{da}} \le P_0 \tag{19}$$

$$C_{i,s,t}^{\mathrm{cap}} = \min\left(\overline{P}_i^{+} - P_{i,s,t}^{\mathrm{ch}} + P_{i,s,t}^{\mathrm{dc}}, \overline{P}_i^{-} + P_{i,s,t}^{\mathrm{ch}} - P_{i,s,t}^{\mathrm{dc}}\right) \; \forall i, \forall s, \forall t \tag{20}$$

$$C_t^{\mathrm{reg}} \le \sum_{i=1}^{N} C_{i,s,t}^{\mathrm{cap}} \; \forall s, \forall t. \tag{21}$$

3.3. The Proposed Strategy under the Novel Business Model

3.3.1. The Optimal Bidding/Offering Model

The novel business model distinguishes itself from the traditional ones in that the PEVs' charging demands are considered to be elastic. Constraint (10) is relaxed by Lagrangian relaxation technology and added to the objective as a penalty function. The Lagrange multipliers associated with constraint (10) are the marginal benefits of the charging demands. The penalty function equals the product of the marginal benefits and energy not charged (ENC) and represents the total lost benefits to PEV owners. In essence, the strategy under the traditional business model is a special form of that under the proposed business model. If the Lagrange multipliers are large enough, the optimal results of the strategy under the proposed business model will be the same as those under the traditional one. Therefore, the optimization results under the proposed business model will not be worse than those under the traditional one.

The marginal benefits of charging demands, which are generally set at the price of the next best alternative to fulfil vehicle demand for mobility, are determined by the PEV owners, who can choose to update the demand curves each day. If they do not update the demand curves, the original curves will be used. The demand curves of all PEV owners rank in descending order by marginal benefits, as shown in Figure 5. The shadow represents the total lost benefits of the ENC. If the opportunity costs of charging energy are higher than the lost benefits, the charging demands PEV will be reduced, resulting in the increase in the net revenues. The system marginal benefit λ_0 is defined as the highest marginal benefit of the charging demand that is not satisfied. The charging demands with marginal benefits higher than λ_0 will be satisfied.

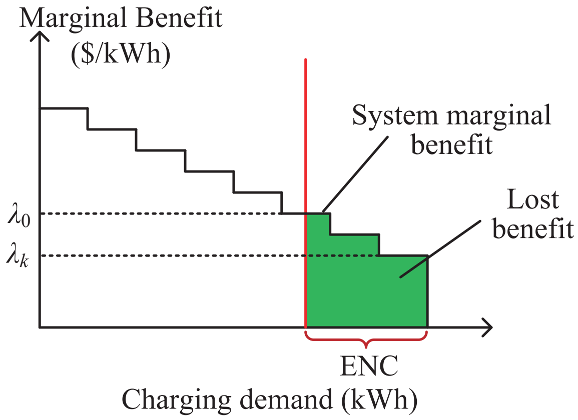


Figure 5. Demand curves ranking in descending order.

The objective under the proposed business model is as follows

$$\max\ \gamma^C V^C + \left(1-\gamma^C\right)\sum_{s=1}^{S}\pi_s\left(\Pi_s - \underbrace{\sum_{i=1}^{N}\sum_{k=1}^{K}\lambda_{i,s,k}E_{i,s,k}^{\mathrm{enc}}}_{I}\right) \tag{22}$$

s.t.

$$L_s \geq \max\left(V - \left(\Pi_s - \sum_{i=1}^{N}\sum_{k=1}^{K}\lambda_{i,s,k}E_{i,s,k}^{\mathrm{enc}}\right), 0\right)\ \forall s \tag{23}$$

$$(4)\text{–}(9), (14)\text{–}(21) \tag{24}$$

$$\sum_{k=1}^{K}E_{i,s,k}^{\mathrm{enc}} = E_{i,s}^{\mathrm{tar}} - \underbrace{\left(\sum_{t=1}^{T}\left(\left(P_{i,s,t}^{\mathrm{ch}}\eta_i^{\mathrm{c}} - P_{i,s,t}^{\mathrm{dc}}/\eta_i^{\mathrm{d}}\right)\Delta t + E_{i,s,t}^{\mathrm{dev}}\right) + E_{i,s}^{0}\right)}_{II}\ \forall i, \forall s \tag{25}$$

$$0 \leq E_{i,s,k}^{\mathrm{enc}} \leq E_{i,s,k}^{\mathrm{d}}\ \forall i, \forall s, \forall k. \tag{26}$$

The term I in (22) represents the total lost benefits of charging demands. The ENC is equal to the difference of the target SOE and final SOE (term II), as shown in (25). The ENC of each segment must not exceed the charging demands of this segment, as shown in (26).

3.3.2. Profit Modeling of PEV Owners

The revenue of PEV i r_i^0 consists of three parts: (a) regulation revenue, (b) discharging revenue in the energy market and (c) revenue by price arbitrage in the DA and (RT) energy markets. The cost of PEV i c_i^0 also consists of three parts: (d) charging cost, (e) degradation cost and (f) lost benefit of ENC.

For PEV i, the (a) regulation revenue, (d) charging cost, (b) discharging revenue and (e) degradation cost are allocated based on its regulation capacity provided, charging energy and discharging energy, respectively. Especially, the (c) revenue by price arbitrage between the DA and RT energy market is allocated to PEV owners on average, and the (f) lost benefit is calculated based on the ENC. The profit of the PEV i can be expressed as

$$F_i = r_i^0 - c_i^0 \tag{27}$$

$$r_i^0 = \underbrace{\frac{\sum\limits_{t=1}^{T} C_{i,t}^{\mathrm{cap}}}{\sum\limits_{t=1}^{T} C_t^{\mathrm{reg}}} \cdot \sum_{t=1}^{T} R_t^{\mathrm{reg}}}_{(a)} + \underbrace{\frac{\sum\limits_{t=1}^{T} P_{i,t}^{\mathrm{dc}}}{\sum\limits_{i=1}^{N}\sum\limits_{t=1}^{T} P_{i,t}^{\mathrm{dc}}} \cdot \sum_{i=1}^{N}\sum_{t=1}^{T} P_t^{\mathrm{dc}} p_t^{\mathrm{rt}}}_{(b)} + \underbrace{\frac{\sum\limits_{t=1}^{T}\left(P_t^{\mathrm{da}}\Delta t\left(p_t^{\mathrm{rt}} - p_t^{\mathrm{da}}\right)\right)}{N}}_{(c)} \tag{28}$$

$$c_i^0 = \underbrace{\frac{\sum\limits_{t=1}^{T} P_{i,t}^{\mathrm{ch}}}{\sum\limits_{i=1}^{N}\sum\limits_{t=1}^{T} P_{i,t}^{\mathrm{ch}}} \sum_{i=1}^{N}\sum_{t=1}^{T} P_t^{\mathrm{ch}} p_t^{\mathrm{rt}}}_{(d)} + \underbrace{\sum_{t=1}^{T} P_{i,t}^{\mathrm{dc}} \cdot p_i^{c}}_{(e)} + \underbrace{\sum_{k=1}^{K} \lambda_{i,k} E_{i,k}^{\mathrm{enc}}}_{(f)} . \tag{29}$$

Note that PEV owners are not compensated directly for ENC. The compensation is included in the energy and regulation revenues. For PEV i, the increased ENC entails the increased lost benefits but increased energy and regulation revenues. Therefore, if the increased energy and regulation revenues are higher than the increased lost benefits, reducing the charging demands increases profits. If the charging demands are not reduced, the profits of PEV owners are the same as that under the traditional business model. Therefore, PEV owners' profits under the proposed business model would not be lower than that under the traditional one.

4. Case Study

4.1. Parameters

We focused on the PEVs at workplaces such as central business districts. The EVA was assumed to manage 800 PEVs whose plug-in duration was from 8:00 to 17:00. The EVA combined the PEVs to participate in the energy and regulation markets. The accuracy performance of the EVA was set to be 0.95. M^{r} was calculated based on the PJM's RegD-type regulation signal data from 1 March 2016 to 28 February 2017 [39]. The daily demand bid limit P_0 was set to be 120 percent of the total target SOE. The reference unit degradation cost was set to be \$0.024/kWh, calculated with the relevant parameters in [40] except that the total cost of the battery was set at \$260/kWh [41]. It was assumed that the marginal benefits of PEV owners obey the normal distribution. Five hundred PEV owners chose the proposed business model and submitted their charging demand curves. The other PEV owners chose the traditional business model and did not submit the demand curves or related information. The charging demands of such PEVs was regarded as being perfectly inelastic and their marginal benefits (Lagrange multipliers) were set to be large positive constants in the optimization model. In addition, γ^{C} and β were set to be 0.5 and 0.9, respectively.

Suppose that the forecasts for uncertain factors are available for the EVA. For simplicity, initial SOE, target SOE and market prices were assumed to follow normal distributions where the means were set equal to the forecast values, and the standard deviations are 10% of the mean values. Furthermore, we assume that the uncertainties are independent [42,43]. Based on the forecast data and distributions of uncertain factors, 1000 scenarios were generated and then reduced to 10 ones by the simultaneous backward method [44]. The forecasts of energy and regulation market prices are shown in Figure 6.

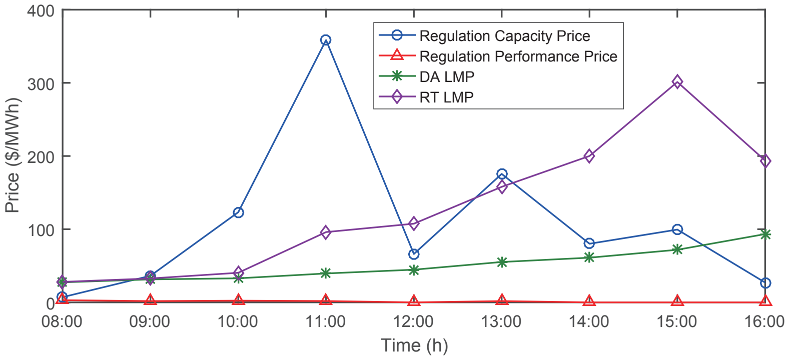


Figure 6. The forecasts of energy and regulation market prices.

The optimal results of the proposed strategy under the traditional and novel business model are compared in the case studies. For the sake of convenience, they are labeled as M1 and M2.

M1: the traditional business model.

M2: the proposed business model.

4.2. Comparison between M1 and M2

4.2.1. Comparison of the Optimal DA Bids and Total Profits

The optimization results of the proposed strategy under M1 and M2 for one of the scenarios considered (#10) are compared. Figures 7 and 8 illustrate the optimal results under M1 and M2, respectively, including DA energy and regulation bids (the first-stage variables) and RT charging profiles (the second-stage variables). In the first two hours, the energy and regulation prices are relatively low, and thus, the PEVs are charged to satisfy the charging demands. In the next six hours, because the RT LMP is higher than the DA LMP, more energy is bought in the DA market from 13:00–16:00. During the last hour when the RT LMP is high and the regulation price is low, the EVA discharges energy to the power grid. Although the EVA has to pay the difference between the DA cleared power and the RT power consumed at the RT market prices, a modest profit can be made through utilizing the price difference between the two markets. Due to the constraints of the available regulation capacity, the charging profiles are determined by not only the energy prices but also the regulation prices. When PEVs are charged, their available regulation capacity is reduced along with the regulation revenue. Therefore, the EVA is inclined to charge the PEVs at the low energy and regulation prices.

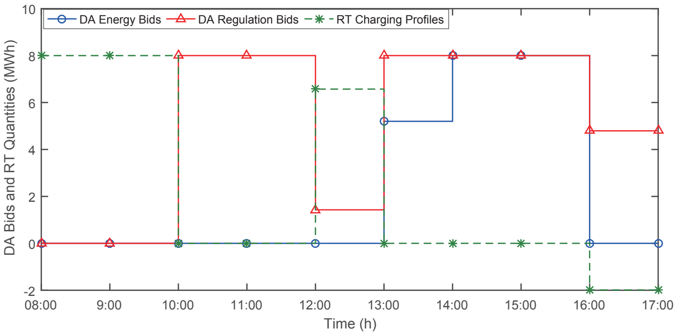


Figure 7. Optimal results in the day-ahead (DA) market under M1.

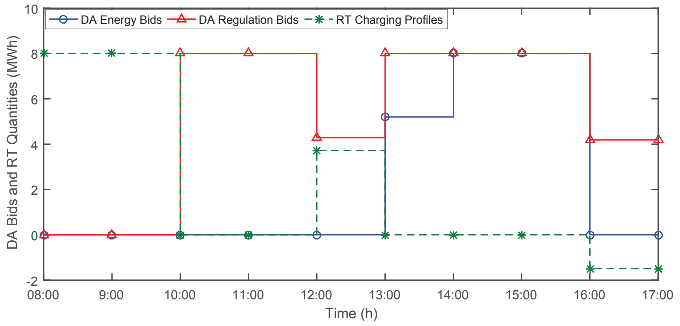


Figure 8. Optimal results in the DA market under M2.

The main difference between Figures 7 and 8 lies in the regulation bids and charging profiles from 12:00–13:00. Since the charging demands do not have to be satisfied under M2, the EVA reduces the charging power from 12:00–13:00 and increase the available regulation capacity. As a result, the charging demands are not fully satisfied, but the revenues in the regulation markets increase.

From Table 2, considerable revenues can be made in the regulation market, which takes 78.09% and 77.08% of the total profits under M1 and M2, respectively. Under M2, the quantity of ENC is 2021.4 kWh, leading to lost benefits of −$81.98. However, the ENC results in a 13.33% and 3.01% increase of the revenues in the energy and regulation markets, which were higher than that under M1. Accordingly, the total profit under M2 was 4.36% higher than that under M1. The proposed novel business model can effectively increase the total profits of all PEV owners.

Table 2. Optimal results under M1 and M2 (one day).

Business Models	ENC (kWh)	Lost Benefit ($)	Energy Revenue ($)	Regulation Revenue ($)	Total Profit ($)
M1	0	0	1970.84	7024.31	8995.15
M2	2021.40	−81.98	2233.53	7235.78	9387.33

Figure 9 depicts the total profits under the two business models in different scenarios. We used H1 to represent the first hour (08:00–09:00). The total profits are equal to the summation of the profits at each hour and the lost benefits of PEV owners (the red block). Note that the lost benefits and the profits of some hours are negative. In each scenario, the main difference between M1 and M2 was the profit of the fifth hour (H5). The chart shows that the negative profit at H5 increases effectively under M2 in all the scenarios by sacrificing a small part of the charging benefits of PEVs. In all the scenarios, the total profits under M2 were higher than those under M1, thus demonstrating the effectiveness of the proposed novel business model.

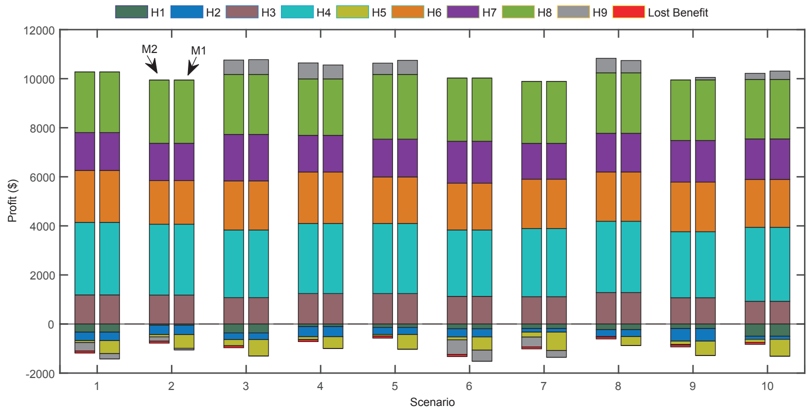
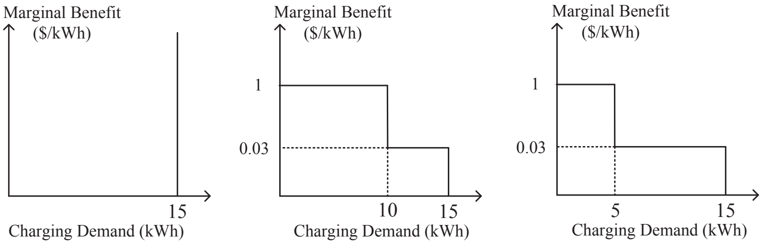


Figure 9. Total profits of PEV owners under M1 and M2 in the DA market in ten scenarios.

4.2.2. Comparison of Profits of PEV Owners

In Figure 10, the profits of three owners (labeled as O1, O2, and O3) are compared, and their demand curves are shown. The three owners have the same total charging demands. However, O1 chose the traditional business model and did not submit the demand curves, so the charging demand was considered to be inelastic. Therefore, the marginal benefit of the charging demand is infinite. The demand curves of O2 and O3 consisted of two segments. Under the assumption that O2 and O3 delay driving home after work, the marginal benefits of the second segment were set to be the LMP of the hour 17:00–18:00, during which time their PEVs will be recharged. As seen in Table 3, the profit of O3 is 15% higher than that of O1. The difference between O2 and O3 lies in the quantity of the charging demand in the second segment. The quantities of ENC for O3 were larger than that of O2, and so are the profits. If the elasticity of charging demands was neglected (under M1), the profits of O2 and O3 will be the same as those of O1. However, by submitting the demand curves or related information, the profits of O2 and O3 increased under M2. The profits of the PEV owners under M2 would not be lower than that under M1. Therefore, PEV owners would be attracted by the proposed business model.



(a) (b) (c)

Figure 10. The charging demand curves. (**a**) PEV owner 1; (**b**) PEV owner 2; (**c**) PEV owner 3.

Table 3. Comparison of PEV owners' profits (one day).

PEV Owner	λ_k ($/kWh)	ENC (kWh)	Lost Benefit ($)	Energy Revenue ($)	Regulation Revenue ($)	Total Profit ($)
O1	$+\infty$	0	0	2.91	10.97	13.88
O2	1, 0.03	5	−0.15	3.27	11.80	14.92
O3	1, 0.03	10	−0.30	3.63	12.63	15.96

Figure 11 depicts the profits of three owners in ten scenarios. The profits of O2 and O3 were higher than that of O1 in all the scenarios, which demonstrates convincingly that the proposed business model can increase the profits of PEV owners. Moreover, by comparing the profits of O2 and O3, the owners' profits markedly increased with the ENC given the same charging demands and marginal benefits

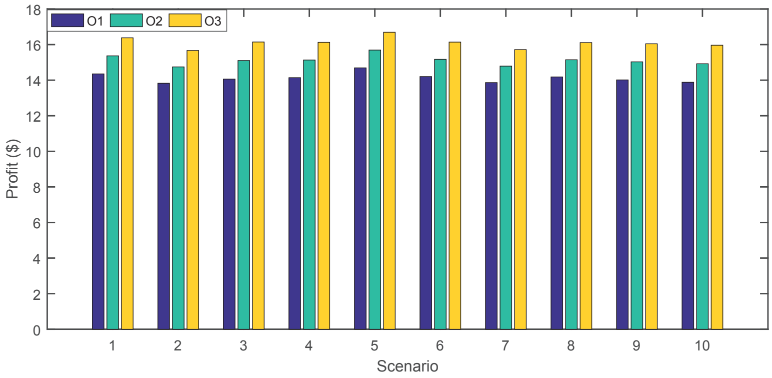
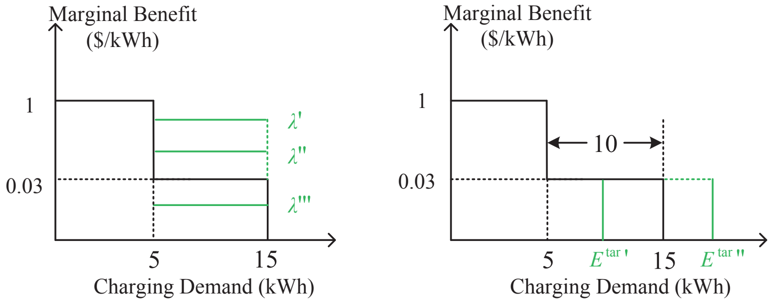


Figure 11. The profits of PEV owners in ten scenarios.

4.3. Impact of Marginal Benefit and Charging Demand

In the proposed business model, PEV owners submitted their demand curves or related information to the EVA. The impact of the demand curves on PEV owners' profits was analyzed in this subsection, which investigates whether the PEV owners have the incentive to submit their real demand curves to the EVA.

The demand curves consisted of marginal benefits and charging demands. Suppose the real demand curve of PEV i is shown in Figure 12, which consists of two segments (the black line). We focused on the second segment of the demand curve and suppose the real marginal benefit and charging demand of this segment are \$0.03/kWh and 10 kWh, respectively. The green lines in Figure 12a,b represent the different marginal benefits and charging demands of the second segment.



(a) (b)

Figure 12. Demand curves with different marginal benefits and quantity demanded. (**a**) different marginal benefits; (**b**) different charging demands.

The impacts of the marginal benefit and charging demand of the second segment on the profits of PEV owners are analyzed. As seen in Figure 13, if the marginal benefit is lower than the system marginal benefit (\$0.058/kWh), there is no impact on the profit. However, if the marginal benefit was higher than the system marginal benefit, the profits of PEV owners reduced significantly. Therefore, the PEV owners had no incentive to exaggerate the marginal benefits, and PEV owners would not submit a marginal benefit lower than the real one. Ultimately, the PEV owners were inclined to submit the real marginal benefit to the EVA. With respect to the charging demand, if the marginal benefit was lower than the system marginal benefit, submitting a false charging demand will not increase the profit of the PEV owner. In this case, the charging demand of the second segment is not satisfied, and the lost benefit is equal to the product of the real charging demand and marginal benefit of this segment. Nevertheless, if the marginal benefit was higher than the system marginal benefit, the PEV owner achieves the maximum profit when the charging demand of the second segment was 10 kWh, which is equal to its real charging demand. In this case, submitting a false charging demand leads to a decrease in profits. Therefore, PEV owners are encouraged to submit real charging demands.

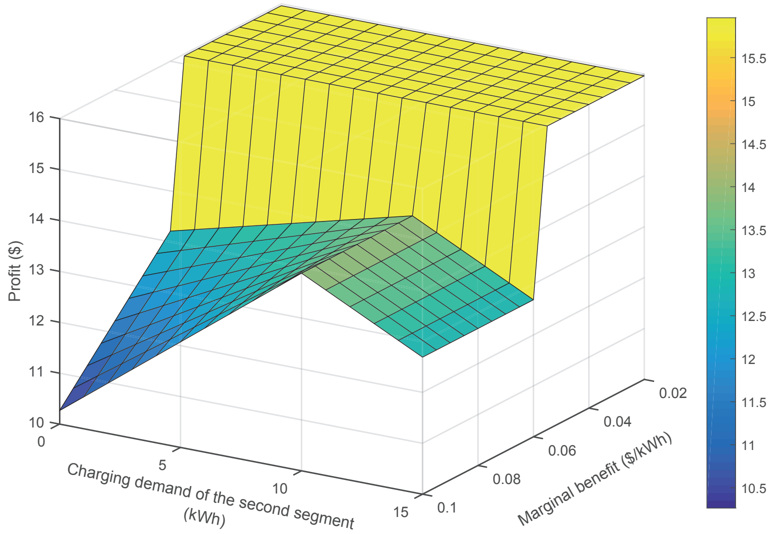


Figure 13. Profit of the PEV owner as a function of marginal benefit and charging demand.

In summary, the proposed business model is incentive-compatible. PEV owners have the incentive to submit the real demand curves or related information to the EVA.

4.4. Impact of Confidence Levels and Weight Factors

The total profits under the proposed business model under different β and γ^C are shown in Figure 14. The total profits decreased with the increment of β and γ^C. It is obvious that the total profits were more affected by γ^C. In particular, when $\gamma^C > 0.7$, the total profits decreased significantly.

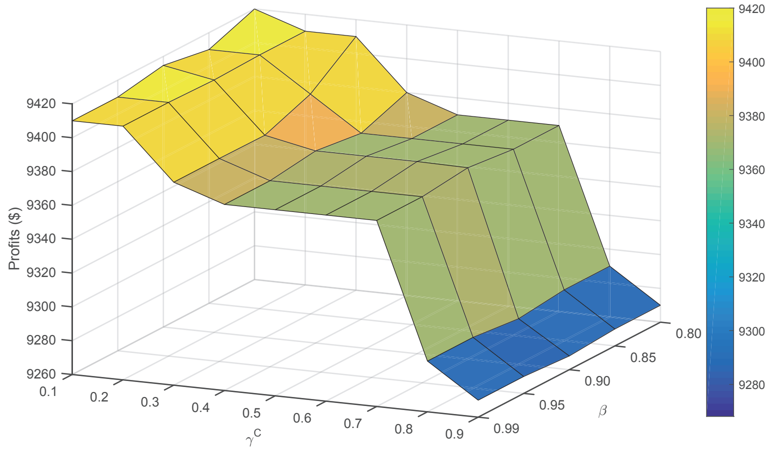


Figure 14. Total profits as a function of β and γ^C.

4.5. Impact of Degradation Cost

Figure 15 illustrates the DA energy and regulation bids under different degradation costs ($/kWh). The degradation cost affected the DA regulation bids but had no effect on the DA energy bids. The DA regulation bids varied with the degradation cost during 12:00–13:00 and 16:00–17:00. However, the total regulation bids during 08:00–17:00 were almost the same under different degradation costs. Figure 16 illustrates the discharging power of PEVs under different degradation costs. It is clear that the discharging power (absolute value) decreases with the degradation cost.

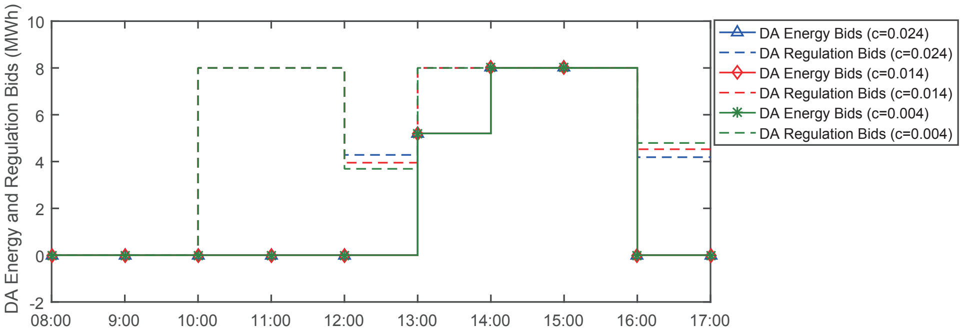


Figure 15. DA energy and regulation bids under different degradation costs.

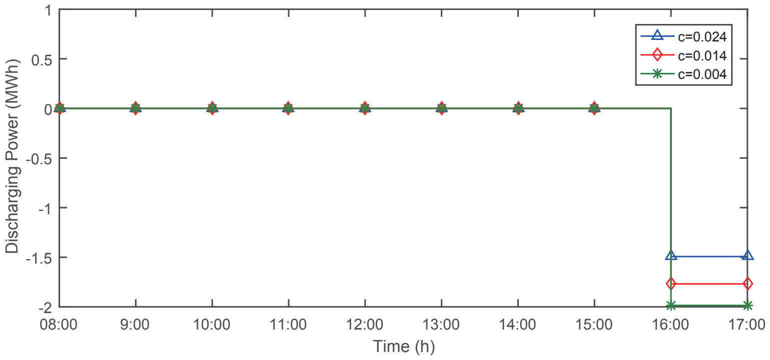


Figure 16. Discharging power of PEVs under different degradation costs.

5. Conclusions

This paper proposes a novel business model for the EVA, followed by the optimal bidding/offering strategy in the joint energy and regulation market. The core of the proposed business model is that the PEVs' charging demands are considered to be elastic. The EVA overcomes the opportunity cost neglect for PEV owners, optimizing their charging energy and charging profiles with full consideration of the demand curves and market conditions. The constraint of satisfying the charging demands is relaxed by Lagrangian relaxation technology in the optimization model. As a result, the optimization potential of the optimization strategy becomes greater. The case studies demonstrate the effectiveness of the proposed business model. Compared with the traditional business model, the profits of the PEV owners increased by 4.36% under the proposed business model. Furthermore, we demonstrate that the proposed business model is incentive-compatible. The PEV owners have the incentive to submit the real demand curves or related information to EVA.

Author Contributions: D.C. proposed the business model and bidding strategy. Z.J. reviewed and commented on the manuscript. H.T. helped with the case studies.

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