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An EV Charging Scheduling Mechanism Based on Price Negotiation

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Abstract: Scheduling EV user's charging behavior based on charging price and applying renewable energy resources are the effective methods to release the load pressure of power grids brought about by the large-scale popularity of electric vehicles (EVs). This paper presents a novel approach for EV charging scheduling based on price negotiation. Firstly, the EV charging system framework based on price negotiation and renewable energy resources is discussed. Secondly, the price negotiation model is presented, including the initial price models and the conditions of transactions. Finally, an EV charging scheduling mechanism based on price negotiation (CSM-PN), including the price adjustment strategies of both the operator and EV users is proposed to seek a final transaction during multi-round price negotiation. Simulation results show that this novel approach can effectively improve the charging station operator's income, reduce the EV users' costs, and balance the load of the power grid while improving the efficiency of the EV charging system.

Keywords: electric vehicle; price negotiation; charging price; renewable energy resources

1. Introduction

Electric vehicles (EVs) are an important branch of renewable energy vehicles, and will undoubtedly play an important role in reducing greenhouse gas emissions and maintaining sustainable development. However, the large-scale charging of EVs which have access to the power grid will bring great challenges, such as increased load pressure of the power grid, an increasing difference between the peak and valley load, and so on [1–4]. To deal with these challenges, reasonable scheduling of EV users' charging behavior and the effective utilization of power generation using renewable energy resources are promising solutions [5–9]. The EV charging price is an important and effective factor in realizing the scheduling of EV users' charging behavior. Moreover, the reasonable utilization of EV charging price will not only promote the operators to invest in the charging station, but can also improve the enthusiasm of people to use EVs [10,11].

Currently, research on EV charging prices keeps growing with the increasing development of EVs. Most research mainly focuses on the reasonable charging price model and strategy by considering the profits of charging station operators and the EV user, the cost and travelling requirements of EV users, and the utilization of renewable energy resources [11–20].

Another paper [11], presents a competitive charging station pricing strategy where each charging station optimizes its charging price based on the prediction of the EVs' charging station selection decisions, and the other station's pricing decision, in order to maximize its profit. The actual electricity prices and predicted prices are both utilized to reduce the cost of each single EV with a presented batch reinforcement-learning (RL) algorithm [12]. Another paper [13], analyzes the charging pricing space in centralized charging and discharging mode, and analyzes the benefit levels of charging station operators at different charging price levels. The authors of [14] proposed a decentralized optimization algorithm for plug-in vehicles (PEVs) during grid–vehicle (G2V) and vehicle–grid (V2G) operations by using the economic model predictive control technique. It considers the state-of-charge (SoC) at a given time as a discrete state space to investigate PEV performance and the schedule of V2G/G2V cycles for the maximum economic benefits of EV users. The authors of [15] presented an optimal scheduling of V2G using the genetic algorithm to minimize the power grid load variance. It allows G2V whenever the actual power grid loading is lower than the target loading, while conducting V2G whenever the actual power grid loading is higher than the target loading. V2G scheduling is used to implement the appropriate peak loading shaving and load leveling services for the grid load variance minimization.

The authors of [16] proposed an energy management scheme (EMS) for a charging station that combines the photovoltaic (PV) and energy storage units (ESU) with the grid. The EMS has the capability to charge EV with a constant per unit price at, and below, the level of solar grid parity, and can reduce the economic loss of the charging station due to cheaper and constant price charging with the involvement of a valley-filling operation by both ESU and EV, along with selling the surplus PV energy to the grid. The authors of [17] studied the utilization of EVs and their used-batteries in supporting small-scale energy management systems. The developed system performs a peak-load shift by utilizing EVs, used EV batteries, and PV panels. The authors of [18] proposed an optimal charging strategy of the EV rational user with different time and mileages based on the time-of-use power price to reduce the cost of EV users and the power network loss rate and achieve the win-win goal of EV users and the electric power company. The authors of [19] used the adaptive price control based on neuro-dynamic programming for EV charging with the consideration of energy supply limitation to tune the EV charging demand to approach the expected level by learning from the EV charging process and EV mobility. The authors of [20] proposed and implemented a smart EV charging algorithm to control the EV charging infrastructures according to users' price preferences. EV drivers can submit their price preferences and daily travel schedules to negotiate with the Control Center to consume the expected energy and minimize charging cost simultaneously.

The above-mentioned research intends to improve the efficiency of the whole EV charging system and to bring more benefits and convenience for each participant of the system by establishing a reasonable charging price model and strategy. However, these approaches mostly develop the pricing mechanism from the point of view of the charging station operator or EV user, with the additional consideration of load shifting and the utilization of renewable energy resources. The thorough interaction about charging price between the charging station operator and EV users, according to their own interests and actual requirements, as well as the consequent change in charging price, have not been considered in depth. One of the two parties is the passive participants in charging pricing, which leads to their relatively lower consequent satisfaction. Therefore, a dynamic charging pricing mechanism that both charging station operator and EV users can actively participate in to improve their participation and satisfaction is needed.

To solve this problem, one effective idea is to switch from the existing charging pricing mode to the charging price negotiation mode. Price negotiation has been widely applied in the field of electronic commerce [21,22], and recently, a real-time pricing mechanism via distributed negotiations between prosumers in the smart grid is discussed and its feasibility proved [23]. Price negotiation transforms the price formulation into a process of reaching an acceptable price for each party. With this price negotiation mode, the balance between interests and the actual requirement of most participants will be reached once a price is accepted by all of the participants, which leads to relatively higher consequent satisfaction. However, in reality, human behavior is complex, and people are not entirely rational in the process of price negotiation. Therefore, a dynamic and reasonable charging price negotiation model is needed.

Based on the above analysis, we mainly studied the EV charging scheduling problem based on price negotiation. Our first contribution to the field was the establishment of a charging price negotiation model. Our second contribution was the proposition of an EV charging scheduling mechanism based on price negotiation (CSM-PN).

The rest of this paper is organized as follows. In Section 2, the EV charging system framework based on price negotiation is introduced. In Section 3, the price negotiation model is presented. The charging scheduling mechanism based on price negotiation is discussed in Section 4. Simulation results are analyzed in Section 5. Section 6 draws the conclusion.

2. EV Charging System Framework Based on Price Negotiation

In this section, an EV charging system framework based on price negotiation, as shown in Figure 1, is discussed. As the name suggests, the main participants of this system are the charging station operator and EV user. Both parties want the EV to be charged at a price that is accepted through negotiation between them.

When an EV needs to be charged, the EV user sends a charging request by using a mobile device that installs the charging price negotiation software (APP) through the cellular communication network. Once the operator of the specific charging station receives the charging request through the same kind of charging price negotiation using APP, the operator will form the initial expected charging price according to the state of charging station, such as the current idle ratio of charging piles, load of power grid, power generation of renewable energy resources, and so on. When both of the two participants desire to reach an acceptable charging price by negotiating with each other, the price negotiation will be started according to their own strategies of price negotiation. Once the price negotiation is successfully formed after several rounds of price bidding, comparing and negotiating, the EV can be charged.

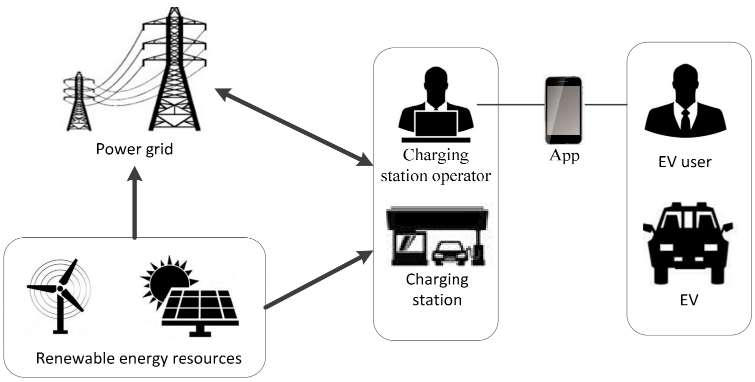

Figure 1. EV charging system framework based on price negotiation.

The renewable energy resources will be given priority to be used. When the renewable energy resources cannot meet the demand of charging power, the charging station operator can send a power request to the power grid to purchase additional power that is needed by the EV user. The renewable energy resources can be operated by a charging station operator or Electricity Services Operator (if the policy of Electricity Services Operator allow). The difference is the cost of the charging station operator. For the first mode, the power generated by renewable energy sources is free, but the charging station operator needs to invest in prophase fixed infrastructure. For the second mode, no additional investment in fixed infrastructure is required, but the charging station operator needs to purchase power from the Electricity Services Operator. Of course, the price must be lower than that purchasing power from power grid. Thus, our technique is not only limited to the application in a self-consumption system. Both “Direct” (this is the sale made on the Power Exchange or through bilateral contracts stipulated with wholesalers) and “Indirect” (form of sale through the stipulation of a simple agreement with the Electricity Services Operator (GSE), which acts as a commercial intermediary between the producers and the electricity system) ways of sale to the electricity network produced by a plant can be chosen depending on the organization of the power infrastructure.

In this mode, the charging station can not only fully use the renewable energy resources and reduce greenhouse gas emissions, but can also reduce the cost and balance load of power grid. An EV charged at a negotiated price will bring operator more profit, which can attract more operators to invest in the construction and operation of charging stations of EVs. Most EV users undoubtedly charge their EVs at a relatively lower price through price negotiation, which not only saves the charging cost but also improves customer satisfaction.

Due to the real-time price and changing load of the power grid and the changing arrival rate of EV users, we set 15 min as the basic time slot of a charging price negotiation. During one basic time slot, all of the above factors are assumed to be constant. Thus, each day 24 h are divided into 96 time slots of a charging price negotiation. If the charging price negotiation is successfully formed in a certain time slot, the EV can be charged in the time slot. In the next time slot, if both the operator and EV user agree that it is not necessary to launch another round of price negotiation the EV can be charged at the last round at the negotiated charging price. Otherwise, the EV will be charged at a new price that is formed by a new round of charging price negotiation.

3. Price Negotiation Model

The basic motivation of all price negotiation is not to maximize the interests of one participant, but to maximize the interests of all participants. Price negotiation is a process where the charging station operator and EV user seek the final negotiated charging price according to the cost and requirement of their own affordable price range. To seek the maximum final transaction rate, the price negotiation model is critical [22]. In this section, the charging price negotiation model is presented.

3.1. Initial Price Model for Charging Station Operators and EV User

3.1.1. Initial Price of EV User

When a charging request is submitted, EV users will form an initial price that meets their own best expectation. To form this initial price, the following factors should be mainly considered.

(1) The travelling requirement of EV user R_i in the next time period

Obviously, the psychological expectation of the charging price of the EV user will increase if the travelling requirement is very urgent. R_i is quantified by the formulation (1).

$$R_i = X_{i,n} \times (\lambda_1 \times M_{i,n} + \frac{\lambda_2}{SOC_i}) \times \frac{\lambda_3}{n} \tag{1}$$

$$X_{i,n} = \begin{cases} 1, & \text{plan to travel in the next } n - \text{th time slot} \\ 0, & \text{not plan to travel in the next } n - \text{th time slot} \end{cases}, n \geq 1 \tag{2}$$

where $M_{i,n}$ is the mileage requirement that is planned in the next n-th time slot, SOC_i is the State of Charge of ev_i. $\lambda_1, \lambda_2, \lambda_3$ indicate the influences of mileage requirement, current remaining battery energy, and urgency of travelling requirement, respectively.

(2) The current load of the power grid $L(t)$

Using a mobile device, the EV user will share information of the real-time load of the power grid. When $L(t)$ is higher, the psychological expectation of the charging price of the EV user will increase. Otherwise, the price will increase.

(3) The distance $d_{i,j}$ between EV ev_i and charging station CS_j

The charging convenience increases as $d_{i,j}$ decreases, which means that charging requirement will be fulfilled in a relatively short time. Thus, the price that an EV user can bear will increase.

Thus, the initial charging price of an EV user is formed as follows.

$$p^u_{i,0} = p_0 \times (R_i + \eta_1 \times L(t) + \frac{\eta_2}{d_{i,j}}) \tag{3}$$

where p_0 is the baseline of price, η_1, η_2 indicate the influences of current load of the power grid and distance $d_{i,j}$ between ev_i and CS_j, respectively.

3.1.2. Initial Price of Charging Station Operator

Similarly, the charging station operator will also form an initial price that maximizes the interests after receiving the charging request. To form this initial price, the following factors should be mainly considered.

(1) The current idle ratio IR_j of charging station CS_j

For different time slots, the load of the charging station is different. Thus, the current idle ratio of the selected charging station is the key factor for pricing. IR_j is quantified by the Formulation (4).

$$IR_j = \frac{DC_{c,j}}{CP_{idle,j}} \tag{4}$$

where $DC_{c,j}$ is the duty cycle of charging devices that are working in the charging station CS_j, $CP_{idle,j}$ is the total number of idle charging devices in CS_j.

(2) The current load $L_j^{cs}(t)$ of charging station CS_j

The current load of the charging station indicates the potential charging power supply for new arrival EVs. It is undoubtedly another key factor of pricing. $L_j^{cs}(t)$ is calculated as follows at time slot t.

$$L_j^{cs}(t) = L_j^{cs,0}(t) - L_j^{res}(t) \tag{5}$$

where $L_j^{cs,0}(t)$ is the total actual load of CS_j, $L_j^{res}(t)$ is the total power generated by renewable energy resources of CS_j at time slot t. $L_j^{cs,0}(t)$ is calculated as follows.

$$L_j^{cs,0}(t) = L_j(t) + \sum_{i \in N} P_i \tag{6}$$

where $L_j(t)$ is the load without any EVs charged, N is the total number of EVs that are charging in CS_j, P_i is the charging power of ev_i.

$$P_i = \frac{(A_i - SOC_i) \times Q_i}{t_i^0} \tag{7}$$

where A_i is charging threshold of SOC_i, Q_i is the battery capacity, t_i^0 is the actual charging time of ev_i. Generally, A_i is set as 0.95.

The charging station needs to meet the following constraints when it allows EVs to be charged. The current load cannot exceed the maximum load $L_{j,\max}^{cs}$ of CS_j; the charging power of ev_i must be between the minimum charging power and the maximum charging power; and the actual charging time should not exceed the desired charging time t_i of the EV user. Generally, Q_i, t_i and SOC_i are sent to the charging station operator together with the charging request.

$$\begin{cases} 0 < L_j^{cs}(t) \le L_{j,\max}^{cs} \\ P_{i,\min} \le P_i \le P_{i,\max} \\ t_i^0 \le t_i \end{cases} \tag{8}$$

Thus, the initial charging price of the operator is formed as follows.

$$p_{j,0}^{cs} = p_0 \times (1 + \delta) \times (\alpha_1 \times IR_j + \alpha_2 \times (L_j^{cs}(t)/EL_j^{cs})^2) \tag{9}$$

where EL_j^{cs} is the daily average load of CS_j, δ is the expectation of profit of the charging station operator, α_1, α_2 indicate the influences of current idle ratio and current load of CS_j, respectively. When the charging station is busy, the charging price will increase. When the current load of the charging station is higher than the daily average load, the charging price will also increase. In order to control the growth of the load of the power grid, the charging price increases with square; which will achieve peak shaving and valley filling.

3.2. Conditions of Charging Station Operators and EV Users for Transaction

Of course, the two prices do not match for the most part. Then, to reach a transaction, multi-round price negotiation will be carried out until a transaction is reached or one party of the price negotiation abandons. We set k_0 as the biggest round number of price negotiation.

After each round of price negotiation, both the charging station operator and the EV user need to decide their next actions. They have three choices according to the different conditions.

For EV users: (1) if $p_{i,k}^u \geq p_{j,k}^{cs}$, then the transaction is reached, and EV can be charged; (2) If $p_{i,k}^u < p_{j,k}^{cs}\&\&k < k_0$, EV users do not accept the price given by charging station operator, but will keep bidding in the next round for price negotiation; (3) If $p_{i,k}^u < p_{j,k}^{cs}\&\&k = k_0$, the EV user abandons the price negotiation with the current charging station operator and will turn to another one.

For the charging station operator: (1) If $p_{i,k}^u \geq p_{j,k}^{cs}$, then the transaction is reached, and the EV is allowed to be charged; (2) If $p_{i,k}^u < p_{j,k}^{cs}\&\&k < k_0\&\&L_j^{cs}(t) \leq L_{j,\max}^{cs}$, the charging station operator does not accept the price given by the EV user, but will keep bidding in the next round for price negotiation; (3) If $p_{i,k}^u < p_{j,k}^{cs}\&\&(k = k_0 \parallel L_j^{cs}(t) > L_{j,\max}^{cs})$, the charging station operator can unilaterally terminate the price negotiation with the current EV user.

4. EV Charging Scheduling Based on Price Negotiation

In this section, the charging scheduling mechanism based on price negotiation is discussed. Obviously, there is more than one EV user negotiating with a charging station operator at the same time. Moreover, EV users can also negotiate with more than one charging station operator. After one round of price negotiation, both the charging station operator and EV user will know some extra information leaked from the last round of bidding prices. Then they will decide their next action according to their expectations of interests and requirements. Price adjustment will be made and EV charging scheduling will be consequently realized.

4.1. Price Adjustment Strategy of Charging Station Operator

After one round of price negotiation, the charging station operator can get all the bidding prices of EV users that negotiated with him in the last round. The price for the next round can be adjusted according to these data.

Firstly, the charging station operator needs to calculate the average bidding price of all EV users.

$$\overline{p_k^u} = \frac{1}{N_n} \sum_{i=1}^{N_n} p_{i,k}^u \tag{10}$$

where N_n is the total number of current bidding EV users.

Secondly, the charging station operator needs to find the relationship between the number of current bidding EV users and the average historical number $\overline{N_n}$ of bidding EV users for the same daily time period. If $\overline{N_n} \leq N_n$, the charging station operator may reduce the reduction ratio of the bidding price for the next round or even reduce the price. Otherwise, the charging station operator may increase the reduction ratio.

The bidding price of charging station operators for the new round of price negotiation is formed as follows.

$$p_{j,k+1}^{cs} = p_{j,k}^{cs} \times (1 - \omega \times \frac{\overline{N_n}}{N_n} \times \frac{(p_{j,k}^{cs} - \overline{p_k^u})}{p_{j,k}^{cs}}) \tag{11}$$

where ω is the decision-making coefficient of the charging station operator, $\omega \in (0, 1)$. If ω turns to 0 it means that the charging station operators have a strong desire for little or no price reduction, otherwise they will reduce the price. Apparently, the lowest price that a charging station operator can accept is the average bidding price $\overline{p_k^u}$ of all EV users.

4.2. Price Adjustment Strategy of EV User

It is hard for an EV user to get more global information. Thus, we assume that our price negotiation system sends the average bidding price $\overline{p_k^u}$ of all EV users for the last round to EV users, together with the new bidding price of the charging station operator, and EV users will make their own price adjustment according to these data.

When the last bidding price of an EV user is not accepted, the EV user will be aware that their bidding price may be lower than the price expected by the charging station operator. If the travelling requirement is urgent, then the next bidding price needs to be increased according to $\overline{p_k^u}$. However, to save costs, there must be a variable threshold for the price increasing ratio. To simplify the process, we set the threshold as 5% when $p_{i,k}^u < \overline{p_k^u}$, and 3% when $p_{i,k}^u \geq \overline{p_k^u}$. We assumed that an EV user that does not update their bidding price will be eliminated.

The bidding price of an EV user for the new round of price negotiation is formed as follows.

$$p_{i,k+1}^u = \begin{cases} p_{i,k}^u \times \varphi \times (1 + \min(5\%, \frac{(\overline{p_k^u} - p_{i,k}^u)}{p_{i,k}^u} \times 100\%), p_{i,k}^u < \overline{p_k^u} \\ p_{i,k}^u \times \varphi \times (1 + \min(3\%, \frac{(p_{j,k}^{cs} - p_{i,k}^u)}{2p_{i,k}^u} \times 100\%), p_{i,k}^u \geq \overline{p_k^u} \end{cases} \tag{12}$$

where φ is the decision-making coefficient of an EV user, $\varphi \in (0, 1)$. When $p_{i,k}^u < \overline{p_k^u}$, the new bidding price of an EV user is close to $\overline{p_k^u}$, and the price increases by up to 5%. When $p_{i,k}^u \geq \overline{p_k^u}$, the new bidding price of an EV user is close to the last bidding price $p_{j,k}^{cs}$ of the charging station operator at half speed, and the price increases by up to 3%.

Of course, to save the time of the EV users that have an urgent travelling requirement and can bear more cost, the variable threshold for the price increasing ratio can be set at a higher value.

5. Simulation Results

In this section, the charging price negotiation service was simulated, and the performance of CSM-PN evaluated. We chose a charging station that installs renewable energy resources using power generation equipment. There are 10 wall-mounted charging piles in the charging station. We set 15 min as the basic time slot of a charging price negotiation, and each day was divided into 96 time slots. We chose the time slot 12:45–13:00 to simulate the process of price negotiation because the number of EV users is relatively large at this time, according to the statistics. We set $p_0 = 0.5$, $\omega = 0.5$ and $\varphi = 0.95$.

Figure 2 presents the bidding price process of EV users and the charging station operator in the first 3 rounds. In the first round, only one bidding price of an EV user is higher than the bidding price of the charging station operator. After one round of price adjustment, three bidding prices of EV users are higher than that of the charging station operator. In the third round, seven EV users can get their EVs to be charged. The final charging price is neither as high as the initial expectation of the charging station operator nor as low as the initial expectation of the EV users, but a value between the two. Both sides can accept that the price formed by price negotiation, which improves satisfaction, while meeting the travelling and interest demand of the EV users. Moreover, an EV user that bids a very low price may risk negotiation failure, and cannot get their EV charged. Thus, EV users should reasonably adjust the price according to their own consideration of convenience and other interests.

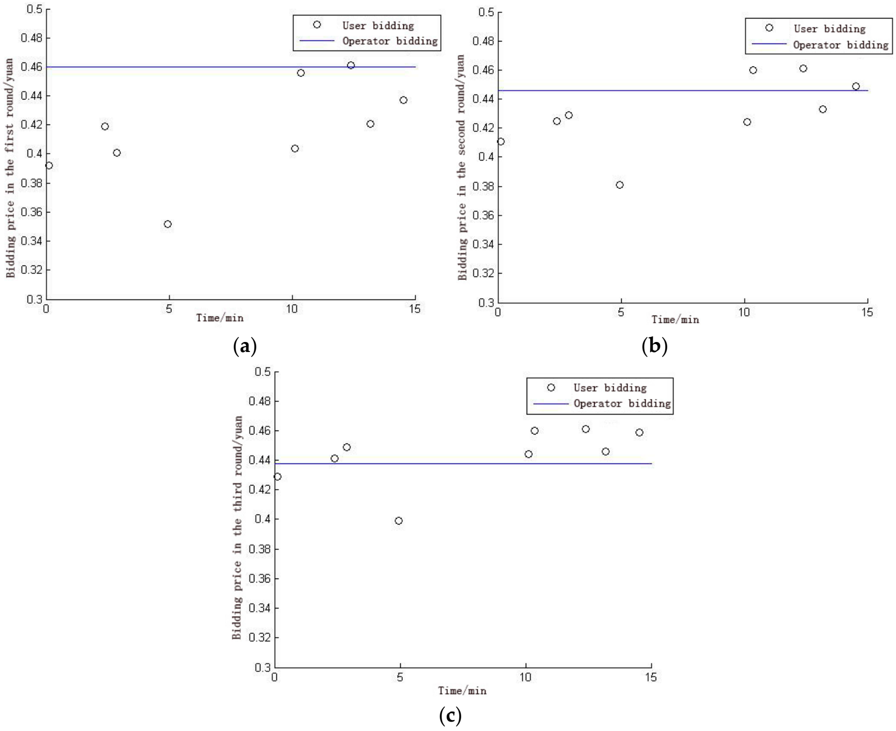

Figure 2. Bidding price process in the first 3 rounds (**a**) first round; (**b**) second round; (**c**) third round.

In the design of a charging price negotiation system, in general, there are some parameters that will significantly affect the performance of the system. We evaluate the system design using three main metrics that represent the operation performance of the system, which are the number of transactions, the charging station operator's income, and the load changes of the power grid. We further evaluated the performance of charging scheduling by comparing two disciplines: a real-time price mechanism and our CSM-PN mechanism. In the real-time price mode, the EV is charged at the real-time price. Figure 3 shows the average statistics of real-time price for 10 days. Figure 4 shows the number of transactions, charging station operator's income, and the load changes of the power grid of the two charging scheduling mechanisms for 10 days.

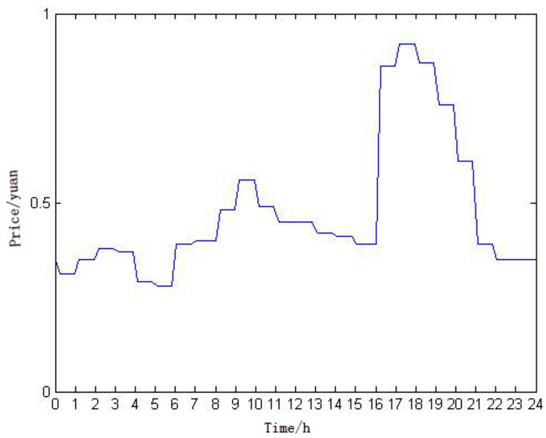

Figure 3. Average statistics of real-time price for 10 days.

Figure 4 shows that our CSM-PN mechanism can attract more EV users to actively participate in charging pricing and finally improves the number of transactions. CSM-PN not only improves EV users' satisfaction but also enhances the benefits of the charging station operator. The number of transactions increases to a relatively large degree, and the final price decreases, but not to the same extent. It is commonly known that the price of energy from renewable energy sources is usually taxed less than energy from non-renewable sources. An increase in the number of transactions means that more energy from renewable energy sources has been used and less taxation occurred. Thus, the total benefits of the charging station operator substantially increase. These results may attract more people and economic entities to invest in the construction and operation of EV charging stations, and will greatly promote the development of the EV industry. Figure 4 also shows that the area surrounded by the red curve is larger than that surrounded by the blue curve, which indicates that the total consumption of power has been improved and more EVs have been charged. The efficiency of the charging system has been improved. Moreover, during Time/h (4:00–6:00), more energy will be purchased from the power grid for a relatively lower price and lower power load in one day. During Time/h (19:00–21:00), more energy from renewable energy sources has been used and less energy will be purchased from the power grid for the relatively higher real-time price. Finally, the peak load of 19:00–21:00 has been reduced, which means that the peak load is transferred to a non-peak time period; load shifting is achieved. It can be concluded that the process and timing of EV charging are more reasonable, while the number of transactions was improved by price negotiation.

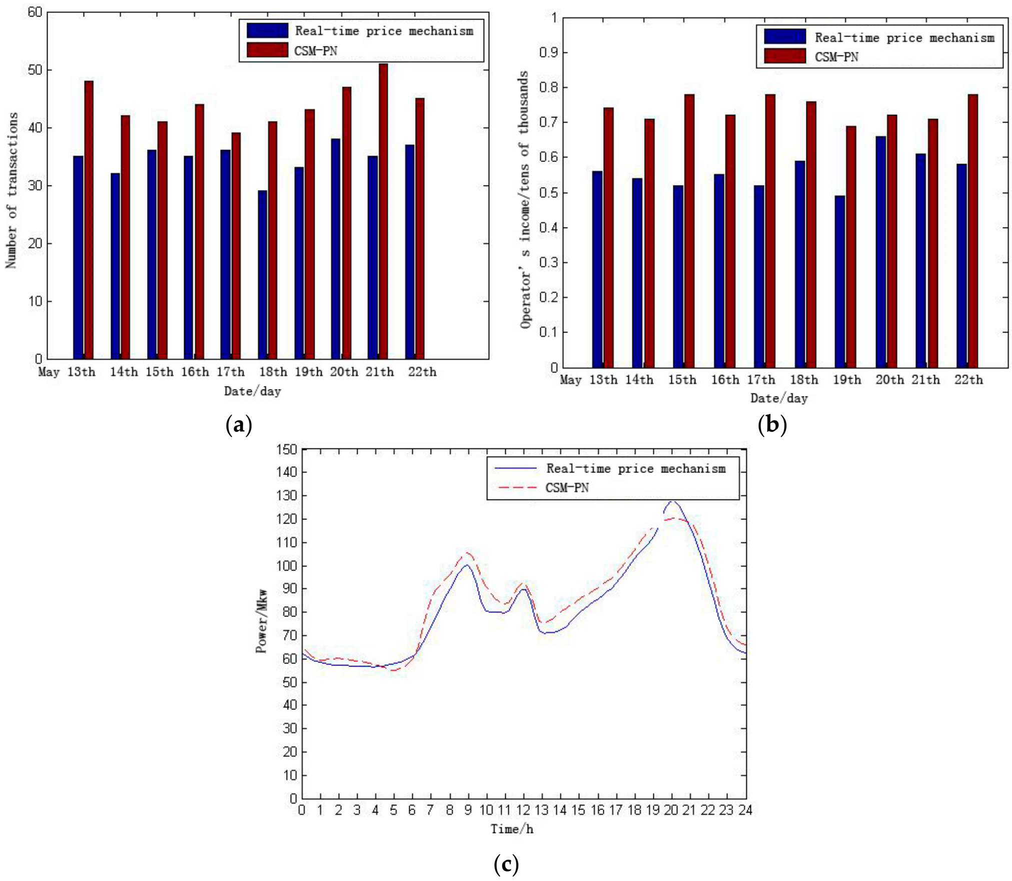

Figure 4. Performance evaluation for 10 days (**a**) number of transactions; (**b**) charging station operator's income; (**c**) load changes of the power grid.

6. Conclusions

This paper proposes an EV charging scheduling mechanism based on price negotiation (CSM-PN) for the charging behavior scheduling of large-scale EV charging systems. We discussed the EV charging system framework based on price negotiation and renewable energy resources. To improve the efficiency of the EV charging system, improve the charging station operator's income, and reduce the EV users' cost, we established a charging price negotiation model and presented the charging price adjustment strategies of the charging station operator and EV users during multi-round price negotiation with the considerations of travelling requirements, load pressure, user and operator interests, and satisfaction. Simulation results show that this novel approach can effectively improve the charging station operator's income and reduce the EV users' cost while improving the efficiency of the EV charging system. In a future work, we will seek to study the accurate setting of the influence and decision-making coefficients of a price negotiation model and price adjustment strategy to make the EV charging scheduling system based on price negotiation more reasonable and efficient.

Author Contributions: B.W. developed the topic, revised, reviewed, and supervised the whole paper. Y.H. performed the calculation, experimentation, and paper writing. Y.X. and Y.L. performed part of the experimentation and reviewed the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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