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Pricing model for the charging of electric vehicles based on system dynamics in Beijing

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ABSTRACT

This paper proposes a system dynamics model to develop a real-time charge pricing (RCP) mechanism of electric vehicles (EVs). The model includes six modules: power consumption of EVs, generator set dispatching, charge pricing, user response, benefit evaluation of all stakeholders and charging stations' life-cycle net income. We consider four charge pricing scenarios and design a RCP mechanism for Beijing according to the simulation results. Sensitivity analysis proves that the model is robust, and the increased charging power of EVs is beneficial for charging service operators. The empirical results indicate that RCP based on the peak-valley time-of-use tariff is propitious for the existing development scale of EVs. In addition, the government subsidies are important to drive EV development in the initial period. However, it should be phased out to reduce the financial burden accompanying the amplification of the scale of EVs.

1. Introduction

Considering the advantages of electric vehicles (EVs) in energy conservation and environmental protection, increasing numbers of countries have set goals to develop the large-scale adoption of EVs. However, uncoordinated charging has negative effects on the economic and environmental performance of EVs, constituting one of the main challenges in the adoption of EVs. In addition, uncoordinated charging causes users to spend more time at charging stations [1]. Worse, it would increase national peak load by 7% when the penetration rate of EVs reached 30%, which could be detrimental to the existing electricity distribution infrastructure [2]. Therefore, some related research has been conducted to achieve better economic and environmental performance by ordered charging for EVs. Schmidt et al. [3] adjusted the charging process of EVs to avoid price peaks, which could save more than 65% in operational costs, compared with a similar diesel-powered vehicle. Foley et al. [4] and Rangaraju et al. [5] both confirmed that off-peak charging for EVs was better for reducing greenhouse gases (GHG) emissions than peak charging. The former showed that generators could be dispatched to rearrange the merit order based on the loads of EVs, and the latter emphasized that the combination of users' driving behaviors and auxiliary energy consumption could achieve ordered charging. Azadfar et al. [6] identified charging infrastructure and EV battery performance as key parameters that influenced plug-in electric vehicle driving patterns and charging behaviors. Dallinger and Wietschel [7] predicted charging behavior using a stochastic model and estimated the variable electricity prices based on marginal generation cost. Xu et al. [8] simulated the charging behaviors of users and proposed a coordinated charging model with time-of-use electricity prices from the perspective of the charging station, and they showed that, although the economic benefits greatly improved, the model generated another load peak.

Due to the price-sensitivity of users, Sun et al. [9] revealed that it was possible to achieve off-peak charging for users by diminishing the difference between the peak and valley of the power grid, while Xu et al. [10] formulated dynamic time-of-use tariffs to which users autonomously responded. By formulating a time-power-varying pricing scheme, Zhang et al. [11] reported that the power grid could indirectly coordinate the users' charging behaviors with a day-ahead pricing scheme, indicating that charge pricing information could drive the charging behavior of users. Valentine et al. [12] developed a statistical Locational Marginal Price and wholesale energy cost model to minimize the operation and energy use costs of power systems. Druitt and Früh [13] suggested that users would benefit from flexible charging and from selling tariffs if they

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participated in balancing markets with the utilization of intermittent renewable generation. Anderson [14] demonstrated that the costs of utilities and users would be minimized when the users perceived the proper price signals and made the best choices. Moreover, they suggested that the two-tier pricing system (different prices for on-peak and off-peak electricity) might be not conducive to utilities were the demand of users to change easily over time.

The previous studies found that coordinated charging is propitious for GHG emissions, power grid or users. Moreover, the charging price has important influences on the users' driving behaviors and the EV operation costs, and it would greatly affect the development of EVs. Therefore, some researchers are currently paying greater attention to charging pricing. Li and Ouyang [15] and Lu et al. [16] established the charging price from the views of charging stations and EV users. The former one calculated the pricing range for charging according to the different energy prices, battery costs and station loads. The later one proposed a cost-benefit analysis model with considering the main factors influencing charge pricing. Pelzer et al. [17] developed a price-responsive charging and dispatching strategy to calculate the profits of EV owners who draw from the supply of ancillary services to the power system in Singapore. To minimize the charging cost and satisfy the charging requirements of user, Arif et al. [18] presented three algorithms for scheduling plug-in vehicles with dynamic pricing schemes. Finn et al. [19] determined that a price based on demand side management offered the most significant benefits to the power grid and users. Based on the valley-filling effect of the supply side and the users' costs, Zou et al. [20] and Hu et al. [21] designed an optimal model for charging pricing. Shi [22] analyzed the interest relationship between the power system and EV users with power demand side management theory and electricity price theory.

The previous studies analyzed charge pricing from the perspective of the power system, charging station or EV users. EV charge pricing is a complex process because it involves benefits to various stakeholders. Shepherd et al. [23] developed a SD model for UK adoption of EVs over the next 40 years. From the view of economics, He and Zhang [24] designed different types of real-time electricity pricing mechanism for China. From Refs. [23,24], it can be known that SD is a modeling technique to resolve complex problems, and it is a suitable approach for depicting the feedback structure in a real-time charge pricing (RCP) system. Unlike Refs. [15–24], this paper considers the factors that impact charge pricing in an integrated system, and proposes a RCP mechanism to balance the benefits of all stakeholders including the electricity supplier, charging stations, EV users and the government. Moreover, by simulating the real-time dispatching of generator sets, it measures costs and GHG emissions of generation to test the impact of different RCP scenarios on the energy supply side. Additionally, it calculates the life-cycle net income of charging stations. In order to improve the effect of RCP, it analyzes the sensitivity of EVs' charging power, government subsidies and charging service fee.

The purpose of this study is to design a RCP mechanism of EVs using SD and to test the economic and environmental performance of different RCP scenarios based on data from Beijing. The work is organized as follows. The RCP model is introduced in Section 2. The simulation results are discussed in Section 3. In Section 4, sensitivity analysis is applied to test the robustness of the model and improve the effect of RCPs. Based on the work in Sections 3 and 4, Beijing's RCP mechanism is proposed in Section 5. Section 6 concludes the paper.

2. RCP model

Considering the effects of different RCP methods, four charge pricing scenarios were proposed: (1) RCP based on a peak-valley time-of-use tariff (TOU); (2) RCP based on the real-time generation costs; (3) RCP based on the marginal generation costs; and (4) RCP based on the average generation costs. We analyze the influence of the four charge pricing scenarios based on the indicators including peak-valley different of EVs' charging power, costs and GHG emissions of generation, benefits of all stakeholders and life-cycle net income of charging stations.

As shown in Fig. 1, the proposed SD model consists of six modules: power consumption of EVs, generator set dispatching, charging price, user response, benefit evaluation of all stakeholders and life-cycle net income of charging stations. Further, charge pricing module and user response module are the core of the SD model. We assume that the generator set dispatching is based on the load of the power grid on the previous day, and users can receive charge pricing tables on a timely basis. The charge pricing is determined by a specific pricing scenario that is related to the charging power of EVs and the electricity price for charging stations during each time period. According to real-time charging price, users adjust their charging behavior, which feeds back quantitatively into the charging power demand in each period, while the new EVs' charging power and the typical load result in a new load

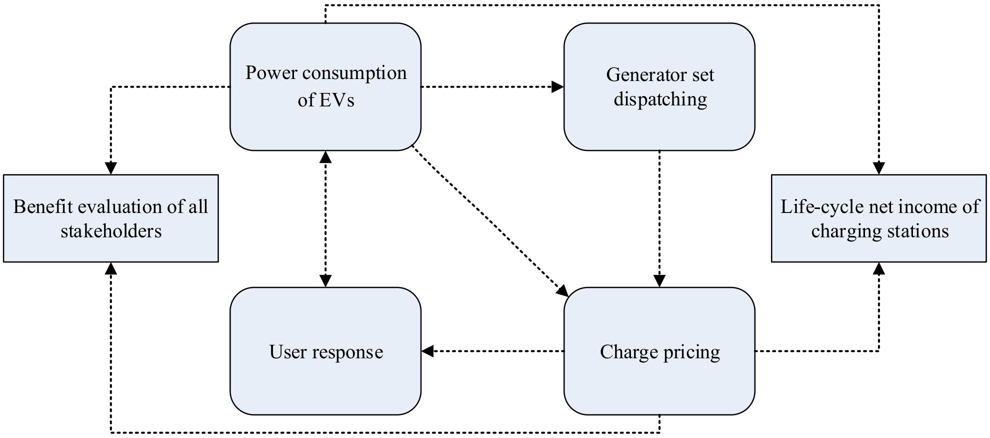

Fig. 1. Basic framework of the model.