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Analysis method and utilization mechanism of the overall value of EV charging ☆

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ABSTRACT

Electric Vehicle (EV) can save energy while reducing emissions and has thus attracted the attention of both academics and industry. The cost and benefit of charging are one of the key issues in relation to EV development that has been researched extensively. But many studies are carried out from a viewpoint of some local entities rather than a global system, focus on specific types or aspects of EV charging, or use mixed models that can only be computed by computer simulation and lack physical transparency. This paper illuminated that it is necessary to consider the value of EV charging on a system scale. In order to achieve this, it presents an analytical model for analyzing the overall value of EVs, an analysis model to evaluate the reduction of pollutions relevant to photovoltaic power, and a model to transfer the intrinsic savings of wind power to the off-peak charging loads. It is estimated that EV charging has a significant positive value, providing the basis for enhanced EV subsidies. Accordingly, a utilization mechanism apt to optimize globally is proposed, upon which sustainable business models can be formed by providing adequate support, including the implementation of a peak–valley tariff, charging subsidies and one-time battery subsidies. This utilization mechanism, by taking full advantage of the operation system of power utilities to provide basic support and service, may provide new approaches to the development of EVs. The method proposed here is of important value for the systematic considerations about EV development and maybe can help broaden the possibility of EV development.

1. Introduction

The escalating issues of oil resource depletion and environmental pollution have drawn worldwide attention to the Electric Vehicle (EV). The EV and charging infrastructure have been extensively studied, and a significant number of demonstrations have been built in various countries [1]. However, in spite of the huge investment and resource, the development of EV remains very slow. The primary reasons include the fact that, the development of the power battery was slower than expected, such that EVs are not competitive with fuel vehicles. Meanwhile, the operational mode of the charging infrastructure remains uncertain, and its construction is slow; both of these have seriously stymied EV development. Additionally, different aspects of the related industry function with near autonomy, lacking coordination and optimization, with the consequence that they are unable to form a resultant, coherent force.

The cost and benefit of charging are the key issues for the development of EV. And they must be considered taking EV, charging infrastructure, and power grid as a whole; and this is the base to determine reasonable charging price scheme and subsidy policy, and maximum the whole social welfare. Though many elaborated researches in relation to the impact, cost and benefits of EV charging have been carried out, there are still some drawbacks as following:

Firstly, it is only from a viewpoint of some local entities rather than a global system that many literatures studied the economy and benefits of EV charging. Jonathan and David [2] using Western Australia, the smallest wholesale electricity market in the world, as a test case, discussed the economic and commercial viability of vehicle-to-grid (V2G). It calculated the benefits of V2G for arbitrage in short term energy market, providing spinning reserve, load following and participating demand side management. And the cost of battery wear, communication systems and alternative options of V2G were analyzed in the other hand. The report concludes that most variants of V2G are currently too costly to

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implement in the light of alternative options. However, EV charging can be added to demand side management without substantial investment. Based on the Well-to-Wheel (WTW) methodology, Ricardo et al. [3] presents a study of the economic and environmental balances for EVs versus fuel vehicle. It takes into account different primary energy supply includes fossil fuels, nuclear and Renewable Energy Source (RES), and different vehicle technologies include Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV) and Plug-in Hybrid Electric Vehicle (PHEV). BEVs have less than a half of the emissions than an fuel vehicle. However, the ownership costs during its life cycle (about 10 year) are similar to an equivalent fuel vehicle, despite the lower operational costs for BEVs. A comprehensive approach with two large-scale distribution areas and three penetrations is proposed to evaluate the impact of PEV on distribution network and shows that, the smart charging can avoid up to 60–70% of the required incremental investment [4]. The comparison in [5] concludes that battery and hybrid EV are offering clearly short-term and medium-term solutions with a large number of common components, and maybe fuel cell vehicles can contribute to long-term solutions. A stochastic model based on the driving behavior of Western European drivers is studied to determine the electrical power required for PHEVs in Belgium and shows that, coordinated charging is essential to minimize the impact, while the double tariffs scheme will create a large, unwanted peak [6]. A value model is presented to assessing the integration of EVs into Australia's electricity industry, which is based on the relationship of supply and demand [7]. In these studies, only the cost and benefits of EV user or power grid are analyzed and optimized, and being under special electricity price scheme or in certain power market; this is distinct from the analysis and optimization in a systematic manners. From the viewpoint of system, it is the electricity price scheme that needs to be optimized at first; otherwise, with an unreasonable electricity price scheme, it is unlikely to maximum system benefits, and will reduce the significance of partial optimization.

Several articles present studies on the cost and benefits just about specific types or aspects of EV charging, while without involving general methods and results about the value analysis of EV charging. The economics of fast charging is studied in a case of Germany [8], where potential users and organization structures are investigated as well as different tariff types. The key drivers of revenue are the tariff, the capacity and the utilization rates. Cost components include initial capital expenditure and operational expenditures. The results show that, a market-driven roll-out of Level III fast charging infrastructure is unlikely to be profitable in Germany at 2011 EV penetration rates. And the general EV adoption rate is detected as being a main risk factor for investment in public charging infrastructure. The economic costs and benefits of "smart charging" policy is explored using a number of variables for creating alternative scenarios: level of PEV penetration, 120 V versus 240 V charging, and whether there is a carbon price or not [9]. There are significant absolute dollar savings associated with load shifting, although they represent a fairly low percentage of total system costs. The value of smart charging policy varies significantly across electric grids. A simple 12–8 am time-of-use tariff coupled with a circuit timer appears to be the most economical way to maximize the net benefits. But the economic benefits of optimal charging cannot justify investing in the smart grid infrastructure. A new broader method is proposed to compare different vehicle technologies, and giving insight on electric grid impact and CO_2 emissions [10]. The method was applied to series and parallel PHEVs with different driving cycles, driving distances and user behaviors. The result shows that, total driven kilometers greatly affects total CO_2 emissions and user cost. A stochastic optimization algorithm is presented and justified to maximize the use of renewable energy, where the Monte Carlo simulation of transportation patterns and Hong's estimation method to mimic renewable energy sources are used [11]. A decentralized valley-filling charging strategy is presented, in which a day-ahead pricing scheme is optimized and broadcasted to EV owners [12]. An intelligent charging method in response to time of use (TOU) price is presented, and the results have validated its effectiveness [13].

Some papers use mixed models with multiple objectives and constraints that can only be computed by computer simulation. Although this method can generate more accurate numerical results, the conclusions tend to be vague in physical transparency, and common analytical models and general rules are difficult to obtain, because a variety of interactions and influence factors are intertwined. Liu et al. [14] estimates the costs and benefits of PHEV by elaborated models. Typical daily driving patterns are derived by the data from Finland, taking into account differences between weekdays and holidays. The model treats the vehicles connected as a storage pool, which participates in the day-ahead and intraday markets, considering reserves and a minimum level for the leaving battery. The impact of different options are compared on the power system of Finland, including using mixed integer programming model or linear programming model, providing spinning/non-spinning reserves or not, and using smart charging or dumb charging. It turns out to be that the system cost of EV charge was around 36 €/vehicle/year by smart charging while around 263 €/vehicle/year by dumb EVs. An assessment of impact of PHEV charging patterns on power system is presented by using of detailed stochastic models, where the problem is formulated by objective function, start-up and shut-down costs constraints, power balance and reserve constraints, coupling constraints of individual unit status, start-up and shut-down indicators, individual unit balance and reserve constraints, individual unit ramping constraints and minimum on/off time, wind power constraints, PHEV load charging balance, PHEV load hourly charging limit, reserve provided by V2G [14]. Rotering and Ilic [15] uses two dynamic programming to find the economically optimal solution for the vehicle owner, and the analysis of the California independent system operator indicates that, smart charge timing reduces driving costs from $0.43 to $0.2. Provision of regulating power substantially improves the daily profits to $1.71. A stochastic optimization algorithm with detail model is presented to coordinate charging of EVs to maximize the use of renewable energy [16].

In addition, for utilization of EV charging value, despite different types of business models are discussed, the overall value of EV charging gets little attentions. A holistic approach to developing business models for EV is presented based on morphological methods, which can capture the complex interrelations, show potential design options, and reveals technical and organizational limitations [1]. Andersen et al. [17] introduces the business model for integration of EVs into private transport systems established by the firm better place, where an intelligent rechargeable network is provided by an Electric Recharge Grid Operator (ERGO).

As mentioned above, because of the comprehensiveness, complexity and uncertainty of EV development, the universal and simple models and methods for the value analysis of EV charging remain a challenge to be resolved. Further, this will lead to various difficult in many aspects, such as policy analysis and decisions, business model selection, and develop route choosing. Therefore, this paper aims to develop an analytical model and method for determination of the overall value of EV charging, so as to provide a useful tool for analysis of charging price, subsidy policy, and other system issues. Section 2 proposes the analysis model of the overall value of EV charging which include marginal cost of electricity for charging, the value of pollution reduction, and the value corresponding to the increase in new energy utilization, presents the evaluation method of each part value, and estimates the change range of the overall value. In Section 3, a utilization