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Electric vehicle charging in China's power system: Energy, economic and environmental trade-offs and policy implications

Ying Li [a,*], Chris Davis [b], Zofia Lukszo [a], Margot Weijnen [a]

[a] Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2600 GA Delft, The Netherlands
[b] Center for Energy and Environmental Sciences (IVEM), University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

HIGHLIGHTS

- We investigate the energy, economic and environmental implications of deploying EVs for China's power system by 2030.
- EVs outperform gasoline-powered vehicles in terms of average fueling costs.
- Controlled EV charging given the expected 2030 capacity portfolio results in more CO_2 emissions than uncontrolled charging.
- Controlled charging has absolute advantages in mitigating the peak load and facilitating RES generation.
- Controlled (dis)charging will not reduce CO_2 for China without generation decarbonization and CO_2-influenced dispatch.

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ABSTRACT

This work investigates different scenarios for electric vehicle (EV) deployment in China and explores the implications thereof with regard to energy portfolio, economics and the environment. Specifically, we investigate how to better deliver the value of EVs by improving designs in the power system and charging strategies, given expected developments by 2030 in both the power system and EV penetration levels.

The impact of EV charging is quantified by applying an integrated transportation-power system model on a set of scenarios which represent uncertainties in charging strategies. We find that deploying EVs essentially shifts the use of gasoline to coal-fired power generation in China, thus leading to more coal consumption and CO_2 emissions of the power system. Economically, EVs outperform gasoline-powered vehicles in terms of average fueling costs. However, the impact of EVs in terms of CO_2 emissions at the national level largely depends on the charging strategy. Specifically, controlled charging results in more CO_2 emissions associated with EVs than uncontrolled charging, as it tends to feed EVs with electricity produced by cheap yet low-efficiency coal power plants located in regions where coal prices are low. Still, compared with uncontrolled charging, controlled charging shows absolute advantages in: (1) mitigating the peak load arising from EV charging; (2) facilitating RES generation; and (3) reducing generation costs and EV charging costs. Hence, in light of this trade-off of controlled charging with the goals of energy security, economic efficiency and reducing environmental impacts, policy interventions in the Chinese power system should opt for controlled charging strategies in order to best realize the benefits of EVs. Accordingly, this paper proposes that increasing the use of cleaner forms of electricity generation, such as RES power and gas power, and establishing energy efficiency and CO_2 emission regulations in power dispatch are critical for China. Lastly, this work illustrates what the optimized charging profiles from the power system perspective look like for different regions. These results can inform Chinese policy makers in creating a better integration of the transportation and the power system.

1. Introduction

The transportation sector accounts for about half of the oil consumption in China, and is the fastest growing contributor to national greenhouse gas (GHG) emissions [1]. To improve the security of energy supply and address climate change, a transition of the transportation sector towards low-carbon and sustainable energy resources is needed [2]. One possible strategy is to electrify transportation through using electric vehicles (EVs), and the Chinese government has been making substantial efforts in this aspect [3]. However, whether EVs are low-carbon and sustainable

* Corresponding author.
E-mail address: y.li-6@tudelft.nl (Y. Li).

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for China compared with conventional vehicles is an open question, as the benefits from deploying EVs is highly dependent on the fuel consumption, costs and CO_2 emissions associated with electricity generation [4]. Given substantial differences in the regional generation portfolios and the expanding inter-regional transmission grid in China, a comprehensive assessment is needed to evaluate the value of deploying EVs in such a large-scale and complicate power system [5].

Furthermore, the implications of EVs are largely influenced by charging strategies. Most studies indicate that uncontrolled EV charging entails a series of challenges for the investments in and the operation of the power system [6]. For instance, it may require additional generation capacity [7] and upgrading of the existing power grid [8]. Accordingly, demand response of EVs has been proposed to cope with this. The key idea behind the EV demand response is that with certain mechanisms, EVs' charging (and discharging) can be controlled as a dispatchable load or as an energy storage system to coordinate with the power system operation [7]. Based on various controlled charging strategies, many benefits can be expected from EV demand response. For instance, studies show that EVs can provide ancillary services in the electricity market [9,10], manage the intermittency issues of RES generation [11,12], and mitigate the need for grid expansion [13,14]. The questions left here are how the implications of EVs are affected by different charging strategies, and which charging strategy would be more suitable in light of the characteristics of China's power system.

In short, this work aims to assess the implications of deploying EVs in the Chinese power system considering regional differences in generation portfolio and the constraints of inter-regional transmission grid capacity, and investigate the influences of the contextual power system and charging strategies on the value of EVs. The results of this work are expected to inform policy makers regarding the possible benefits and threats associated with EV deployment, and how to better exploit the promises of EVs by improving designs in the power system and charging strategies. Specifically, this work will answer three questions: (1) what are the implications of EV deployment in China from the energy portfolio, economic efficiency and environmental sustainability perspectives? (2) to what degree can the implications of EVs be affected by charging strategies? and (3) what can be improved in the power system and charging strategies to better deliver the value of EVs?

Although many studies assessing the value of EVs have been conducted in the literature, this paper distinguishes itself in two main areas. First of all, this paper distinguishes itself by providing a comprehensive evaluation of the value of EVs in China from the combined perspectives of energy portfolio, economic efficiency and environmental sustainability. We argue that these three perspectives are all desirable for policy designs to achieve an effective and efficient low-carbon transition in the long-term. Hence, this work can provide well-rounded policy evaluations of the value of EVs with regard to the different aspects and trade-offs involving goals related to these perspectives. However, the existing literature has omitted certain perspectives of the three, which might lead to biased policy decisions. For instance, [1,5,15,16] only focused on the environmental aspect of deploying EVs; [7,12,17–20] focused more on energy portfolio effects especially for the integration for renewable energy; other studies, such as [21,22], focused more on a mix of two perspectives. Also, there are studies of EVs focusing on their impact on the distribution and transmission grids, such as [13,14]; and other studies focusing more on aspects of the electricity market, such as [9,23].

Additionally, this paper distinguishes itself by developing a new integrated transportation-power system model, which enables a better quantification of the value of EVs. First, the model can statistically estimate the temporal availability of EVs connecting to the grid. This addresses the lack of accurate driving data which has been identified as a key issue in creating EV-grid models [6]. Additionally, the model enables the simulation of power system operation with a high temporal and spatial resolution. Temporally, the model simulates power system operation on an hourly basis, which can estimate what types of power plants are reacting to the changes in EV load. Because of this, the model is better in terms of evaluation accuracy when compared with life-cycle assessment methods (e.g. [1,21]), or with methods assuming a fixed generation portfolio or a given merit order (without considering start-up constraints of power plants) for EV charging (e.g. [5,15,24]). Spatially, the Chinese power system is modeled as a six-region power system, which incorporates the constraints of inter-regional transmission capacity and the differences in regional generation portfolio by technology. In particular, this work highlights the influence of inter-regional power exchange on the value of EVs given the fact that it might shift EV-associated regional power supply to interconnected regions [4]. This shift is likely to be more significant in China in light of its mismatches of distribution between power resources and electricity demand as well as the fast expanding inter-regional transmission grid [25]. However, existing model-based studies for the Chinese case, such as [17,20], fail to take this into consideration. Hence, this model enables a more accurate estimation of the value of EVs, and can provide a theoretical reference for the methods that can be used in studies that model the integration of EVs into the power system.

The model is applied to a set of scenarios which represent the Chinese power system by 2030 with different charging strategies. The Chinese power system consists of six regional power systems, whose diversity in generation portfolio and grid connections enables us to explore the implications of EVs with different power systems. Further, four charging strategies are modeled, including: (1) two uncontrolled charging strategies which allow EV users to charge freely, yet differ in the accessibility of EV charging infrastructures; and (2) two controlled charging strategies in which EV charging is optimized from the power system operators' perspective, with one strategy where EVs can also discharge back into the grid when needed.

This paper is organized as follows. Section 2 introduces the transportation-power system model. Section 3 presents the scenario definitions and the key data used in this work. Section 4 analyzes the scenario results regarding the energy-economic-environmental implications of EVs. Section 5 discusses the policy implications of the scenario results and how to better deliver the value of EVs for real applications. The final conclusions are provided in Section 6.

2. Research methods

2.1. An integrated transportation-power system model

This paper develops an integrated transportation-power system model to quantify the interactions between EVs and the power system. The framework of the model is shown in Fig. 1. Specifically, the transportation model calculates the electricity demand of EVs, statistically estimates the availability of EVs connecting with the grid, and defines the strategies of using EVs. The statistic estimation method used in our transportation model can be useful for similar studies, since the lack of accurate driving data has been identified as a key issue in creating useful EV-grid models [6]. Specifically, the possible strategies of using EVs in this work are: (1) using EVs as loads (only charging) or as an energy storage system (both charging and discharging); and (2) having EVs' charging and discharging controlled by the power system operator or by EV owners [26].