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A bi-criteria optimization model to analyze the impacts of electric vehicles on costs and emissions

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ABSTRACT

Electric vehicles (EV) are emerging as a mobility solution to reduce emissions in the transportation sector. The studies environmental impact analysis of EVs in the literature are based on the average energy mix or pre-defined generation scenarios and construct policy recommendations with a cost minimization objective. However, the environmental performance of EVs depends on the source of the marginal electricity provided to the grid and single objective models do not provide a thorough analysis on the economic and environmental impacts of EVs. In this paper, these gaps are addressed by a four step methodology that analyzes the effects of EVs under different charging and market penetration scenarios. The methodology includes a bi-criteria optimization model representing the electricity market operations. The results from a real-life case analysis show that EVs decrease costs and emissions significantly compared to conventional vehicles.

1. Introduction

Sustainability of energy supply chains is questioned more frequently today due to increased environmental consciousness and concerns about global climate change. Intense research is conducted around the globe to find alternative technologies in order to decrease energy consumption and related greenhouse gas (GHG) emissions. Between 1990 and 2007, all sectors in EU-27 decreased GHG emissions, except the transportation sector whose emissions increased by 26% and road transportation accounted for 13.5% of total GHG emissions in 2007 (European Commission, 2010). Therefore, search for alternatives to internal combustion engine vehicles (ICEV) has accelerated.

Among alternatives, battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) are the most mature technologies that are expected to play a significant role in moving towards a sustainable path (Delft, 2010). In this paper, the term electric vehicle (EV) is used to cover both of these technologies, BEV and PHEV. EVs are more efficient than ICEV and they provide opportunity to decrease annual fuel expenditures, primary energy consumption and GHG emissions of the transportation sector thus provides the opportunity to address some of the sustainability issues related to ICEVs (WWF, 2008). However, these potential benefits can be actualized only when the electricity that charges the batteries of EVs is generated from clean and efficient sources.

The introduction of EV affects the electricity generation, distribution and transmission by changing the demand profile and increase the production and consumption in the system (Delft, 2010). The sources of electricity generation show significant variance within a region depending on the demand level and profile. Therefore, the energy mix that is used to charge electric vehicles would be different from the conventional energy mix of the region in question. Since the parameters of this dynamic energy mix, such as carbon intensity, marginal price, affect the performance of electric vehicles, a realistic analysis on the impacts of EVs must be analyzed before the introduction of EVs to help policy makers shape EV regulations and practices. It was shown that CO2 emissions due to the use of EVs highly depend on regional characteristics of electricity generation in US (Tamayao et al., 2015). The optimal location of charging stations in Beijing considering the travel pattern of approximately 12,000 over a period of three weeks was considered by Shahraki et al. (2015). Since it is intractable to conduct large scale experiments by charging EVs, mathematical modeling and optimization techniques must be used to analyze impacts and determine possible outcomes of wide use of EVs.

Despite the fact that there are numerous studies dating back to 1990's, scenario analysis was the dominant method, in which calculations are based on general assumptions about the average energy mix, without a realistic mathematical model. Reports analyzing impacts of EVs have used national average emissions (WWF, 2008)

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or pre-defined energy mix assumptions to calculate emissions of EVs (Delft, 2010). In an effort to calculate life-cycle emissions of different vehicle technologies, Samaras and Meisterling (2008) have considered three electricity mix scenarios and shown how life cycle emissions change accordingly. Emissions of EVs in Dublin, Ireland have been calculated by Brady and O'Mahony (2011) assuming an average energy mix supported by wind power. Environmental performance of EVs in China has been calculated by using average mix of different regions (Huo et al., 2010), who have also shown that EVs might perform worse than ICEVs if charged from a coal intensive generation mix. Despite the fact that these works provide valuable understanding about EVs, emissions calculated by using average mix lead to results far from the actual case if carbon intensity of the marginal electricity is different than the average mix. Base-load generators are taken into account in the average mix scenarios despite the fact that their contribution to supply increase is limited. If base-load generators use a different technology than peak-load generators (which is the case in the majority of electricity markets), the characteristics of electricity supply change significantly. This difference has been shown in the work of McCarthy and Yang (2010), who have used a merit-order dispatch algorithm based on historical data to determine marginal generators in California. The idea of marginal dispatch has also been used by Craig and Sullivan (2008) in their emissions calculations. Similarly, this study proposes a methodology that uses marginal electricity approach in order to prevent misleading results of using average mix.

Mathematical modeling and optimization tools have been used by a limited number of studies in the literature. Among these, Wang et al. (2010) constructed a model to analyze impacts of EV charging on marginal electricity prices and Sioshansi et al. (2010) used a model to determine the marginal generators used to charge EVs. The optimization models in these studies use the business-as-usual model in the electricity market to satisfy the total demand at the minimum cost. In general, cheaper generators such as coal generators emit more GHG than costly generators like hydro power and natural gas plants. The impact of EVs on the energy generation systems and the energy markets were investigated recently. It was argued that the uncertainty inherent in wind electricity production dictates keeping nearly equal amounts of conventional generation resources in reserve should wind electricity output should suddenly dip (Hodge et al., 2010). The authors recommend the introduction of plug-in hybrid electric vehicles into the personal transportation fleet. Koltsaklis and Georgiadis (2015) presented a generic mixed integer linear programming model that integrates the unit commitment problem with the long-term generation expansion planning framework. The authors test their model on an illustrative case study of the Greek power system. The same authors also analyzed the effect of EVs on the unit commitment model for flexible and responsive load management (Koltsaklis and Georgiadis, 2016). Li et al. (2016) investigated different scenarios for EV deployment in China and explores the implications of energy portfolio considering economical and the environmental aspects. They investigated the improvements in the design of the power systems and their impact on EV charging strategies. Madzharov et al. (2014) presented a mixed-integer linear programming unit commitment model with focus on the effect of EVs on the generation side. Their results demonstrated that optimized charging (centrally controlled) is economically more advantageous and allows for higher EV penetration, compared to random charging.

The impacts of EVs on the energy generation systems were mainly analyzed from the economic perspectives. The single objective models lead to undesirable results regarding emissions in regions where cheap electricity is generated from carbon intensive energy sources. The impacts of future scenarios of EVs on the German power system were analyzed (Schill and Gerbaulet, 2015). In the case of Germany, it was shown that the cost-driven EV charging strongly increases the utilization of hard coal and lignite plants in 2030, whereas additional power in the user-driven mode is predominantly generated from natural gas and hard coal. The life cycle assessment indicators for the optimal EV charging strategies was analyzed recently (Bustos et al., 2016). Economic and environmental performances are two conflicting objectives and cost oriented policies are shown to lead to higher pollution levels (Peterson et al., 2011). This conflict can be analyzed by using the Pareto solutions generated by multi-criteria decision algorithm. Using multi-criteria decision tools lead to generation of efficient solutions and enable the policy makers to choose among numerous options depending on their preferences of being cost or emissions oriented.

Another shortcoming in the studies is the use of scenarios to representing charging demand. Charging patterns are given as inputs to the model and results are compared without finding optimal charging hours. This approach limits the ability of the model to optimize performance of the EVs. Therefore, charging hours need to be defined as decision variables in determining the most appropriate charging hours. Despite the fact that first chargers have been installed and first EVs have been registered, there are no studies that analyze the impacts of EVs in the Turkish market. The methodology proposed in this paper is an attempt to fill these gaps in the literature. The methodology is applied to the Turkish electricity market with the data from Turkish Electricity Transmission Company (TEIAS); however, it can be applied to any region with their own data set.

The paper addresses these shortcomings in a four step methodology that puts emphasis on marginal electricity generation instead of the average energy mix. The methodology considers two objectives; minimization of the costs and GHG emissions and uses a bi-criteria solution algorithm to generate the set of efficient solutions. The model also enables to define charging hours as decision variables to overcome limitations of scenario analysis methods. Although the methodology is applied to real world data from Turkish electricity market, it can be applied to any region by changing the region specific data inputs described in detail. The main contributions of this paper can be listed as:

i The marginal electricity generation values are used rather than the average energy mix in the assessment of the impact of EVs on the electricity generation system. Since EVs will impose additional electricity demand, the marginal electricity generation values correspond to the bids that would have been accepted for the additional demand coming from EVs.

ii The impact assessment model is a bi-objective optimization model where the efficient frontier for the costs and also GHG emissions for satisfying the electricity demand of EVs are analyzed to understand the compromise between these two conflicting objectives.

iii The optimization model introduces the concept of charging hour optimization. This concept allows us to balance the load on the electricity generation system and shifts the charging times to the most desirable time slots considering availability of capacity at the electricity generators as well as the economic and environmental impacts.

iv The case study is conducted by using the real data from Turkish electricity market. In order to analyze the electricity generation system under different seasonal characteristics and conditions, we applied our approach on 6 different days.

This paper is organized as follows: four main steps of the methodology is explained in detail in the second section. The third section is dedicated to results and discussion of the Turkey case and the fourth section concludes the paper.