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Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration

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A B S T R A C T

Electric vehicles (EVs) and renewable energy sources offer the potential to substantially decrease carbon emissions from both the transportation and power generation sectors of the economy. Mass adoption of EVs will have a number of impacts and benefits, including the ability to assist in the integration of renewable energy into existing electric grids. This paper reviews the current literature on EVs, the electric grid, and renewable energy integration. Key methods and assumptions of the literature are discussed. The economic, environmental and grid impacts of EVs are reviewed. Numerous studies assessing the ability of EVs to integrate renewable energy sources are assessed; the literature indicates that EVs can significantly reduce the amount of excess renewable energy produced in an electric system. Studies on wind–EV interaction are much more detailed than those on solar photovoltaics (PV) and EVs. The paper concludes with recommendations for future research.

Contents

1. Introduction

The world's transportation and electric power generation sectors are directly linked to some of the key driving issues of this century: peak oil, climate change, and energy independence. Electricity generation and transportation account for over 60% of global primary energy demand; a majority of the world's coal demand is for electricity generation and a majority of the world's oil demand is for transportation [1]. Alternative vehicle technologies, such as electric vehicles (EVs), are being developed to reduce the world's dependence on oil for transportation and limit transportation related CO_2 emissions. Likewise, renewable energy

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sources are being developed and deployed to displace fossil fuel based electricity generation, reducing greenhouse gas emissions as well as the emission of other pollutants such as nitrous oxides (NO_x) and sulfur dioxide (SO_2). The integration of the transportation and electricity sectors, in combination with EVs and renewable energy, offers the potential to significantly reduce the world's dependence on fossil fuels and the consequent emission of greenhouse gases.

There are a number of barriers to the large-scale integration of renewables into the electricity system [2]. Renewable energy sources, such as wind and solar photovoltaic (PV) electricity, tend to be variable in supply with no correlation to changes in demand. Whereas natural gas turbines can be ramped up and down to follow fluctuations in demand, renewable energy sources like wind and solar are only available when the wind is blowing or the sun is shining. A variety of strategies have been developed to manage supply fluctuations of varying timescales; these include storage, dispatchable loads (or demand response), and alternative generating capacity [3]. Electric vehicles with an electric grid connection can support all of these strategies; therefore the wide-spread adoption of EVs could play an important role in the integration of renewable energy into existing electricity systems [4].

The basic goal of this paper is to review and assess the literature that discusses the impacts of electric vehicles on the electric grid, with the main focus on the integration of renewable energy into the electricity system. Section 2 gives an overview of EVs, including the key concepts that are pertinent to vehicle interaction with the grid. Section 3 discusses and compares the modeling approaches used in the literature to analyze EVs and the electric grid. Some general impacts and benefits of EVs on the electricity system are presented in Section 4. Section 5 gives a more thorough review of the literature on electric vehicles and renewable energy integration. Section 6 concludes by summarizing the key results of the review and identifying some key knowledge gaps that could inform future research projects.

2. Electric vehicles

2.1. Vehicles and energy sources

An electric vehicle will be defined, for the purposes of this paper, as any vehicle in which some or all of the driving energy is supplied through electricity from a battery. In a conventional internal combustion engine vehicle (ICEV), gasoline or diesel fuel is combusted to create mechanical energy that provides the power to move the vehicle forward. A number of EV technologies are currently in use or under development, as discussed in Jorgensen [5]. A hybrid electric vehicle (HEV) has a small electric battery that supplies electricity to the drivetrain in order to optimize the operating efficiency of the combustion engine. The battery in an HEV can be charged by the engine or through captured kinetic braking energy from a process called regenerative braking. HEVs are more fuel efficient than ICEVs, but ultimately the vehicle is fully powered by liquid fuels. A plug-in hybrid electric vehicle (PHEV) is similar in concept to an HEV, but with a larger battery and a grid connection. The grid connection allows the battery to be charged with electricity and the larger battery size enables the car to drive a significant distance in all-electric mode. An all-electric range of twenty miles can be denoted through the notation PHEV-20, and a forty mile all-electric range would be PHEV-40. A battery electric vehicle (BEV) is fully powered by grid electricity stored in a large onboard battery. EVs use energy much more efficiently than ICEVs; a traditional ICEV fuel efficiency is 15–18%, while a BEV can be as high as 60–70% efficient [5].

Fuel cell vehicles (FCVs) are another type of electric vehicle, in that the fuel cell generates electricity through an electrochemical process in the fuel cell stack. FCVs have an onboard fuel source, such as natural gas or hydrogen, and can either be fully reliant on the fuel cell or designed with a battery in a hybrid arrangement like an HEV or PHEV. Future visions of a hydrogen economy involve the use of FCVs for transportation; if the hydrogen is created through the electrolysis of water using renewable electricity or from biomass sources then the FCVs would be utilizing renewable sources as well. Currently, the vast majority of the world's hydrogen is produced from fossil fuel sources and the creation of a sustainable hydrogen economy still faces a number of hurdles [3]. While hydrogen from electrolysis is an important potential use for renewable electricity, the transition to a hydrogen economy is too broad a topic to be considered in this paper

EV technologies offer opportunities for a transportation sector powered by renewable energy. To the extent that traditional transportation fuels can be replaced by sustainably grown biofuels, such as ethanol or biodiesel, HEVs can be run from renewable energy sources. PHEVs can also use biofuels in their internal combustion engine, while both PHEVs and BEVs can be completely operated with renewables if charged with renewable electricity from the grid. As such, the vehicle technologies that will be considered for this paper are those with the capacity to store electrical energy from the grid: PHEVs and BEVs (from here on referred to jointly as EVs).

2.2. Charging and grid connections

The battery of an electric vehicle can be recharged from the grid with varying measures of external control, labeled here as charge plans. A simple, or unconstrained, charge plan is a system in which the vehicle immediately begins recharging as soon as it is connected to the grid. A delayed charge plan offsets the battery charging by a set amount of time, for example three hours. Nighttime charge plans delay charging to occur over the course of the night when electricity prices are lowest, with the battery fully charged for use in the morning. Smart charging implies some measure of intelligent control over the charging of the vehicle by the utility or system operator. This can either be direct charging, through direct control of the vehicle, or indirect charging by designing the vehicle to respond to price signals. Dallinger and Wietschel [6] suggest that indirect charging is a more promising concept as it is more likely to lead to consumer acceptance than direct external control.

The idea behind smart charging is to charge the vehicle when it is most beneficial, which could be when electricity is at its lowest price, demand is lowest, when there is excess capacity, or based on some other metric. The rate of charge can be varied within certain limits set by the driver; the most basic limit being that the vehicle must be fully charged by morning. Lunz et al. [7] suggest that one focus of smart charging should be to manage battery performance and lifetime, which can improve the lifetime economics of the battery.

A vehicle-to-grid (V2G) capable EV is one that is able to store electricity and then return it to the electric grid. V2G power is an interesting concept that was first proposed by Kempton and Letendre [8]. The authors suggested that V2G could be used to generate a profit for vehicle owners if the power was used under certain conditions to provide valuable services to the electric grid. These services include regulation (second by second balancing of demand and supply), spinning reserve, and peak power provision. The energy could in theory be supplied from the battery of a BEV or PHEV, from the engine of a PHEV in generator mode, or from the fuel cell of an FCV [9]. Pang et al. [10] suggest that vehicle-to-building (V2B) technology is closer to being a viable option than