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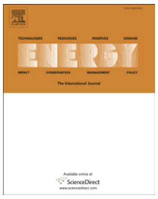

Boosting the adoption and the reliability of renewable energy sources: Mitigating the large-scale wind power intermittency through vehicle to grid technology

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ABSTRACT

The integration of wind energy in the electricity sector and the adoption of electric vehicles in the transportation sector both have the potential to significantly reduce greenhouse gas emissions individually as well as in tandem with Vehicle-to-Grid technology. This study aims to evaluate the greenhouse gas emission savings of mitigating intermittency resulting from the introduction of wind power through Vehicle-to-Grid technologies, as well as the extent to which the marginal electricity consumption from charging an electric vehicle fleet may weaken this overall environmental benefit. To this end, the comparisons are conducted in seven independent system operator regions. The results indicate that, in most cases, the emission savings of a combination of wind power and Vehicle-to-Grid technology outweighs the additional emissions from marginal electricity generation for electric vehicles. In addition, the fluctuations in newly-integrated wind power could be balanced in the future using EVs and V2G technology, provided that a moderate portion of EV owners is willing to provide V2G services. On the other hand, such a combination is not favorable if the Vehicle-to-Grid service participation rate is less than 5% of all electric vehicle owners within a particular region.

1. Introduction

The wind power capacity of the U.S. electricity sector has been increasing rapidly since 2014, and as a clean and widely supported energy source with low operating costs [1], wind power has represented one-third of this power capacity growth in the U.S. since 2007. In the year 2014, 4854 MW of new wind power capacity was added to the overall U.S. electric system, while 29 GW of gross wind capacity entered the interconnection queues managed by independent system operators (ISOs) and regional transmission organizations (RTOs) [2]. The growing share of wind power in the U.S. electricity mix will undoubtedly help to mitigate greenhouse gas (GHG) emissions, as the use of wind energy has already reduced the GHG emissions of the electricity sector by approximately one million tons in the year 2013 [1].

The generation and consumption of electricity must both occur simultaneously, or else either the end-user demand cannot be met if not enough electricity is immediately available, or any resulting surplus of electricity is ultimately wasted. Furthermore, because of the intermittent and unpredictable nature of wind power, grid operators have to sign capacity-related contracts with ancillary service providers to ensure the reliability of the power system [3]. Nevertheless, the current U.S. electric system is able to integrate a certain amount of wind capacity without any significant adverse impact on the grid, as has also been proven by system operators in Minnesota [4] and in New York [5]. However, to accommodate a higher level of wind capacity, transmission infrastructures have to be upgraded in order to balance the supply and demand of electricity and ensure that the reliability of the system is not adversely affected. A fast, smart, and sub-hourly market needs to be developed for this purpose, and more importantly, the balancing ability of the host area must be increased [6]. As a promising ancillary service solution, Vehicle-to-Grid (V2G) technologies can use idle electric vehicle (EV) batteries as power storage units to provide grid ancillary services [7], and can therefore be integrated with wind energy to respond to fluctuating power demand levels as needed [8].

However, the minimum capacity of a regulation service contract

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Nomenclature

σ_T	standard deviation of the regulation requirements after wind integration
σ_C	standard deviation of the current regulation requirements
n	number of new wind projects
σ_P	standard deviation of the regulation requirements for each newly integrated wind project
R_{add}	additional regulation power
$P_{vehicle}$	available power when EV is plugged into the grid
$B_{capacity}$	battery capacity
D_{vmt}	daily vehicle mileage travelled
D_{buffer}	buffering range
B_e	battery efficiency
C_e	conversion efficiency of electricity
$T_{dispatch}$	effective regulation provision time
Re_i	regulation requirements for region i
Es_i	emission savings from using V2G services
P_{cycle}	regulation signal strength in each regulation cycle
$N_{dispatch}$	number of regulation signals accepted per night
T_{cycle}	time period per regulation signal
Ct_{emi}	combustion turbine emission rate
Er	efficiency rate of energy storage
Ea_i	additional emission rate due to large-scale electric vehicle charging
R_{night}	percentage of EVs that are charged at night
W_j	percentage of EVs with charging schedule j
$R_{willingness}$	percentage of EV owners willing to provide V2G services
$R_{availability}$	portion of available EV owners in the total population
Ec_i	non-base-load marginal electricity emission rate of region i
Em_i	average emission rate of the electricity mix in region i
i	index of regions
j	index of charging schedules

in PJM regions is usually 1 MW [9,10], which could be met by 20–30 large-capacity battery electric vehicles [11] (although more vehicles may be needed for passengers cars with lower battery capacities), and taking into account the necessary willingness and availability of EV owners to meet this requirement, the required large EV population willing to provide such services may lead to additional GHG emissions because most EVs are charged at night [12], while coal power plants are used to supply marginal electricity demand in many areas of the U.S [13]. Thus, as wind power becomes more strongly integrated into the U.S. electric system, it could be environmentally beneficial to use V2G systems to meet the incremental ancillary service needs, but the fast-growing EV fleet might also consume a large amount of marginal electricity and thereby cause additional GHG emissions.

The rest of the paper is categorized as follows. First, a literature review is conducted in Section 2. Next, Section 3 illustrates in detail the assumptions and calculations in this study. Finally, the results and conclusions of this study are discussed in Sections 4 and 5, respectively.

2. Literature review

Parsons et al. [3] summarized the cost of supporting wind integration in the CAISO and NYISO regions as well as certain states in the MISO region, and concluded that additional regulation capacity will be required as the grid share of wind energy increases. Albadi et al. [14] studied wind power's intermittency impact on the grid system, and two important conclusions are drawn from this research: firstly that the cost of balancing services increases significantly when wind penetration is higher and that economic concerns could therefore be a main obstacle for greater wind penetration, and secondly that an important factor for reducing wind power operational costs is the availability of fast responding generation sources. Korchinski's research [15] also revealed that large amounts of backup capacity will need to be maintained in order to guarantee stable output from wind power, whereas the current wind power system lacks backup generators or transmission lines [16]. Since the grid therefore cannot accommodate an unlimited amount of wind power, Bird et al. argue that 20%–35% wind penetration is feasible in the U.S. power system [17].

Weiller and Neely have studied the potential use of V2G technology as an energy storage tool, as well as the relevant short-term and long-term applications and the bottlenecks of V2G systems [18]. Arslan and Karasan have developed an energy management model and concluded that EV aggregation as virtual power plants could potentially reduce both costs and emissions [19]. Kempton et al. [7,9] have studied the feasibility of a combination of V2G technology and renewable energy, as well as the quantification of V2G revenue. Short et al. [20] have concluded that greater wind penetration could be made possible by connecting PEVs to the grid, and that there is a significant opportunity to reduce fossil fuel consumption through V2G systems. Wang et al. have developed a multi-objective optimization model in order to evaluate the performance of V2G systems as stabilizers for wind power output [21]. Ekman has studied the use of V2G systems in conjunction with wind energy for high wind penetration levels, and has concluded that V2G technology is most likely to be used for regulation and reserve services [22]. Similar analyses have been performed with respect to the performance [23] and economic benefits [24] of distributed hybrid energy systems (HES) such as osmosis desalination or nuclear power plants [25] as ancillary service carriers.

Past research conducted by the authors of this paper has indicated that a particular V2G system on its own could achieve significant GHG emission reductions throughout its life span [26,27], and that V2G systems have also been proven to be feasible for maintaining the reliability of the power grid [28]. On the other hand, each system may have underlying effects [29], and some researchers argue that, because EV charging consumes marginal electricity [30], such charging activities may offset or even negate the environmental benefits of V2G systems [31]. McCarthy and Yang's study illustrated this point by showing that the marginal electricity from running low-efficiency combustion turbine plants often results in additional GHG emissions from such marginal electricity demand [32], and Green et al. [33] likewise confirmed the impacts of massive EV integration. In addition, the Department of Energy has gathered information from smart grid projects to evaluate the impact of EV owners' charging behaviors on the grid [34], while Kintner-Meyer et al. [35] studied the PEV charging impacts in 12 ISO/RTO regions and sub-regions, thereby identifying EVs that could be charged using marginal electricity.

On the other hand, the potential GHG emission reductions from the integration of wind energy into the power grid and from the adoption of EVs have been extensively studied in current literature. However, whether the potential GHG emission savings from the use

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