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# Assessing the stationary energy storage equivalency of vehicle-to-grid charging battery electric vehicles

Brian Tarroja*, Li Zhang, Van Wifvat, Brendan Shaffer, Scott Samuelsen

*Advanced Power and Energy Program, University of California Irvine, 323 East Peltason Drive, Irvine, CA, 92697-3550, USA*

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ABSTRACT

A study has been performed to understand the quantitative impact of key differences between vehicle-to-grid and stationary energy storage systems on renewable utilization, greenhouse gas emissions, and balancing fleet operation, using California as the example. To simulate the combined electricity and light-duty transportation system, a detailed electric grid dispatch model (including stationary energy storage systems) was combined with an electric vehicle charging dispatch model that incorporates conventional smart and vehicle-to-grid capabilities. By subjecting smaller amounts of renewable energy to round-trip efficiency losses and thereby increasing the efficiency of renewable utilization, it was found that vehicle-to-grid energy storage can achieve higher renewable utilization levels and reduced greenhouse gas emissions compared to stationary energy storage systems. Vehicle-to-grid energy storage, however, is not as capable of balancing the power plant fleet compared to stationary energy storage systems due to the constraints of consumer travel patterns. The potential benefits of vehicle-to-grid are strongly dependent on the availability of charging infrastructure at both home and workplaces, with potential benefits being compromised with residential charging availability only. Overall, vehicle-to-grid energy storage can provide benefits over stationary energy storage depending on the system attribute selected for improvement, a finding amenable to managing through policy.



## 1. Introduction

Concerns over impacts of climate change induced by anthropogenic GHG (greenhouse gas) emissions have driven the increased usage of low carbon energy resources. Worldwide renewable power capacity has increased from 85 GW in 2004 to 657 GW in 2014 [1]. The electric power and transportation sectors have received increased attention for decarbonization since these sectors are the two largest contributors to GHG emissions in many regions such as California [2] and in the U.S. as a whole. In the U.S., electric power contributed 31% of the nation's GHG emissions and the transportation contributed 27% of the nation's GHG emissions [3] in 2013. Renewable electricity is slated to fulfill a key role in decarbonization due to the 31% contribution of GHG emissions from the electric power sector but also because many of the promising pathways for the decarbonization of other sectors rely on electrification, such as light-duty transportation and heating [4]. Wind and solar resources which comprise the bulk of the renewable resource base, however, are variable in their generation profile and not dispatchable unlike other generation resources. This poses issues for harnessing these resources to meet the electric load demand for stationary and transportation needs.

To address the issue of renewable variability, measures such as grid energy storage for shifting excess renewable generation to align with electric loads are being explored and deployed. Grid energy storage consists of different technologies including but not limited to batteries, hydrogen energy storage, pumped hydropower, compressed air systems, and flywheels. Since energy storage has not historically had a large presence on the electric grid, these systems need to be newly installed to the appropriate capacity to support the integration of variable renewable resources.

In parallel, plug-in electric vehicles are being deployed in the transportation sector as a means for increasing the end-use efficiency and reducing carbon and criteria pollutant emissions from this sector. These vehicles inherently eliminate tailpipe emissions and can be integrated with the electric grid with grid-communicative smart charging to better align charging loads with renewable generation to minimize or eliminate upstream emissions. These vehicles, however, carry batteries which can be used as a means of grid energy storage when deployed in sufficient

* Corresponding author. Tel.: +1 949 824 7302x11348.
*E-mail address:* bjt@apep.uci.edu (B. Tarroja).

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numbers. This application involves allowing electric vehicle batteries to both charge and discharge electricity back to the grid within the constraints of maintaining enough range to meet consumer travel demands, called V2G (vehicle-to-grid) charging. Since electric vehicles are already being deployed to meet transportation sector emissions targets independent of the evolution of the electric grid, allowing V2G integration of these vehicles poses an opportunity to leverage already-deployed storage capacity for meeting renewable utilization targets.

The use of V2G charging and discharging of electric vehicles to support renewable integration, however, is distinctly different than the use of SES (stationary energy storage) systems for the same purpose in many key ways. While SES systems can be charged and discharged freely within the constraints of their energy capacity, the charging and discharging of electric vehicles is constrained by additional factors which can limit the ability of these vehicles to support renewable integration. For example, the capacity available for charging and discharging electric vehicles varies in time since the number of vehicles plugged into the electric grid is different at each hour and the state of charge of each vehicle when it is plugged in is also variable. This is an artifact of consumer travel patterns and the need to meet vehicle travel demands. Therefore, the flexibility afforded by V2G capacity may be less than that for SES capacity, and therefore equal capacities of energy storage as stationary systems or in V2G-integrated electric vehicles may not have equivalent benefits for the electric grid.

With these differences in mind, the primary problem of interest is to understand how the differences in characteristics between stationary energy storage and V2G-integrated electric vehicles affect their relative ability to support renewable integration into the electric grid. This is relevant for policy considerations such as AB 2514 [5] in California which are attempting to set energy storage procurement targets. Addressing this problem provides insight into whether V2G vehicles should count towards meeting energy storage capacity targets, and if so, how a unit of capacity of these vehicle batteries is represented compared to the same capacity in an energy storage system.

The primary objective of this paper is to determine how equivalent capacities of energy storage systems deployed as either stationary energy storage or V2G-integrated vehicles impact system renewable penetration, greenhouse gas emissions, and balancing power plant operation in scenarios with large capacities of installed renewable generation. This will be accomplished by modeling of the dispatch of stationary energy storage systems of different types, modeling of electric vehicle charging dispatch as constrained by travel patterns, and integrating these into a larger model of the electric grid to compare their impact.

This study adds to the state of knowledge regarding energy storage systems for renewable integration support by quantifying differences in the benefits and impacts of stationary energy storage compared to V2G-integrated vehicles. The notion of V2G-integrated vehicles not being identical to stationary energy storage systems has been mentioned qualitatively and speculated about in previous studies [6], but an actual examination of how these applications are different and what those differences signify for renewable grid deployment is not well-represented in the literature.

## 2. Background

The impacts of V2G dispatch of electric vehicle charging have been studied from a wide variety of perspectives.

Some studies have focused on the benefits of V2G-enabled electric vehicles for aiding the integration of renewable resources into the electric grid. The concept of using V2G-enabled vehicles in this manner was described by Kempton [7]. Lund and Kempton [8] examined the benefit of adding V2G technology to electric vehicles in Denmark using the EnergyPLAN model with respect to increasing the integration of wind power into the Danish electricity system. This study found that enabling V2G decreases the level of excess generation from wind power and allows higher utilization of wind resources in the electricity system, and that higher battery capacities further improve this benefit. Further, it was also found that using V2G in combination with regulation of CHP (combined heat and power) plants further reduced excess generation and increased wind power utilization. Haddadian [9] examined the use of V2G for allowing higher penetrations of variable renewable resources without compromising system security using a model which resolved the dispatch of grid resources. This study found that V2G-enabled vehicles perform well at smoothing out the variability of renewable generators, which has the benefits of reducing operation costs, emissions, and increasing uptake of wind generation.

Many studies have highlighted the role of V2G-enabled electric vehicles in providing electric grid services such as frequency regulation and peak-load shaving. Udrene [10] used the EnergyPLAN model for the Latvian electricity system to examine V2G-enabled vehicles providing peak-shaving services, showing that annual $CO_2$ reductions of 100 kg per passenger car can be achieved with 11% of the vehicle battery capacity providing these services. White [11] explored the financial aspect of frequency regulation and peak-load reduction services provided by V2G-enabled vehicles. It was found that the incentive for provision of peak-load shifting but potentially large returns are possible for provision of regulation services, and it is suggested that programs which enable both services provide the largest financial returns. Sekyung [12] focused on developing an aggregator for enabling the provision of frequency regulation by V2G-enabled vehicles which optimally determines the charging control of each vehicle connected to the system. Noori [13] examined the greenhouse gas emissions and net revenue benefits for different ISOs (independent system operator) and RTOs (regional transmission organizations) for electric vehicles using V2G-enabled charging to provide frequency regulation services up to 2030. This study found that significant emissions savings and revenue benefits can be garnered by this application. Zhao [14] examined the net present revenue and greenhouse gas mitigation impacts of using electric delivery trucks to provide frequency regulation services using V2G charging taking into account life cycle impacts, and also found significant greenhouse gas reduction savings and revenues from this application. Zhao [15] had also examined the use of electric trucks providing frequency regulation services through V2G considering battery degradation impacts and corresponding life-cycle emissions, also finding that significant greenhouse gas emissions savings are present from this application.

Studies have also focused on using V2G-enabled vehicles for stabilizing the operation of electric grid systems. Drude [16] examines the use of V2G-enabled vehicles to provide peak demand reduction in an urban electricity system in Brazil with high penetrations of solar photovoltaic to stabilize electric load fluctuations. This study concluded that the use of V2G-enabled vehicles can reduce grid operation costs and have a high potential for stabilizing electric load fluctuations, but realizing potential benefits requires an adequate energy policy strategy to prevent interference from different stakeholders. Fathabadi [17] examined the use of V2G-enabled vehicles with renewable distributed generation on an electric distribution system using a power flow model. This study found that V2G-enabled vehicles can decrease the overall cost of power production and circuit losses while also improving the voltage power. When combined with renewable DG, power losses are reduced even further. Lopez [18] examines the use of V2G-