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PEVs Meet Balancing Requirements for Integrating Renewable Power Technologies: How Does Customer Behavior Influence the Resource Availability?

Michael Kintner-Meyer[1], Francis Tuffner
[1]*Pacific Northwest National Laboratory, Richland, WA, USA, michael.kintner-meyer@pnnl.gov*

Abstract

Smart charging and Vehicle-to-Grid application can provide balancing services for grid operators to accommodate the variable output from wind and solar generation resources. With the nation's aspiration to increase the generation mix of renewable energy sources, the balancing requirements are expected to grow in accordance.

A recent study for the Pacific Northwest in the USA estimated the number of vehicles necessary to accommodate the incremental balancing requirements for a 2020 grid that would meet the states' renewable portfolio standards. This study assumed customer driving behavior based on statistics using conventional vehicles. This paper will focus on customer behavior from very recent American Recovery and Reinvestment Act (ARRA) charging monitoring studies that reveal how customers drive EVs and EREV (extended range electric vehicle), and when they are plugging vehicles into the power supply.

Explored will be uncertainties associated with customer driving and charging behavior and the impacts on its resource availability to provide services to the grid as a smart load or as V2G resources. The results provide key insights to grid operators to assess the value and certainty of the emerging resource. It also provides important insights to policy makers and customers to understand what the potential value and revenue expectations for advanced grid services using EVs, EREVs, and PHEVs could be.

Keywords: BEV, V2G, dynamic charging, smart grid, power management

1 Introduction

Renewable portfolio standards are driving significant deployments of wind and solar generation. Unfortunately, wind and solar generation sources often have significant variability in the output[1]. Lulls in the wind and clouds across the photovoltaic panel can significantly reduce the output of such generation sources. Conversely, a sudden gust of wind can create an excess in generation that is difficult to manage from grid operations perspective. Such fluctuations can have significant impacts on the power system[2]-[4]. To stabilize and mitigate these fluctuations, storage or reserve generation is often required [5][6].

The emerging electric vehicle (EV) fleet has significant potential as a flexible load and as an energy storage resource to mitigate the fluctuating energy production from wind and solar technologies [7]. With appropriate hardware, the vehicle can even provide power into the grid, much like a generator. With an appropriate control technology and control strategy, the vehicle could offer these grid services as long as the vehicle is fully or sufficiently charged when the vehicle owner needs it. In the time between connection to the grid and departure, which may be hours, the battery can be charged and discharged at a variety of rates and schedules and still meet the 100% state-of-charge requirement at departure.

Electric vehicles can provide benefit to the local power system by controlling the charge and discharge rates of the battery in response to grid stress. Several approaches to this problem exist, including centralized and decentralized control schemes [8]-[10]. As part of the Grid Friendly Charger technology development at the Pacific Northwest National Laboratory (PNNL), one such decentralized scheme was developed.

The PNNL Grid-Friendly Charger incorporates a charging and discharging method described as a "regulation-services" mode, or vehicle-to-grid (V2G)[10]. In this operating mode, local indications of grid stress, such as frequency, are utilized to vary the charging and discharging rate for an electric vehicle. Utilizing this autonomous, decentralized control scheme, a population of electric vehicles can help meet the additional imbalance and variability in power generation caused by renewable generation sources.

This paper explores utilizing electric vehicles to help offset the additional imbalance requirements associated with the capacity expansion from 3.3 GW (2008) to 14.4 GW (projected in 2019) wind generation into the Northwest Power Pool (NWPP) in the United States (~11 GW additional). A previous report explored meeting this imbalance using National Household Travel Survey (NHTS) data as a basis for electric vehicle behavior [11][12]. With measured data from the Idaho National Laboratory (INL) EV Project [13], this paper discusses the number of EVs required for meeting the future balancing requirements based on observed driving and charging behavior.

The INL EV project provides data on actual charging behavior. It also includes information on the times a vehicle is physically connected to a charging station, and therefore available as a grid resource. The results obtained from these measurements are compared against the original, NHTS-based simulations to explore how actual customer charging behavior affects the number of vehicles needed to mitigate of the additional imbalance associated with renewable generation sources.

The rest of this paper is divided as follows: Section 2 describes the approach used in the simulation, including the underlying data sets and methodology. Section 3 presents results from the different simulations. Finally, the paper concludes with Section 4.

2 Approach

To investigate the benefits EVs can provide the grid, their charging behavior needed to be simulated. All simulations were carried out in an identical manner, but using different base populations or underlying population behaviors. The subsections that follow will provide details on the different aspects of the simulation.

2.1 Simulation Environment

All simulations were carried out in the Mathworks MATLAB environment. Each vehicle was individually simulated over a 10-day period and aggregated into a total population. Individual charge and discharge rates, states of charge, and vehicle locations (e.g., work, home, driving) were all tracked during the simulation runs.

Simulations conducted varied a parameter of the vehicle population. All other parameters of the simulation were held constant. For example, the percentage of EVs that utilize a V2G charging scheme were varied. However, other variables, such as the departure/arrival schedule of those vehicles, were fixed for each V2G penetration level. This ensures changes in the total number of EVs needed to mitigate the renewable generation are associated with a specific parameter

2.2 Wind Imbalance Data

The V2G-based EV population is trying to offset the variability associated with increased renewable generation sources on the power system. In this case, about 11 GW of additional wind generator has been added to the NWPP to represent a 2019 scenario. The introduction of the additional wind generation resulted in additional power balancing requirements on the power system. These additional requirements were developed from a stochastic-based methodology detailed in [14]. Fig. 1 shows a single day of the estimated additional balancing requirements.

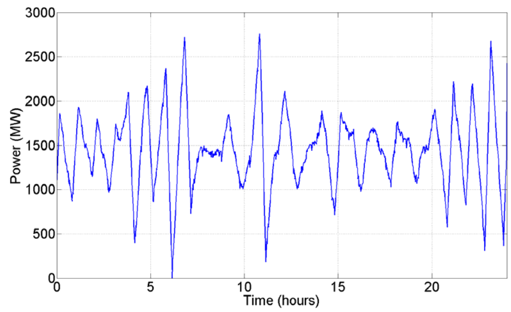

Figure 1: Additional Balancing Requirements for 2019 Wind Deployment Scenario

For the charging and discharging strategy employed by this study, frequency of the power grid is used as a measurement of local grid stress. The additional balancing requirements shown in Fig. 1 were converted to frequency deviations using a variation of the swing equations in power systems:

$$\frac{\Delta P}{D} = \Delta f \ . \qquad (1)$$

In equation (1), ΔP is the change in power, D is a load-damping constant, and Δf is the change in frequency [15][16]. For this study, D was selected to be 94.74 GW/Hz and the base frequency is assumed to be 60 Hz.

2.3 Vehicle Population

To fully capture the uncertainties of customer charging and driving behavior, each individual vehicle was simulated separately. While the charging schedule varied, most of the other vehicle parameters were drawn from a common set.

Battery efficiency and sizing were one such common parameter. All vehicles in this simulation were assumed to be battery electric vehicles designated as BEV-110 vehicles. This assumes the battery has the capacity to optimally drive 110 miles on a single charge. Different vehicle sizes have different efficiencies on the amount of energy needed to travel a single mile. Table 1 shows the four different vehicle types used in this simulation, along with the estimated efficiencies [17][18]. Battery sizes, in kWh, were obtained by scaling the per-mile efficiencies to the 110-mile desired range. For example, a compact car requires a 28.6 kWh battery to meet the 110-mile range (0.26 kWh/mile * 110 miles).

Table 1: Vehicle Types and Efficiencies

Vehicle Type	Energy Efficiency (kWh/mile)
Compact	0.26
Mid-size	0.30
Mid-size SUV	0.38
Full-size/Pickup	0.46

All vehicles simulated are assumed to have access to level 2 AC charging at both home and work. All simulated vehicles cycled their charge and discharge rates based on the Grid Friendly Charging Controller (GFCC) V2G scheme developed at PNNL. Using the simulated frequency given in Section 2.2, the GFCC adjusted charge rates in response to grid stress and customer constraints (when to finish charging). Fig. 2 shows an abbreviated response of a typical charging cycle. Notice that the battery is both charging and discharging during this period, an indication of full V2G capabilities.

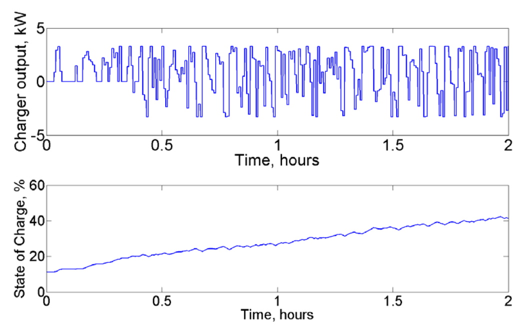

Figure 2: Example V2G Charge Cycle

Availability of the vehicles to operate in V2G mode was governed by two data sources. The first source uses survey data from the 2001 NHTS report [12]. The second source uses information from the INL EV Project report [13]. These two data sources provided the arrival and departure times of the individual vehicles, dictating the overall charging constraints to the system.

2.3.1 NHTS Data

The previous study used availability data extracted from the 2001 National Household Travel Survey [12]. This survey was not specific to electric vehicles, but provided general guidance on typical driving behavior.

The first item NHTS data provided was the arrival and departure times for different vehicle types and settings. Electric vehicles were mapped to random entries in this data set. All vehicles were assumed to have charging capabilities whenever at home or work. Furthermore, departure from home was always assumed to be to work, and departure from work was always assumed to be to home. Fig. 3 shows a small subset of the NHTS data. Transit times were variable, per the NHTS data, but no explicit incidental trips were modelled in this study.

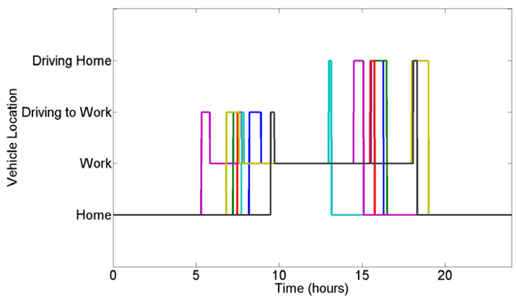

Figure 3: Sample 2001 NHTS Data

Distances from the NHTS data were utilized to discharge the BEV battery. Using the efficiencies of Table 1, the appropriate quantity of energy was deducted from the BEV battery any time a work-to-home or home-to-work trip occurred.

2.3.2 EV Project Data

To add more realistic behavior to the charging of the electric vehicles, information from the INL EV Project was obtained [13]. The EV Project is a U.S. Department of Energy project monitoring various aspects of Chevy Volt and Nissan Leaf electric vehicles. One aspect is the charging behavior of the electric vehicle customers.

The EV project provided two sets of data to further examine the additional uncertainties of realistic EV charging and customer behavior. The first data set is the aggregated charge of the full population of 2690 Nissan Leaf vehicles on a day of peak charge demand. This data was made available in February 2012. This data set is shown in Fig. 4. It is important to note that this data encompasses many cities, not just those in the Pacific Northwest. However, individual cities followed similar demand profiles.

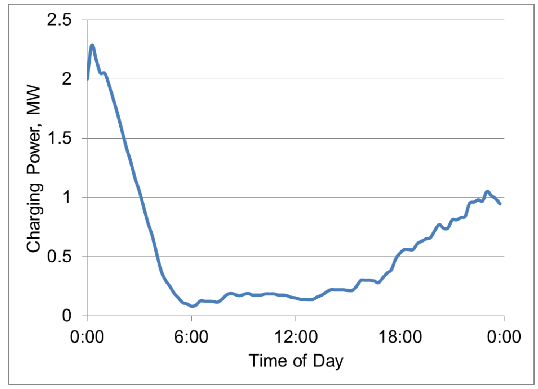

Figure 4: Peak charging demand from EV Project data

The second data piece from the EV Project is detail on times an EV is connected to a charging station. This is similar to the arrival and departure times of the NHTS data, but derived from actual measured quantities. Unfortunately, the data from the EV Project is only publicly available as the aggregate population. Individual vehicle behavior is not available.

To extrapolate individual behavior from the data, the 2001 NHTS data was utilized. A 1000-vehicle subset was taken from the NHTS data. This subset was fit via a least-squares technique. The technique solved for the number of individual vehicles in 1000-vehicle subset needed to create an aggregate availability profile that matched the EV Project data. Fig. 5 shows the extracted EV Project data, as well as the least-squares fit of NHTS data.

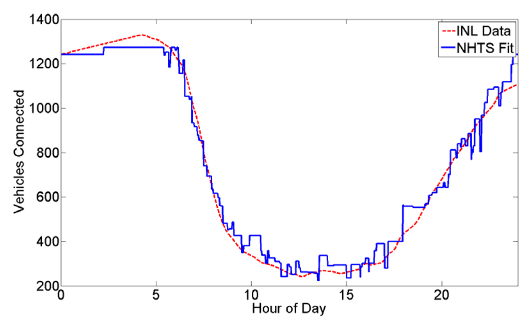

Figure 5: EV Project vehicle availability and NHTS-fit data

Given the individual behavior's origins in the NHTS data, distances associated with those specific vehicles were utilized in the EV Project data set. Average travel distance and statistics on the distances are available in the EV Project report, but consistency with travel times required the associated NHTS distances to be used.

Once the populations of electric vehicles under various availability scenarios were simulated, the output results needed comparing. The underlying goal of the simulations was to determine the number of electric vehicles to aid the integration of about 11 GW of additional wind in the NWPP.

The number of vehicles required to meet the future balancing requirements begins with an aggregate charge curve. Each individual vehicle's charging power is accumulated into a data set similar to Fig. 4. This accumulated curve was mathematically divided into the balancing requirements data of Fig. 1 to determine the scaling of the initial EV population needed. This population scale was used to provide an equivalent charging profile for larger populations of EVs. The energy difference between this charging profile and Fig. 1 was used as a parameter to describe compliance with the future balancing requirements (see Fig. 6). Note that Fig. 6 is the ideal, stationary storage (100% availability) simulation case.

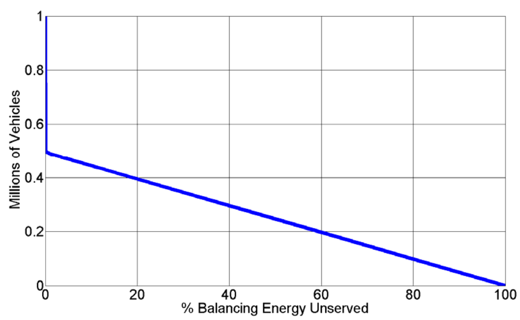

Figure 6: Number of Vehicles as a Function of Balancing Energy Unserved – assuming stationary storage or V2G

As the population of EVs increases, more of the additional balancing requirements associated with the wind generation are met. As such, the energy not served is decreased.

3 Results

Simulations for a variety of different scenarios were carried out. For each data set, the balancing energy unserved associated with the future balancing requirements of the 14.4 GW of wind generation was determined. These values were plotted to examine the impacts real EV behavior has on previous assumptions. With the same grid stress signal, only changes in the population and its behavior will produce changes on the unserved energy curves.

3.1 NHTS-based Charging

The first scenario examined is utilizing a 1000-vehicle population based on the 2001 NHTS data. The authors' previous wind integration study utilized this same data set, but under different charging scenarios [11].

Fig. 7 shows the compliance to meet future balancing requirements. As one would expect, the amount of balancing energy unserved decreases as the number of vehicles increases. With a larger population of EVs, the resource availability increases and more of the additional balancing requirements can be met.

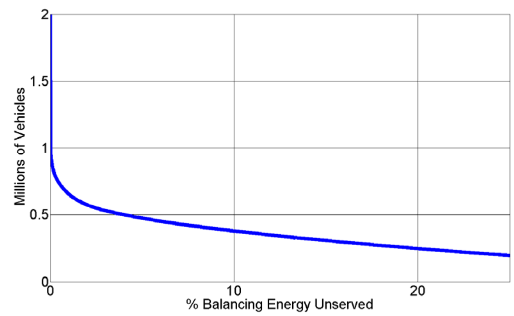

Figure 7: Number of Vehicles as a Function of Balancing Energy Unserved – NHTS population

Fig. 7 serves as a baseline for this study. It incorporates the energy requirements of individual vehicles, as well as survey-based customer behavior data. Compared to the stationary storage case of Fig. 6, it is clear that a larger population is required. Decreased resource availability associated with driving times and full batteries requires a larger population to meet the additional balancing requirements. However, the vehicle information is based off of normal, petroleum-powered transportation and may not accurately reflect EV customer behavior.

3.2 Measured Charging Behavior – EV Project

The first EV Project data set was the aggregate charge curve for all Nissan Leaf vehicles in the project, as was shown in Fig. 4. No individual simulation took place for this section. The underlying vehicle population of 2690 vehicles was scaled to various levels to examine the balancing energy unserved at each population point. Fig. 8 shows the results of the simulation.

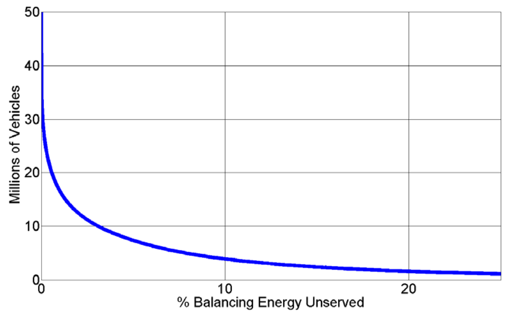

Figure 8: Number of Vehicles as a Function of Balancing Energy Unserved – Measured EV Project population

Using measured data of EV charging, the curve of Fig. 8 does not appear to differ significantly from Fig. 7. While the overall shape of the energy curve is the same, the populations associated with it are vastly different. The measured data indicates nearly 20 times as many vehicles are needed to meet the additional balancing requirements.

The significantly larger population is likely a result of two differences with Fig. 7. Vehicles in the EV Project demonstration are not charging in a "grid-sensitive" manner. That is, they are not responding to local grid stress, so may be over charging during periods the grid requires relief. The vehicles are serving customer constraints first, with little regard to impact on the grid.

The second significant contributor is charging availability. Vehicles in the EV Project (Nissan Leafs, for this data set) are designed to delay charge until after midnight. The result is low resource availability during the day and early evening hours. To meet the additional balancing requirements associated with these time periods, significantly more vehicles are required to be available.

3.3 Recorded Availability

The next simulations utilized the extrapolated INL EV Project availability to simulate a population of V2G-capable EVs. These vehicles are simulated in a manner similar to the NHTS-data population earlier, with individual energy requirements and customer departure constraints governing the charge.

3.3.1 Diverse BEV Results

To provide a comparable simulation to the NHTS data, the EV Project availability is first applied to a diverse vehicle population. Like the NHTS data, this population is composed of all four vehicle types shown in Table 1. The result is a different overall energy capacity of the EV fleet, with larger SUV batteries requiring (and potentially providing) more energy to the grid.

Fig. 9 shows the unserved portions of the additional balancing energy requirements for the diverse population. With the ability to vary their charge rate and respond whenever connected (including during the day and early evening), the EV population is significantly lower than the population of Fig. 8. Greater resource availability allows the electric vehicles to provide more energy storage to the grid, offsetting more of the imbalance associated with the 11 GW of additional wind.

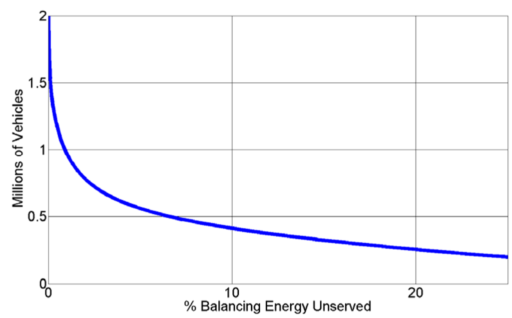

Figure 9: Number of Vehicles as a Function of Balancing Energy Unserved – Diverse population

3.3.2 Compact Car Results

To be more in line with the measured results of Fig. 8, the EV Project availability was used on a second vehicle population. Rather than being a diverse mix of vehicle sizes, all vehicles were fixed to a 110-mile compact car. This should be synonymous with the Nissan Leafs currently deployed in the EV Project.

As Fig. 10 shows, even with similar battery sizes, the population required is still significantly lower than that of Fig. 8. This again is due to greater resource availability. Even though a smaller battery capacity is available, the ability for the vehicles to respond to wind energy imbalances is vastly increased. Allowing GFCC-based V2G charging during the daytime and early evening hours reduces the number of vehicles required to offset the additional wind balancing requirements.

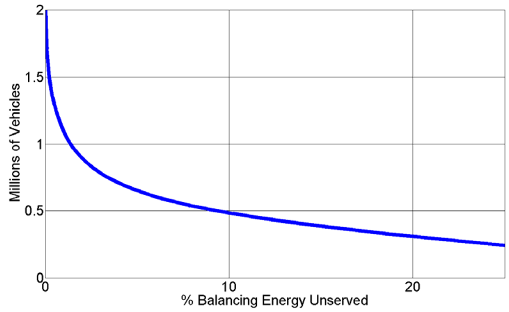

Figure 10: Number of Vehicles as a Function of Balancing Energy Unserved – Compact car population

3.4 Simulation Comparison

The simulation results for Fig. 7, Fig. 9, and Fig. 10 are all very similar. To determine the impacts the customer variability had on the required population, a direct comparison is necessary. Fig. 11 shows the overlay of the different simulations, as well as the ideal, stationary storage case.

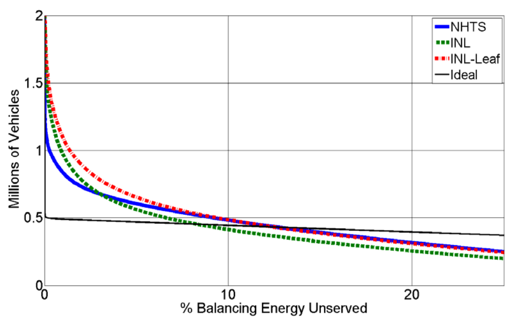

Figure 11: Number of Vehicles as a Function of Balancing Energy Unserved – Simulation comparison

Clearly the EV Project availability is increasing the required number of vehicles to meet the additional balancing requirements. Both the EV Project availability (INL) and EV Project with compact car (INL-Leaf) curves require more vehicles than the base NHTS simulation to meet the full energy requirements.

Given the EV project charging behavior, the previously estimated numbers of vehicles necessary to accommodate the future balancing requirements are about 50 percent higher than those using NHTS data sets. This is primarily attributable to more diversity and different charging times than were inferred from the NHTS data. The NHTS data was also fundamentally based around traditional petroleum-fueled vehicles, so customer behavior associated with EVs may not have been accurately represented.

It is useful to point out how much the variability of vehicle use influences the required number, in general. The diversity in the charging behavior and availability as a grid resource requires nearly double the amount of storage (as embodied in vehicles) compared to a stationary resource with a 24/7 availability. The use of measured EV Project availability further refines this customer variability's impact on the simulation results.

4 Conclusions

From the impact of overall balancing energy unserved percentages, the additional variability of real customer use appears to have minimal impact on the use of EVs as a grid resource. The largest factor is the nature of the charging. Charging the vehicles with a simple dispatch scheme and "grid agnostic" method required significantly more vehicles than any other situation. Previous work demonstrated that by adding simple intelligence to the charging hardware, the ability in help integrate renewables is significantly improved [11].

Under ideal situations, the EV Project availability increased the required vehicle count by approximately 50% (to achieve 100% energy served). While the numbers are higher, the behavior is not significantly different than the NHTS data used in earlier situations. The results indicate that the EV Project customer behavior causes resource availability to be less than that of the NHTS simulations, and should serve as a more conservative estimate than NHTS-derived data.

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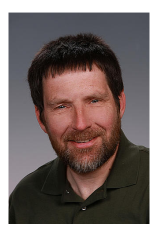
Authors



Michael Kintner-Meyer received a Ph.D. in Mechanical Engineering from the University of Washington and a MS in Engineering from the University of Aachen, Germany. Dr. Michael Kintner-Meyer, is Staff Scientist at the Pacific Northwest National Laboratory. He leads the Laboratory's grid analytics for energy storage and manages the Laboratory's electrification of transportation research.

Francis Tuffner received his Ph.D. in electrical engineering from the University of Wyoming in 2008. He is currently with the Pacific Northwest National Laboratory as a power system engineer. His research interests include signal processing applied to power systems, PHEV integration, and embedded control devices.