Using Electric Vehicles to Mitigate Imbalance Requirements Associated with an Increased Penetration of Wind Generation

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***Abstract*--The integration of variable renewable generation sources continues to be a significant area of focus for power system planning. Renewable portfolio standards and initiatives to reduce the dependency on foreign energy sources drive much of the deployment. Unfortunately, renewable energy generation sources like wind and solar tend to be highly variable in nature. To counter the energy imbalance caused by this variability, wind generation often requires additional balancing resources to compensate for the variability in the electricity production. With the expected electrification of transportation, electric vehicles may offer a new load resource for meeting all, or part, of the imbalance created by the renewable generation.**

This paper investigates a regulation-services-based battery charging method on a population of plug-in hybrid electric vehicles to meet the power imbalance requirements associated with the introduction of 11 GW of additional wind generation into the Northwest Power Pool. It quantifies the number of vehicles required to meet the imbalance requirements under various charging assumptions.

***Index Terms*—electric vehicle, imbalance requirements, renewable integration, vehicle-to-grid, wind generation.**

I. Introduction

RENEWABLE generation sources are being deployed at a significant rate. Much of the drive comes from mandated renewable portfolio standard. As a mitigation strategy to climate change. Renewable generation sources, such as wind and solar, provide a carbon-free solution for generating electricity domestically.

One downside of wind and solar generation sources is the 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. . These 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].

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Traditionally, the energy storage and reserve generation resources are on the transmission network directly. However, end use loads can also be used to meet this imbalance[7]. The emerging electric vehicle fleet provides a significant resource that could be used to meet these imbalance requirements[8]. Unlike traditional demand response schemes, an electric vehicle has greater flexibility to be scheduled as a load to accommodate grid needs. The end requirement is typically to have a full battery by a specific time. In the time between connection to the grid and departure, which may be hours, the battery can be charged at a variety of rates and schedules and still meet the 100% state-of-charge requirement at departure.

One method for providing grid benefits through electric vehicle charging is to utilize some form of control to vary the charge rate in response to grid stress. Many approaches to this problem exist, including centralized and decentralized control schemes [9]-[11]. 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 method described as a "regulation-services" charging mode, or vehicle-to-grid 0.5 (V2G-HALF)[11]. In this charging mode, local indications of grid stress, such as frequency, are utilized to vary the charging 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.

In this paper, V2G-HALF-based charging is simulated on a population of electric vehicles to help offset the additional imbalance requirements associated with the introduction of 11 GW of additional wind generation into the Northwest Power Pool (NWPP) in the United States. A previously generated wind imbalance signal is utilized, along with National Household Travel Survey data, to investigate the benefits a population of plug-in hybrid electric vehicles (PHEV), or battery electric vehicles (BEV), can provide in the mitigation of the additional imbalance associated with renewable generation sources.

The rest of this paper is divided as follows: Section II describes the approach used in the simulation, including the underlying data sets and methodology. Section III presents a subset of the results from the different simulations. Section

IV provides conclusions from these results. The paper concludes with Section V, which outlines future work for these investigations.

II. APPROACH

The investigation into electric vehicle benefits for renewable resource integration is performed by means of a simulation using Mathworks MATLAB environment [12].

Simulations in MATLAB involved two primary steps. The first is, of course, to obtain the underlying data and assumptions of the simulation. This took the form of a power imbalance signal and information about the underlying vehicle population. The details of these data sets are explained in the following section. Once this external data was secured, the overall methodology for the different simulation studies could be performed.

The second step of the MATLAB simulations involved the simulation itself. Each simulation was performed under a similar framework, with different population characteristics or settings modified. The details for this approach are in Section 2.B.

A. Data

1) Imbalance Signal

To estimate the benefits PHEVs and BEVs may bring to the grid, a suitable imbalance signal was required. PNNL developed a stochastic-based methodology for creating future imbalance signals on the power grid [13]. For this paper, an imbalance representing 11 GW of wind generation in the NWPP is used. The NWPP is includes the states of Washington, Idaho, parts of Montana, Oregon, and Utah.

The imbalance of the power output from the NWPP study was offset appropriately so that all of the requirements can be met by a load. This assumed that some baseload power plant would be dispatched to produce the additional energy in the amount of the offset. Using this offset, the final imbalance output was available. A 1-day sample of the imbalance for August 2019 is shown in Fig. 1.

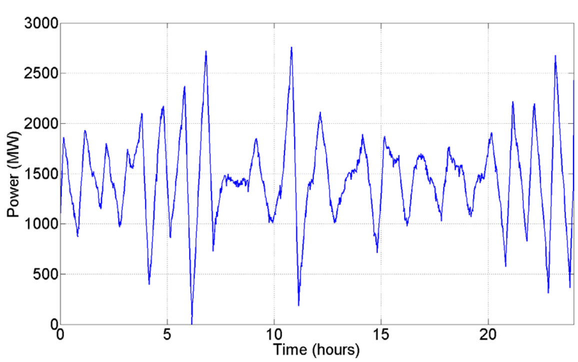

Fig. 1. Single day of wind imbalance data in NWPP

For the purposes of this study, frequency of the power grid is used as an indication of overall stress and imbalance. The imbalance signal from the NWPP simulation is translated into a frequency term using the equation

$$\frac{\Delta P}{D} = \Delta f \tag{1}$$

where ΔP is the change in power, D is a load-damping constant, and Δf is the change in frequency [17][18]. For this study, D was selected to be 94.74 GW/Hz.

2) Vehicle Population and Behavior

With a suitable imbalance signal obtained, a characteristic population was necessary. To provide a realistic basis and reflect actual driving patterns, the population was built on information from the Department of Transportation's 2001 National Household Travel Survey (NHTS) [19]. The 2001 NHTS data represents a sample of 26,038 national samples from a total of 69,817 households. The survey includes many measurements, including trip distance, departure and arrival times, vehicle occupancy, and many others. However, a very small subset of this data was necessary for this research.

To evaluate the impact of electric vehicles for renewable integration, the first set of interest from the NHTS data is the departure and arrival times of vehicles. In order to provide benefits to the grid, an electric vehicle must somehow have a physical connection to the grid. With time information about the vehicles, it is possible to extrapolate when the vehicle is parked at either home or work, and available for charging and grid services. Furthermore, the departure time provides information about how long the vehicle will be available at a given location, which aids in the charging algorithms. Fig. 2 shows the data associated with a small subset of the population.

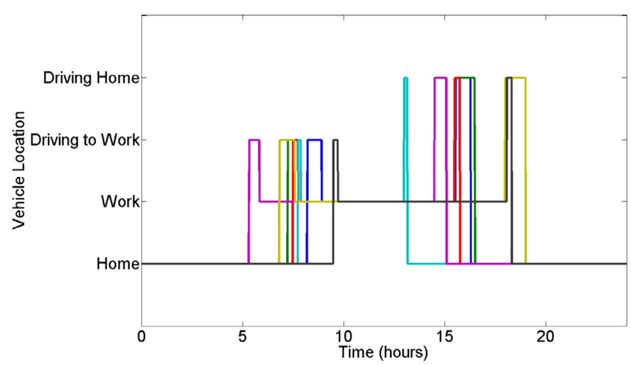

Fig. 2. Sample data from 2001 National Household Travel Survey

The other item of interest from the NHTS data set is the distance vehicles traveled. One of the key aspects of this study is to incorporate the energy requirements of the electric vehicles. When a vehicle is stationary, it is able to charge and work towards a 100% state-of-charge on the batteries. However, for this resource to be available to occur the next day or after a commute to or from work, a discharge must also occur. With the distance information, the amount of energy required to move the vehicle from one location to another can be deducted from the vehicle's state of charge. This information helps provide a more realistic basis for electric vehicle utilization, as a 100% state-of-charge (full battery) means the vehicle can no longer accept power from the electric grid.

B. Methodology

Once all of the proper data was available, the actual simulations could proceed. Despite investigating many different parameters, all simulations followed the same framework. This similar framework aids in comparing the different parameter adjustments, as all data sets should be run on an identical population and under identical conditions (aside from the parameter changes). Simulations began with initializing the vehicle population. Once initialized, time-series modeling of the various actions of the electric vehicle occurred. Once complete, analysis of the results could begin.

The framework begins with the initialization of the vehicle population. All parameter investigations in this report utilized a 1000-vehicle population. This population was selected as 1000 random travel profiles from the NHTS data. While the initial selection of the 1000 vehicles was randomized, all subsequent studies utilized the same 1000-vehicle basis. The underlying properties of the vehicle population remain fixed (unless explicitly modified by a parameter change) for the rest of the simulations. This helps ensure that any changes observed are predominately caused by the parameter adjustments and not a particular sampling of the NHTS vehicle population.

With the 1000-vehicle population obtained, initial properties for each of the vehicles were also assigned. The first parameter of interest was the vehicle type. This was divided into the four categories shown in Table I. Also listed in Table I are the "energy efficiencies" of that vehicular class, as determined from publications of the Electric Power Research Institute's (EPRI's) Hybrid Electric Working Group [20][21]. This information was necessary as all battery sizes in the study were determined by "optimal range," rather than direct capacity in kWh. That is, all vehicles may be labeled as a 33-mile PHEV (PHEV-33). Obviously, a larger vehicle like an SUV would need a larger battery. However, coupled with the efficiency in Table I, this larger battery is functionally equivalent in range to a compact car's battery. Variations in the population's battery size are feasible, but were ignored in this study to keep things simplified.

TABLE I. 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

For all scenarios and comparisons in this study, two primary battery sizes were utilized. The first was a PHEV-33-based size. This size represents a plug-in hybrid electric vehicle that is expected to go approximately 33 miles before requiring a recharge, or an alternative energy source (such as an internal combustion engine). The second battery sized utilized was a PHEV-110 battery size. Similar to the PHEV-33 notation, this is a vehicle that is expected to go 110 miles before a recharge or alternative energy source. The designation PHEV-110 is not necessarily accurate for these scenarios, since the battery size was selected to be similar to upcoming battery electric vehicles (BEVs), such as the Nissan Leaf or BMW Mini-E.

Once a proper battery size was obtained, the vehicle's current state of charge was randomized. As part of this randomization, it is often necessary to remove the first day of simulation results from each parameter investigation to mitigate initialization problems. This first day is often used to initialize the population into its charging routine, so some abnormal behavior is often present.

It should also be noted that vehicle battery sizes and states of charge are calculated as the fully available capacity. That is, a 3.0 kWh battery is assumed to have all 3.0 kWh of energy available for use. The industry practice of keeping a battery in an optimal state of charge band (i.e., 25% to 90% [22]) to extend life is not utilized here. One can reasonably assume that the battery capacities mentioned could merely be an "adjusted battery size". That is, the 3.0 kWh battery is really a 4.62 kWh batter, but only 3.0 kWh is normally available for use.

Throughout the simulation process, electrical efficiencies were also considered. Table II shows the assumed electrical efficiencies for various portions of the model [23]. "Battery Charging" and "Battery Discharging" were predominately used in adjustments to the batteries' state of charge during charging and discharging operations. For example, if 1.0 kWh of energy were put into a battery during the charging process, only 0.85 kWh worth of actual capacity would be added to the current state of charge (the other 0.15 kWh is assumed lost to heat). "Power Transmission" is not influential on the actual battery state of charge, but serves as an overall scale value for aggregate charging curve. That is, if a vehicle population requires 10 kW of instantaneous power, transmission efficiencies mean this actually requires 10.86 kW of power generated.

TABLE II. ELECTRICAL EFFICIENCIES

Process	Efficiency (%)
Battery Charging	85%
Battery Discharging	87%
Power Transmission	92%

Utilizing the departure and arrival times from the NHTS data, a vehicle's location was constantly checked. If the vehicle was located at home, it was available for charging. If the vehicle was located at work, it would be available for charging only if work charging was available (a parameter of study is the availability of work charging). At each of these locations, the actual charge rate was determined by the availability of 240 Volts, or Level-2, charging at that location. If 240 Volts was available, a charge rate of 3.3 kWh was assumed (240 Volts at 13.75 Amps). If 240 Volts was absent, a 120-Volt connection was assumed and a charge rate of 1.7 kWh utilized (120 Volts at 14.2 Amps). Other charge scenarios, such as Level-3 DC charging or 240 Volts at 30 Amps were not considered in this study.

If a vehicle was not located at home or work, it was considered in transit. At the beginning of every transit period, the state of charge was immediately adjusted. That is, as soon as a vehicle departed work or home, the necessary energy for the entire trip was deducted from the battery's state of charge. For example, if a compact car had a 10 mile commute, it is assumed to need 2.99 kWh (after efficiency) of capacity to get there. This amount was deducted immediately upon leaving home, with the rest of the commute not affecting the state of charge. The state of charge could be slowly adjusted over the course of the trip, but the focus of this report is only on power impacts on the grid. These impacts are only present when the vehicle is stationary (at work or home), so the commute deductions can be handled many different ways without affecting the study results. As long as the proper energy is deducted from the battery (to allow charging to resume at the new location, if available), no ill effects are introduced. It is also useful to note here that vehicles are assumed to be PHEVs. That is, if a commute requires more energy than is available in the battery, it is assumed that a combustion engine of some sort allows the commute to finish.

Despite the many different parameters of the simulation, only two primary charging scenarios are simulated: dumb charging and vehicle-to-grid-half (V2G-HALF). Dumb charging had no charge limiting controls in place. If a vehicle was plugged into a 120-Volt source, it immediately begins charging at 1.7 kWh until 100% state-of-charge is reached (or the charging period ends). For the purposes of this study, no time-of-use (TOU), critical-peak-pricing (CPP), or other deferred charging schemes were implemented. This study is investigating the pure potential of electric vehicles to help integrate renewable generation sources, without considering system-loading limitations.

Vehicle-to-grid-half switches the charger into a regulation-based charging mode. Using indications of the grid stress (frequency deviations, in this case), the charge current is adjusted. If a rise in frequency occurs, this indicates an excess of generation. As such, a charger employing V2G-HALF would increase its charge rate to help offset this imbalance. Conversely, if the frequency dropped (indicating a generation short-fall), the charge rate would be reduced. Throughout all of these changes, customer satisfaction is an underlying goal. As such, the algorithm restricts the range of charger variation to try and meet a full battery charge by the imposed deadline (the next commute to or from home). For example, if a vehicle was schedule to go to work in 30 minutes, the V2G-HALF algorithm would bias the charge variations such that a full charge condition is met. Fig. 3 shows a sample V2G-HALF charging scenario. Note the decrease in variability at the 1.8-hour mark as the "charge-by" deadline approaches.

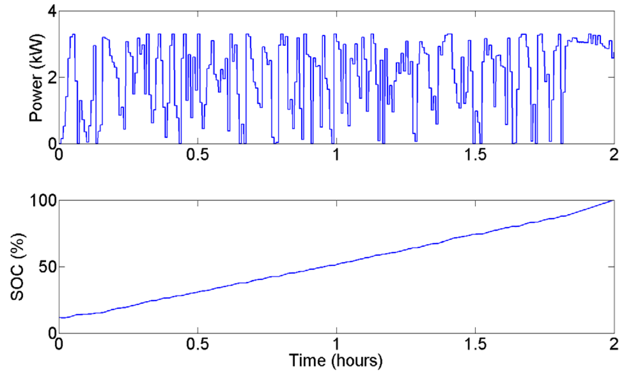

Fig. 3. Vehicle-to-grid half charging example

Once the individual charge profiles and characteristics of each vehicle were simulated, a population-level charge rate was obtained. This was simply an aggregation of all of the vehicle charge rates for a given time. To determine the number of vehicles required to meet the renewable generation imbalance, the current imbalance amount was divided by the aggregated charge rate. The result is a time-series of multiples of the current vehicle population needed to meet the imbalance requirements. The details of this time-series are presented in the Results section.

Utilizing the base population parameters and the two charging scenarios, many different scenarios and parameter sets were explored. It is important to point out that while the results are examined on a population-level, each individual vehicle received a unique, independent simulation. Individual departure and arrival times, battery sizes, charger availability, and state of charge requirements dictated the behavior of each vehicle. Managing each vehicle from an energy-based perspective helps not only improve the viability of the scenarios, but also ensures parameters like battery size are properly considered.

III. Results

Several simulations were run for many different parameters. The complete results are available in [24]. Key parameters investigated included: the availability of 240-Volt charging infrastructure at home (level 2 charging), the ratio of V2G-HALF to "normal charging" vehicles, and the availability of work charging options. Simulations were performed for both a PHEV-33 vehicle, as well as a PHEV-110 vehicle.

To evaluate the impact of the parameters, the results are presented as a relationship between the required maximum population and the unserved imbalance energy percentage. The unserved imbalance energy as a percentage of the total imbalance energy is also called *"% Energy unhandled"*. The relationship is shown in Fig. 4 for a selected example. It relates the number of vehicles necessary to the percentage of imbalance requirements not met or 'unhandled'.

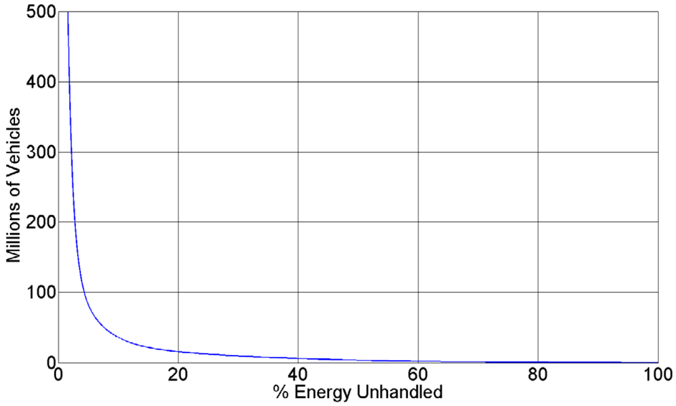

Fig. 4. Unhandled imbalance energy for 5% work charging availability

Fig. 4 can be interpreted by following the curve to the desired unserved energy point, or the desired maximum vehicle population. For example, a population of 100 Million vehicles would result in roughly 5% of the imbalance energy not being served for this particular scenario.

It is important to keep in mind that the unserved energy curves represent the maximum number of vehicles allowed to be active in a population at any given time. The unserved energy curves provide a rough guideline of how unserved energy and the parameter of interest are influenced by population size. To add validity to this answer, the mean-square-error (MSE) between the population's aggregate charging curve and the wind imbalance signal must be used. Fig. 5 shows the plot of the MSE for different levels of work charging availability. In this case, the minimum MSE (and best fit of the imbalance signal) occurs at a 35% work availability. All MSE values are based around an arbitrary population of 10 million vehicles.

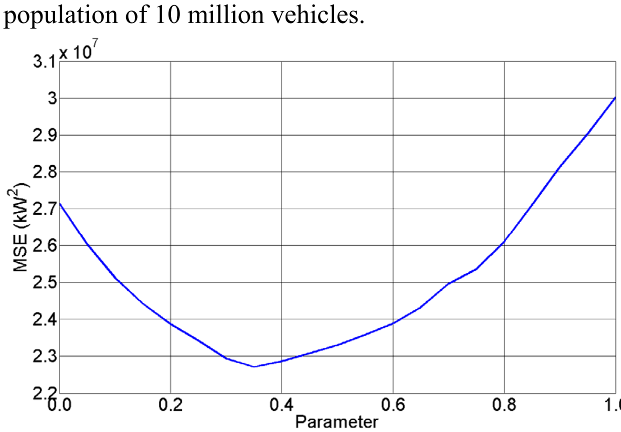

Fig. 5. Mean-square-error against wind imbalance for 35% work charging availability

It is important to note that the unserved energy and MSE plots provide two different pieces of information. The unserved energy provide a relationship between the maximum number of vehicles to meet the wind generation imbalance for a given percentage. The MSE plot shows which value provides the least error for a fixed population size. Unserved energy plots serve as a maxima indicator, while the MSE values serve as a realistic parameter selection for the greatest benefit to the grid.

A. Availability of 240-Volt Charging at Home

The first question of interest is what kind of impact the availability of faster charging at home will have on meeting the imbalance associated with additional wind generation. The parameter varied for these simulations was the level of 240-Volt charging available when the vehicle is charging at home, with 0% representing the simulation where all vehicles only have 120-Volt charging available. Fig. 6 shows the unhandled energy curves for different levels of availability for a PHEV-33 vehicle population, while Fig. 7 shows the results for a PHEV-110 vehicle population.

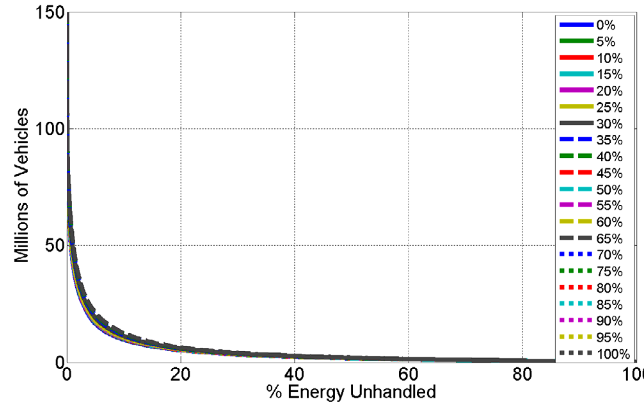

Fig. 6. Unhandled energy for different levels of 240-Volt home charging - PHEV-33 population

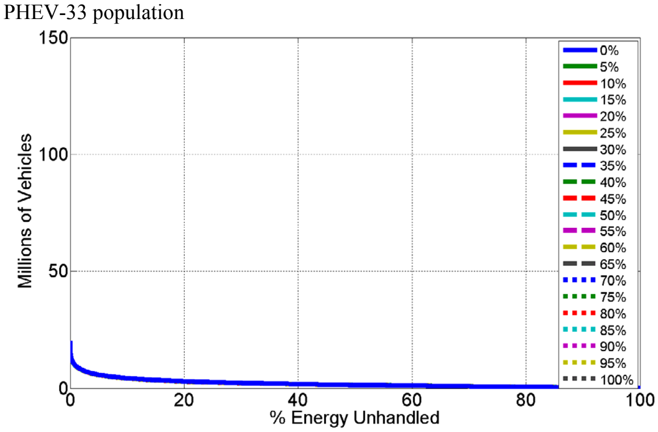

Fig. 7. Unhandled energy for different levels of 240-Volt home charging - PHEV-110 population

As the results in Fig. 6 and Fig. 7 demonstrate, the availability of 240-Volt charging infrastructure at home has little impact on the meeting the imbalance requirements. In other words, retrofitting the home charging infrastructure from 120-V to 240-V will have very little influence toward providing less or more balancing resources.

The MSE-based selections are shown in Table III. Table III compliments the results of the two figures, indicating that the lowest error is obtained for no home 240-Volt availability. Both of these results are not surprising for two different reasons, both dealing with availability of the resource (the electric vehicle).

TABLE III. OPTIMAL PARAMETER ASSOCIATED WITH LEAST MSE ON IMBALANCE SIGNAL FOR HOME 240 CHARGING AVAILABILITY

Battery Population	MSE Parameter
PHEV 33	0%
PHEV 110	0%

With a fast charging rate available, the vehicle has the ability to run more charge into the battery over a shorter interval. While this allows it to be a greater resource for handling the wind imbalance requirements, it also means the electric vehicle is available for a short time. Hence, when it is finished, another must be available to accept that portion of the imbalance.

The other aspect of availability associated with this particular analysis is that is only deals with modifications to home charging. For the majority of the vehicle profiles in the NHTS dataset, the vehicle is home in the evening and early morning. However, this same majority are at work during mid-day. During this time, there are fewer resources available to pick up the imbalance signal, and there is no change to the availability of this resource (the work-charging availability ratio is fixed for this study). As such, a large population is still needed to meet the mid-day demand.

B. *Ratio of V2GHalf to "Normal Charging"*

The next item of interest involves how much benefit electric vehicles provide the grid if only part of the population supports regulation services. Since the feature is not likely to be ubiquitous as EVs emerge, does a partial deployment of V2G-HALF provide significant benefit to the offset the imbalance in wind? Fig. 8 shows the results of this simulation study for a PHEV-33, while Fig. 9 shows the results for a PHEV-110.

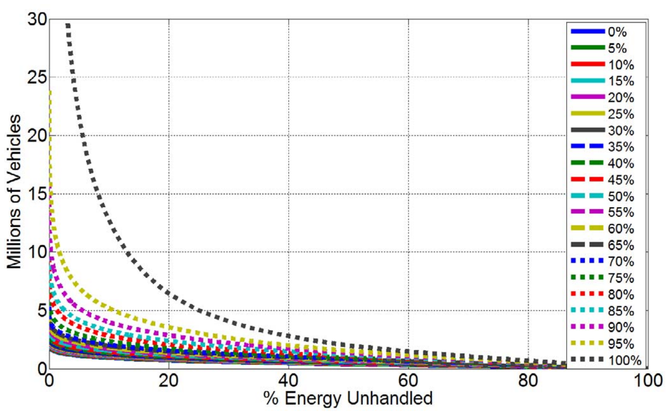

Fig. 8. Unhandled energy for different penetration levels of V2G-HALF - PHEV-33 population

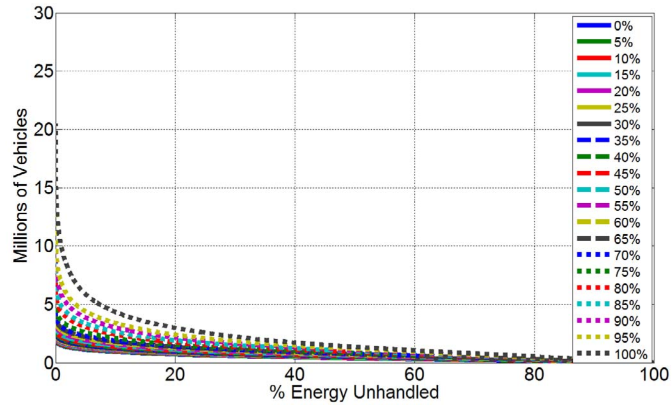

Fig. 9. Unhandled energy for different penetration levels of V2G-HALF - PHEV-110 population

Fig. 8 and Fig. 9 highlight the need to include MSE results. From the two figures, a higher V2G-HALF availability appears to require a higher population for the same unhandled energy percentage. However, the MSE values in Table IV indicate differently. While it is true there are instances in the simulation where a higher peak vehicle count is necessary to meet the imbalance, that is only for a specific time instances. Overall, the higher the concentration of regulation-capable vehicles, the less imbalance signal error is present.

TABLE IV. OPTIMAL PARAMETER ASSOCIATED WITH LEAST MSE ON IMBALANCE SIGNAL FOR V2G-HALF CHARGING AVAILABILITY

Battery Population	MSE Parameter
PHEV 33	100%
PHEV 110	100%

C. *Ratio of Work Charging Availability*

A key aspect to utilizing electric vehicles for handling the additional imbalance associated with a renewable energy source is the availability of the vehicle as a resource. For the majority of NHTS data, the participants worked during the day. In order for the electric vehicle to be useful for handling the additional imbalance, it must be able to charge.

To investigate the impact of work charging on meeting the additional imbalance requirements, the availability of work charging was varied and simulated. Fig. 10 and Fig. 11 show the unhandled energy curves for the PHEV-33 and PHEV-110 battery populations, respectively.

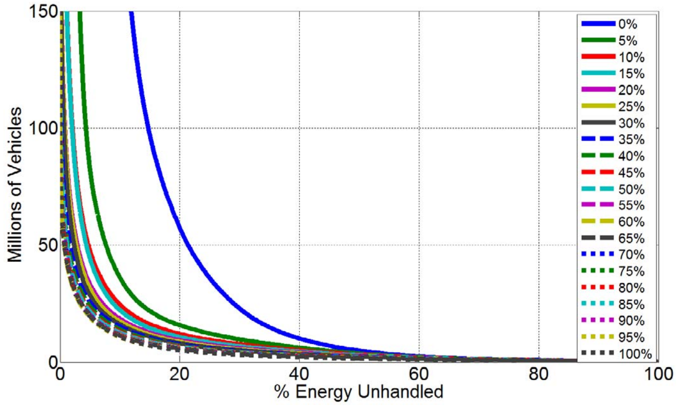

Fig. 10. Unhandled energy for different work charging availability - PHEV-33 population

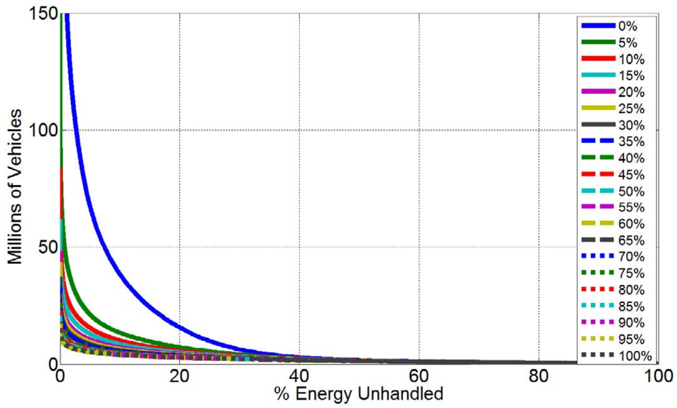

Fig. 11. Unhandled energy for different work charging availability - PHEV-110 population

Fig. 10 and Fig. 11 show a very significant result. The peak number of vehicles required to meet the imbalance drops significantly with even a 5% work-charging availability. With even a modest implementation of work charging and a decentralized-regulation services charging scheme, electric vehicles can provide tremendous benefit to handling the additional imbalance associated with a renewable energy source.

The MSE values for the 10 million vehicle population, shown in Table V, show results in line with Fig. 10 and Fig. 11. For the PHEV-33 vehicle population, only 35% of the workplaces required charging availability to minimize the error associated with the renewable imbalance. The PHEV-110 population required 60% penetration to meet maximum effectiveness. This is a fairly significant percentage, but even a modest work-charging penetration will provide beneficial services toward offsetting the imbalance associated with the renewable generation.

TABLE V. PARAMETER ASSOCIATED WITH MSE ON IMBLANACE SIGNAL FOR WORK CHARGING AVAILABILITY

Battery Population	MSE Parameter
PHEV 33	35%
PHEV 110	60%

IV. CONCLUSIONS

Simulations of an electric vehicle population, while considering the energy requirements of the system, yielded significant benefits to aiding in the integration of renewable generation sources. Using electric vehicle charging as a means to help offset the additional imbalance associated with a higher penetration of renewable generation shows significant promise. In particular, the addition of even a modest amount of "at work" charging significantly boosted the vehicles' benefits.

Utilizing a decentralized regulation-based charging scheme, only 35% of the population needed access to work charging to provide significant benefits to the power grid. For the vehicles to be viable as a resource for mitigating the additional variation associated with renewable generation sources, they must be connected to the grid. Work charging availability provides this connection and even in low availability ratios, allows electric vehicles to provide significant benefit to the grid while charging. It should be mentioned that PHEV charging by itself is insufficient to provide the all of the expected new imbalance requirements. However, they can provide significant resources toward meeting the new requirements. Furthermore, the use of 240-V charging (Level 2) charging at home did not appear to improve the resource availability toward meeting imbalance requirements. Vehicles with larger batteries typically require a significantly lower population to meet the additional imbalance. With a larger battery to fill, the vehicle is actively connected to the grid longer, providing regulation abilities during that time.

V. FUTURE WORK

Initial studies into the use of electric vehicles to aid in the integration of renewable generation resources look promising. The results for this paper were based upon a decentralized regulation-services-based charging algorithm. Future studies can include a centralized version of the regulation-based charging. With proper aggregation and scheduling, a centralized algorithm may reduce the peak vehicle population required, as well as the level of penetration of specific technologies on the system (such as regulation-services charging). Future studies will evaluate the benefits of allowing the EV batteries to discharge back into grid, operating under a vehicle-to-grid-full scheme.

VI. ACKNOWLEDGMENT

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VIII. Biographies

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