INL/EXT-14-33986

Investigating the Usefulness of Grid-Connected Plug-in Electric Vehicles as Controllable Loads

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December 2014

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

Prepared for the U.S. Department of Energy
Office of NuclearEnergy Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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1. INTRODUCTION

As market penetration of plug-in electric vehicles (PEVs) increases over time, the number of PEVs charging on the electric grid will also increase. As the number of PEVs increases, their ability to collectively impact the grid increases. The idea of a large body of PEVs connected to the grid presents an intriguing possibility. If an aggregator (e.g., a utility or other managing entity) could control PEV charging, it is possible that PEVs could act as a distributed resource to provide grid services. The technology required to control charging is available for modern PEVs. However, a system for wide-spread implementation of controllable charging, including robust communication between vehicles and utilities, is not currently present. Therefore, the value of controllable charging must be assessed and weighed against the cost of building and operating such as system.

In order to grasp the value of PEV charge control to the aggregator, the following must be understood:

1. The magnitude of controllable energy and power capacity available to the utility
2. The variability of the controllable capacity from day to day and as the number of PEVs in the market increases.

Controllable capacity represents the load the aggregator can either shed by curtailing charging or add by commencing charging. Understanding the variability of controllable capacity is important because PEVs are not a typical resource. The primary purpose of PEVs is to provide transportation. As a result, the location, connection status, and energy storage capacity of PEVs are continually changing. For PEVs to be a viable grid resource collectively, that resource must be consistent. The more consistent the resource, the more predicable it is from day to day and the more valuable it is for utilities.

There are many factors describing PEV charging that should be considered when determining the value of PEV charge control to the aggregator, including the following:

- Direction of power flow
- Magnitude of the power flow as a function of the charge rate of individual vehicles and the total number of vehicles charging
- Location of vehicles when charging
- Time of day when charging occurs
- Aggregator's level of control over charging.

The focus will be on quantifying the magnitude and variability of controllable capacity of PEVs by analyzing data collected from a large group of PEVs in the United States between 2012 and 2014. This analysis will focus on times when PEVs are parked at home and charging during the evening and night-time hours at the AC Level 2 charge rate. Only power flow from the grid to the vehicle is considered. The magnitude and variability of controllable capacity with respect to other factors, including vehicle-to-grid charging, should be explored in future work.

2. DIRECT ANALYSIS OF THE ELECTIC VEHICLE PROJECT DATA

In order to quantify the magnitude and variability of controllable capacity when PEVs are charged at home during the evening and night-time hours, data from The Electric Vehicle (EV) Project were analyzed. The EV Project included thousands of Nissan Leaf battery electric vehicles in 17 U.S. metropolitan locations. Owners of these vehicles agreed to allow researchers to collect data from their vehicles. This analysis used data from 430 privately owned Nissan Leafs in the Seattle area, during regular weekdays from October 1, 2012 to October 1, 2013. Regular weekdays are weekdays that are not holidays. The selected dataset was used to quantify the magnitude and variability of controllable capacity that can be expected from a group of electric vehicles. These two ideas will be analyzed separately in Sections 3 and 5, respectively.

3. MAGNITUDE OF CONTROLLABLE CAPACITY

The magnitude of controllable capacity refers to the quantity of energy and power that the aggregator is able to control. The quantity of energy that the aggregator is able to control will be referred to as the available charge energy; the quantity of power that the aggregator is able to control will be referred to as the available charge power. As mentioned previously, the analysis that follows will be limited to unidirectional power flow from the grid to the vehicle. Within this power flow scheme, it is possible to both increase and decrease the net load by controlling the PEV load. To see how this is possible, imagine that charging of 100 PEVs can be controlled at a given point in time. If each PEV has a maximum charge rate of 3 kW, all 100 PEVs are connected to the grid, and 60 of the 100 PEVs are actively charging, then the net load could be reduced by up to 180 kW by interrupting the charging of those 60 PEVs. Alternatively, the net load could be increased by up to 120 kW by commencing charging of the 40 PEVs that are not charging (assuming those PEVs batteries were not already fully charged).

In order for a PEV to provide available charge energy or available charge power to the grid, the PEV must be plugged in. Therefore, the first step in quantifying available charge energy and available charge power is to determine the connection state of PEVs over time. This was done by calculating, from the EV Project data, the percent of time that PEVs were plugged in at home. Figure 1 shows how the percent of Leafs connected to home electric vehicle supply equipment changed throughout the day in Seattle.

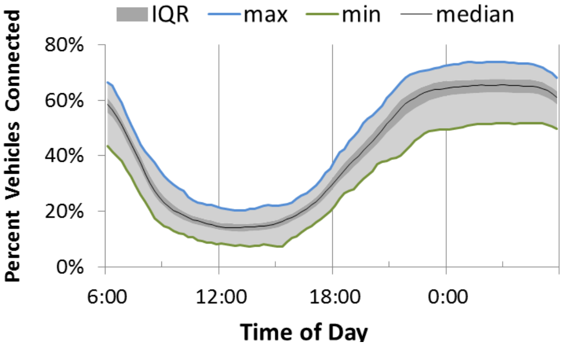

Figure 1. Percent of Nissan Leafs connected to home charging throughout the day in Seattle.

The behavior in Figure 1 is consistent with EV Project Leaf drivers in other regions and represents typical at-home plug-in behavior. In general, about 65% of Leafs are plugged in at home between 10 p.m. and 6 a.m. every regular weekday. This means that there are a number of PEVs on any given day that are not at their home location or are not plugged in overnight; therefore, they cannot provide grid services. Because not every vehicle is plugged in at night, the results in this analysis are normalized by the total number of PEVs being analyzed, not just those plugged in. These normalized results can then act as multipliers for large, hypothetical PEV fleets.

3.1 Available Charge Energy

Available charge energy for a given PEV is the quantity of energy that it can accept from the grid before the battery is fully charged. The amount of available charge energy that is accessible to an aggregator at a point in time is the sum of the available charge energy of all PEVs that are connected to the grid. During the day, available charge energy is very low because most PEVs are not plugged in and those that are plugged in usually have full batteries. Because the largest number of PEVs are plugged in at home overnight, that will be the time with the greatest available charge energy. At night in Seattle, the available charge energy was 6.5 kWh for each Leaf. If there were 1,000 Leafs in Seattle, the total amount of energy needed to charge the subset of Leafs that are plugged in is 6,500 kWh.

The available charge energy on any given night varies a lot from vehicle to vehicle. The vehicles that are plugged in do not all require the same amount of energy to fully charge their batteries. Figure 2 shows the available charge energy for all overnight home charges by Leafs in Seattle.

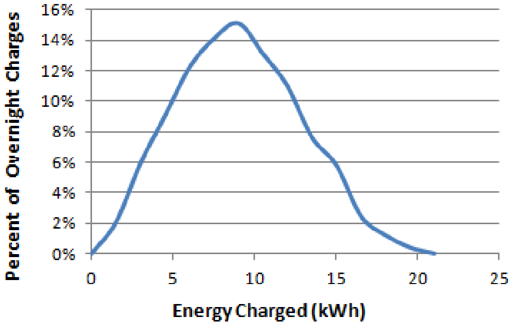

Figure 2. Histogram of energy charged overnight by Nissan Leafs in Seattle.

Some PEVs required very little energy to fully charge their battery, while others required almost a full charge. Most PEVs required between 5 and 15 kWh of energy to fill up their battery.

3.2 Available Charge Power

Available charge power for an individual PEV is the maximum charge rate of the onboard charger for that PEV. The amount of available charge power that is accessible to a utility at a point in time is the sum of the maximum charge rates of all PEVs that are both connected to the grid and that do not have a full battery at that point in time. As PEVs charge and their batteries fill up, the available charge power that is available to the aggregator decreases. Because the time that a PEV can sustain charging at a given charge rate is determined by the amount of energy the battery needs to fully charge and because there is a large variation between PEVs in the amount of energy needed to fill the batteries, there will also be a large variation between PEVs in the amount of time that is required to fill up the battery at a given charge rate. In other words, for a given charge rate, some PEVs will be able to sustain charging for a longer amount of time than other PEVs. In Figure 3, the available charge power accessible to the aggregator is shown for three different charge rates. These results are normalized by the total number of Leafs in the Seattle area.

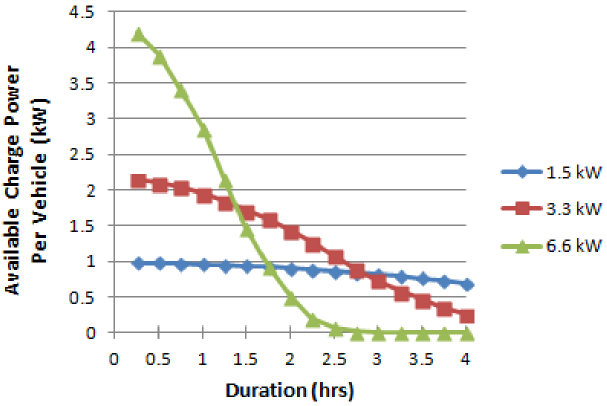

Figure 3. Available charge power per Nissan Leaf in Seattle at different charge rates.

All three available charge power curves decrease through time as PEVs stop charging when their batteries are full. At faster charge rates, more available charge power is initially accessible, but it quickly decreases because higher charge rates fill up the batteries in a shorter amount of time. At slower charge rates, less available charge power is initially accessible; however, it can be sustained for a longer time because lower charge rates take more time to fill up the batteries. In practice, if an aggregator has the ability to control charging, it will likely want to conserve available charge power until times when it is needed. Ideally, PEVs that do not require a lot of energy to fill the battery would not be charged until times when the aggregator would like to increase its net load substantially. In this way, PEV charging could be used in a more optimal way.

4. HYPOTHETICAL PLUG-IN ELECTRIC VEHICLE PENETRATION SCENARIOS

In order to better understand the magnitude of available charge energy and available charge power that might be accessible to utilities in the future, two hypothetical PEV penetration scenarios for the greater Seattle area (i.e., Seattle, Tacoma, Olympia, and nearby suburban areas) are discussed in this section. These scenarios will be used to highlight the potential PEV charging impact on net loads and the ability to integrate wind energy.

4.1 Description of Plug-in Electric Vehicle Penetration Scenarios

The first scenario is a short-term scenario that assumes, in the near future, there will be 10,000 PEVs in the greater Seattle area. Using 10,000 PEVs in the greater Seattle area is a relatively conservative estimate for the near future. At the end of 2013, there were nearly 1,000 Nissan Leafs participating in The EV Project in the Seattle area, which represents a subset of the total population of PEVs in Seattle. There were over 8,000 PEVs in the state of Washington at the end of 2013 [1]. The total number of PEVs can be expected to grow a great deal in the coming years, especially when considering the recent rise in the number of available PEV models and their increasing production numbers. In the following discussion, this scenario (with 10,000 PEVs) will be referred to as the short-term PEV penetration scenario.

The second scenario is a longer-term scenario that is projected to the year 2030. From census data, it has been estimated that the greater Seattle area had nearly 1 million light-duty vehicles as of 2010 [2]. If the vehicle fleet in Seattle grows at a similar rate as national projections, it should have about 1.3 million light-duty vehicles by 2030 [3]. According to a study done at University of California, Berkeley, PEVs will make up 24% of the U.S. light-duty vehicle fleet by 2030 [3]. Assuming this is the case, one would expect Seattle to follow, if not exceed, this trend because Seattle is currently one of the largest PEV markets. In the following discussion, the 2030 scenario (with 312,000 PEVs) will be referred to as the long-term PEV penetration scenario.

4.2 Total Available Charge Energy for Both Scenarios

As was mentioned previously, a reasonable multiplier to estimate the total available charge energy for a hypothetical number of PEVs is 6.5 kWh per PEV. Using this multiplier, the total available charge energy for the short-term PEV penetration scenario is 65 MWh per night (6.5 kWh x 10,000 PEVs). Likewise, the total available charge energy for the long-term PEV penetration scenario is about 2,000 MWh per night.

4.3 Total Available Charge Power for Both Scenarios

The total available charge power for both the short-term and long-term PEV penetration scenarios is shown in Figure 4.

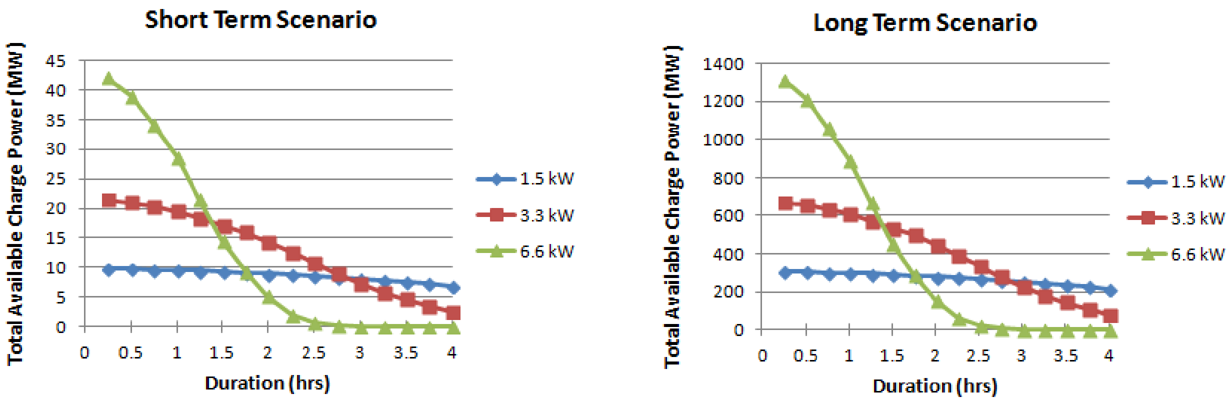

Figure 4. Total available charge power for both the short-term and long-term PEV penetration scenarios.

For the short-term PEV penetration scenario and a charge rate of 6.6 kW, there would be over 40 MW of total available charge power, but only for a very short period of time and it would decrease rapidly as charging continued. If the PEVs were charged at 3.3 kW, there initially would be 22 MW of total available charge power and about 14 MW after 2 hours. For the long-term PEV penetration scenario, there would be hundreds of megawatts of total available charge power for sustained periods of time. For example, at the 3.3-kW charge rate, there initially would be 650 MW of total available charge power and about 450 MW after 2 hours. Even if only a fraction of the PEVs charging could be controlled, this still presents a significant controllable load.

4.4 Potential Impact on Utility Loads

The short-term and long-term total utility loads in the greater Seattle area were estimated using the 2013 Federal Energy Regulatory Commission (FERC) 714 load forecasts submitted by the balancing authorities to FERC. The total utility load in the greater Seattle area consists of the loads from the following balancing authorities: Seattle City Lights, Tacoma Power, and Puget Sound Energy. In order to estimate the utility loads in the greater Seattle area for the long-term scenario, the load forecasts in the 2013 FERC 714 submission were extrapolated to the year 2030 (the last year of the forecasted loads in the 2013 submission was 2023). A comparison of the utility load in the greater Seattle area to the PEV loads for both the short-term and long-term PEV penetration scenarios is given in Table 1.

Table 1. Comparison of total utility load to PEV loads for both the short-term and long-term PEV penetration scenarios.

	Short Term Scenario		Long Term Scenario	
	Peak_MW	Energy_MWh	Peak_MW	Energy_MWh
Total Utility Load	7150	108500	8400	117400
PEV Load	14	65	450	2000
PEV Load as Percent of Utility Load	0.20%	0.06%	5.4%	1.70%

The energy numbers in Table 1 are the daily energies; the utility peak is the forecasted annual peak; and the PEV peak is the total available charge power after 2 hours, given a 3.3-kW charge rate.

For small PEV penetrations, there is almost no impact on utility loads. In the short-term PEV penetration scenario with 10,000 vehicles, PEV charging consisted of only 0.2% of the utility's peak load and 0.06% of the energy. As the number of PEVs increases and approaches the long-term scenario penetration estimate, they will begin to have an impact on utility loads. This is especially true for afternoon peaking utilities like those in the Seattle area during the winter time. The load in Seattle during the winter months tends to increase between 5:00 p.m. and 6:00 p.m., when people arrive home and usually peaks between 6:00 p.m. and 9:00 p.m. in the evening. If PEV owners plug in and begin charging their PEV when they arrive at home, the PEV charging will be coincidental to the utility peak load. For the long-term scenario, this could lead to a perceptible increase in peak load.

4.5 Ability to Integrate Wind Energy

It has long been thought that controlled PEV charging could be used to aid integration of intermittent generation, especially wind [4][5][6][7][8][9]. It has also been hypothesized that the penetration of wind energy could increase to produce 20% of the energy used in the United States, as early as the year 2030 [10][11]. Wind generation is generally greatest at night, when loads are typically low. This could lead to wasted energy, unless measures are taken to use wind energy as it is generated. Because most PEVs are plugged in at night, it makes sense to assume that controlled PEV charging could be used to aid in the integration of wind generation. There are many studies that support this assumption [5][6][8].

In both hypothetical PEV penetration scenarios, there would be enough available charge power to be useful to utilities when integrating wind. In the short-term PEV penetration scenario, there would be over 14 MW of available charge power for 2 hours. In the long-term PEV penetration scenario, there would be over 450 MW of available charge power for 2 hours. A small amount of available charge power will go a long way in mitigating the unpredictability and volatility that is inherent to wind generation.

5. VARIABILITY OF AVAILABLE CHARGE ENERGY AND AVAILABLE CHARGE POWER FROM DAY TO DAY

In Section 4, it was shown that nighttime PEV charging can provide a useful amount of available charge energy and available charge power. The value of controlling nighttime PEV charging, in large part, depends on how consistent the available charge energy and available charge power is from day to day. A resource that is consistent from day to day can be depended on to provide services that support system reliability, such as integrating wind at night. Because the location, connection status, and energy storage capacity of PEVs are continually changing, PEVs must be aggregated together to provide a consistent resource from day to day. The relationship between the number of PEVs aggregated together and their collective variability is investigated in this section.

For the purposes of this section, a vehicle set is a group of PEVs that are aggregated together and the vehicle set size is the number of vehicles in the set. The vehicle set sizes that were investigated are the multiples of 10 from 10 to 150. Each vehicle set was analyzed by randomly selecting the appropriate number of vehicles from the overall dataset and using those vehicles to calculate the available charge energy and available charge power for every regular weekday in the study period. The nighttime available charge energy was calculated at 1:00 a.m. since nearly all PEVs are plugged in for the night by this time. The nighttime available charge power was calculated assuming a 3.3-kW charge rate and duration of 2 hours. In order to achieve statistical confidence, this process was repeated 30 times for each vehicle set size. Using these data, the 95/95 tolerance interval (95% coverage with 95% confidence) was calculated for each vehicle set size. Conceptually, the 95/95 tolerance interval describes the range of values where it can be expected with 95% confidence that 95% of the days will lie within the specified interval.

Figures 5 shows the tolerance intervals as error bars extending above and below the average available charge energy and average available charge power for each vehicle set size analyzed. The figure also shows the maximum and minimum available charge energy and available charge power for each vehicle size set.

The variability in the available charge energy and available charge power as the vehicle set size increases share the same basic trends. First, for small vehicle set sizes, the tolerance interval and the spread between the maximum and the minimum are large. Second, as the vehicle set size increases, the tolerance interval and the spread between the maximum and the minimum decreases. Finally, as the vehicle set size exceeds 80 vehicles, the tolerance interval is almost constant and the spread between the maximum and the minimum decreases slowly. When there are at least 100 vehicles, the available charge energy per vehicle is between 5 and 8 kWh on 95% of the days and the available charge power per vehicle is between 1 and 2 kW on 95% of the days.

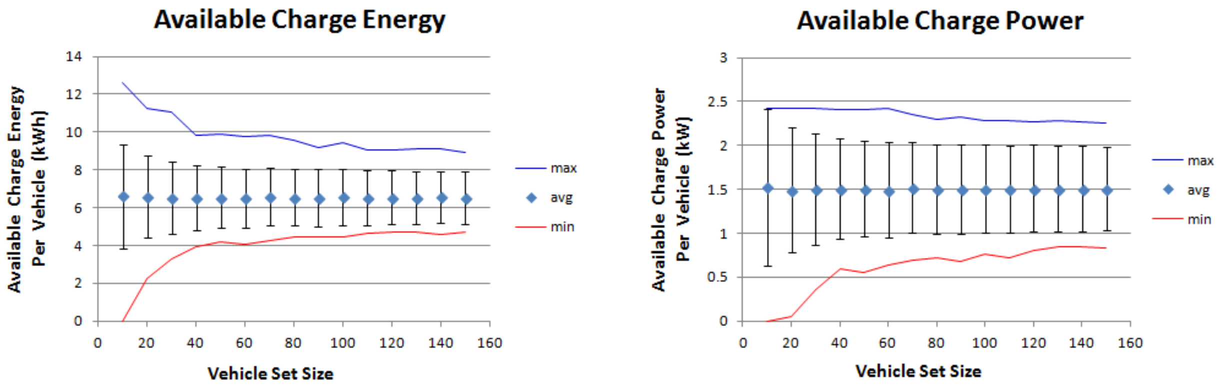

Figure 5. The 95/95 tolerance interval (95% coverage with 95% confidence) for available charge energy and available charge power.

For a resource to reliably provide grid services, there must be a minimum amount of that resource that is consistently available from day to day. For vehicle sets containing at least 100 vehicles, on every single day there was at least 4.5 kWh of available charge energy per vehicle and 0.73 kW of available charge power per vehicle. Also, on 95% of the days, there was at least 5 kWh of available charge energy per vehicle and 1 kW of available charge power per vehicle. The predictability on a given day can be better than indicated here if forecasting methods, which use current conditions to estimate the value of interest into the near future, are employed. For example, wind generation is estimated using current wind and climate conditions (among other things) to predict future wind generation. Using similar forecasting techniques, the available charge energy and available charge power on a given day could be predicted much more precisely than suggested by Figure 5. In either case, when there are at least 100 vehicles aggregated together, the available charge energy and available charge power is sufficiently consistent from day to day to be useful to a planning entity.

6. CONCLUSIONS AND RECOMMENDATIONS

The preceding analysis has determined that nighttime home charging of PEVs has desirable properties as a controllable load. The magnitude of available charge power and available charge energy is sufficient to be useable as a controllable load. Also, for groups of at least 100 vehicles, available charge power and available charge energy are consistent from day to day. Therefore, PEVs have the potential to provide grid services that support reliability, such as integrating wind energy during the nighttime hours.

The broader question of whether the value of controllable PEV charging justifies the cost of building and operating a robust system to integrate PEVs with the grid depends on the future attributes and characteristics of the grid. In order for the grid to be stable, the balance between the load and generation must be maintained at all times. Conceptually, the load-generation balance is maintained by using sources of flexibility in the grid to mitigate sources of variability in the grid. Some common sources of flexibility are dispatchable generation, energy storage, and loads that can be controlled by the system operator. Some common sources of variability are loads that cannot be controlled by the system operator and intermittent resources like wind. In the future, the value of PEV charging to a system operator will depend on the need and incremental cost of additional sources of flexibility. This is determined, in part, by the future resource mix (in particular, the penetration of variable resources like wind and solar) and the future cost of other forms of controllable load and energy storage. Likely future scenarios should be investigated using PEV/grid simulation tools to inform intermediate decisions.

In order to make accurate modeling assumptions and to properly understand and validate the results of the simulation tools, the following work is needed:

1. Additional analysis of real-world PEV charging data is warranted to further explore the magnitude and variability of controllable PEV charging over a wide range of factors. These factors include geography, vehicle type, charging time of day, charging location, and vehicle to grid charging.
2. It is important to understand how current and future production PEVs behave as controllable loads on the grid. This requires testing to characterize the steady-state and dynamic electrical interaction of PEVs with the grid. With this knowledge, PEVs can be modeled accurately in a host of PEV/grid simulation tools.
3. It is important to understand the characteristics of the various communication schemes that are currently being developed to facilitate communication between the PEVs and the grid. In particular, the effect of communication latency on the value of PEVs as a controllable resource should be studied.

Continued analysis of real-world data and characterization of real hardware are highly recommended to enable accurate simulation of PEVs integrated with the grid.

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