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Plug-in Electric Vehicle Fast Charge Station Operational Analysis with Integrated Renewables

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Abstract

The growing, though still nascent, plug-in electric vehicle (PEV) market currently operates primarily via level 1 and level 2 charging in the United States. Fast chargers are still a rarity, but offer a confidence boost to oppose "range anxiety" in consumers making the transition from conventional vehicles to PEVs. Because relatively no real-world usage of fast chargers at scale exists yet, the National Renewable Energy Laboratory developed a simulation to help assess fast charging needs based on real-world travel data. This study documents the data, methods, and results of the simulation run for multiple scenarios, varying fleet sizes, and the number of charger ports. The grid impact of this usage is further quantified to assess the opportunity for integration of renewables; specifically, a high frequency of fast charging is found to be in demand during the late afternoons and evenings coinciding with grid peak periods. Proper integration of a solar array and stationary battery pack thus helps ease the load and reduces the need for new generator construction to meet the demand of a future PEV market.

Keywords: fast charge, renewable, PEV, grid impacts

1 Introduction

Plug-in electric vehicles (PEVs) present a viable alternative to petroleum-fueled automobiles fulfilling a variety of common transportation needs. For vehicle/fleet owners and operators whose needs can be met within 70–100 miles of daily range, PEVs can replace conventional vehicles and reduce fuel costs, maintenance costs, and emissions.

However, many conventional vehicle owners and operators are accustomed to refueling their vehicles in less than 5 minutes once or twice each week, and enjoy the ability to take occasional long-distance trips. The commonly available infrastructure that supplies power to PEV batteries is far from being able to practically "refuel" vehicles as quickly as conventional refueling. New fast chargers being deployed across the country will begin to close that gap—at what cost?

The National Renewable Energy Laboratory (NREL) is studying the impact of fast charging to the local, regional, and nationwide grid infrastructure from PEV fast charging. This paper documents an initial phase of this research, characterizing potential usage patterns of a single fast-charge station with multiple charge ports by a local fleet. In addition, the study includes a look at sizing solar arrays and stationary batteries to accompany a fast charger, providing renewable fuel to PEVs and reducing electricity bills to the station.

2 Scenario Assumptions

According to the Electric Power Research Institute "charging pyramid" [1], PEV owners and operators will charge most frequently at home. This trend is certainly playing out so far in the "EV Project" demonstration where, during the third quarter of 2011, 98% of the charging events took place at home [2]. This trend may shift as more drivers adopt PEVs and as more public infrastructure becomes available, but assumptions that residential charging remains the dominant method will guide this study.

Fast charging, defined here as providing direct current power to a vehicle at approximately 50 kW, is not expected be available in the home, and thus will generally be found at the following destinations:

1. Interstate rest stops, supplying food and fuel for long-distance travel;
2. Local commercial hubs, such as grocery stores, malls, or parks, where a user may spend more than 15 minutes at a time; or
3. Designated fueling stations, similar in function to gas stations frequented by motorists today.

This investigation focuses primarily upon the later two options, where it is expected that drivers within a certain small radius (on the order of 5 to 10 miles) will utilize the station as a needed resource when running low on energy.

2.1 Driving Profiles

To simulate fast charge usage based on real-world needs, real-world driving times, speeds, and distances collected from the Puget Sound Regional Council's (PSRC) 2008 Traffic Choices Study formed the basis for vehicle utilization in this study [3].

The Traffic Choices Study was an investigation of the response of travel behavior to variable toll charges in the Seattle metropolitan area. The study placed global positioning systems in 445 vehicles from 275 volunteer households that recorded driving patterns over an 18-month average per household period. The experiment started with a 3-month control period in which no behavior was influenced by the tolls. This study uses data only from the control period.

A negligible percentage of data was removed from the dataset to eliminate vehicles and trips containing obvious errors in the logs. The remaining useful data consists of every trip taken by over 400 vehicles throughout April and June of 2005. Individual trip times, speeds, and distances were employed in the simulation to predict times vehicles need fast charging, though no geospatial data were used to correlate distance of the vehicles from a central station.

The resulting data set contains over 149,000 trips, spanning a wide variety of driving patterns. The charts in Figure 1 display statistics for each vehicle trip (with multiple trips occurring each day).

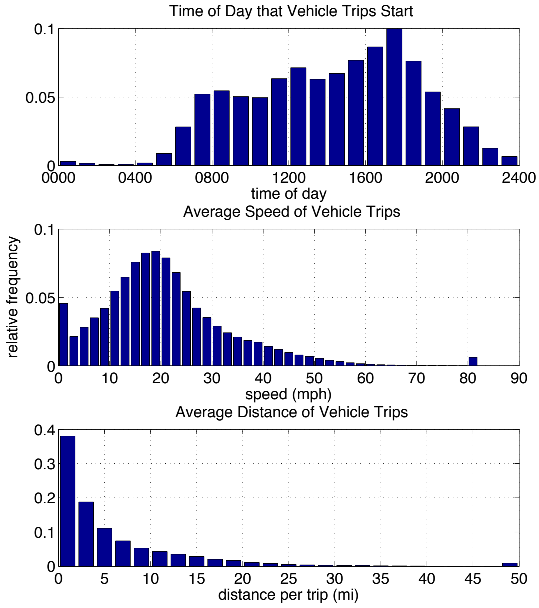

Figure 1: PSRC Vehicle Trips Summary

2.2 Vehicle Specifications and Usage

Vehicle usage profiles are selected from the Traffic Choices Study dataset randomly and modeled as all-electric vehicles with lithium-ion batteries of consistent size (varied as an input parameter). The vehicles are assumed to utilize a state-of-charge window of 80% (between 10% and 90%).

All PEVs are assumed to consume energy at an average rate of 300 Wh/mi, approximating an electric compact or midsize commuter vehicle. The parametric simulation is designed to evaluate scenarios of varying fleet size and vehicle battery size, as well as station design parameters.

For this study a "forgetfulness factor" of 10% is applied to the fleet, indicating how frequently the drivers will forget to plug in their PEVs at home. In addition, if a PEV owner is driving at midnight, it is assumed that they will not be charging overnight.

Fast charges occur as a secondary option only as needed. If a PEV depletes the entire state-of-charge window while driving, the simulation stops driving to immediately initiate a fast charge. The

remainder of that trip (as determined by the PSRC dataset) will resume after the fast charge. Any trips originally scheduled during the time for which the interrupted trip is now rescheduled will be skipped. This models a potential sacrifice made by the driver in need of a fast charge.
The logic governing vehicle charge timing is show in Figure 2.

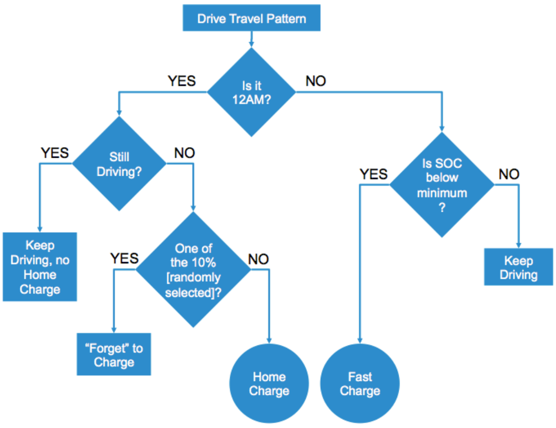

Figure 2: Vehicle charge decision tree

2.3 Charging Profiles

At home, a constant level 2 charge is assumed to take place overnight for those owners simulated as remembering to plug in according to the "forgetfulness factor." Home charging is initiated at midnight when needed, avoiding grid on-peak periods and refueling PEVs at 3.3 kW until full.
Fast charges are simulated as only refilling the PEV batteries to a state-of-charge of 80% because the last bit of charge must be trickled into lithium-ion batteries at a slower rate. This has been verified in test charges conducted with a CHAdeMO-compliant Mitsubishi i-MiEV at NREL (see Figure 3). In addition, fast chargers are assumed to operate at 85% efficiency given anticipated losses from internal battery resistance and AC-to-DC power conversion.

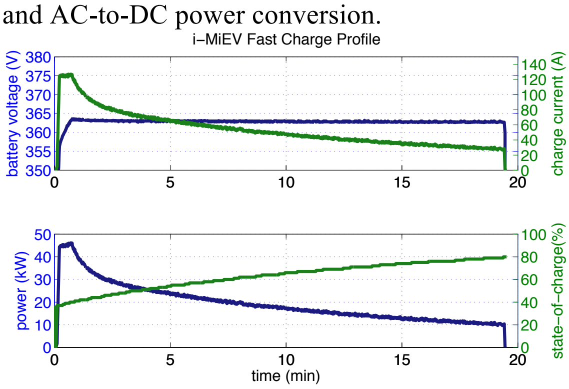

Figure 3: Data from fast charge of i-MiEV at NREL

2.4 Station Configuration

This analysis investigates the usage profile for a single fast charge station serving a local population of up to 400 all-electric vehicles. In 2010, nearly 160,000 gasoline fueling stations existed in the U.S. [4], or about one station for every 1,500 vehicles. Assuming a similar use of about one or two "fills" per week, one fast charge station is chosen to address the needs of a few hundred PEVs.
The simulation models the station as having between one and four charging ports installed, supplying as much as 50 kW from each simultaneously. Assuming a 25% safety factor, a four-port station will require a 250-kW transformer on-site.
The station operates on a "first come, first served" basis. If a vehicle arrives while all of the ports are in use, the simulation applies a wait time to the vehicle and driver until the next port becomes available.

2.4.1 Renewable Fueling Options

Currently operating fueling stations do not require nearly the same power of a fast charger—this extra load may cause voltage droop on the local electric distribution network depending upon the fast charge station's location within a utility's grid [5].
In an effort to mitigate these impacts, the station model includes a photovoltaic (PV) array and a stationary battery from which the simulation allocates power for fast charging. For this simulation, the stationary battery is only charged with excess solar power. To maintain a minimal load on the grid, the fast charger always pulls power from the PV array first, then the stationary battery, unless the battery is empty. The fast charger prioritizes power in the following order depending upon availability:

1. PV array
2. Stationary battery storage
3. Utility grid

An example station layout is given in Figure 4.

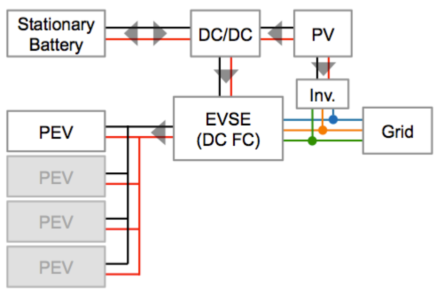

Figure 4: Renewable fast charging station schematic

The solar array production is modeled with real irradience data collected in 2011 by the Solar Radiation Research Laboratory at NREL [6]. This irradience is then scaled proportionally to the solar array size to simulate power output from the PV.

3 Results

3.1 Single Case Focus

A single scenario during a single week in April is presented here with the following design inputs to demonstrate the simulation performance:

- Fleet Size: 200 PEVs
- PEV Battery Capacity: 16 kWh
- Fast Charger Ports: 2
- PV Array Size: 50 kW
- Stationary Battery Capacity: 100 kWh

3.1.1 Time of Day Use

Because of the inclination to charge at home in the early morning, the majority of fast charges occur later in the day. The daily driving patterns, also heavier in the evenings, exacerbate this trend. The relative frequency of fast charges occurring at each time of day is plotted in Figure 5.

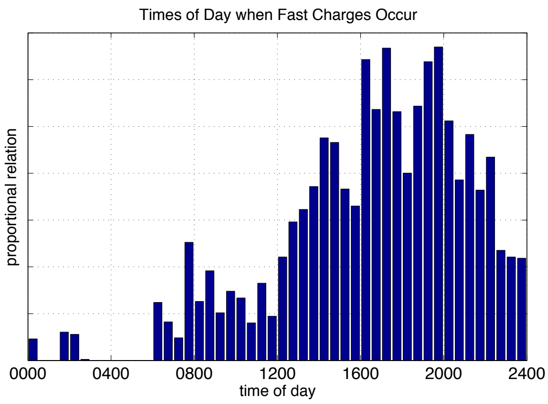

Figure 5: Likelihood of fast charge by time of day

On average, the fast charger was used by the 200-vehicle fleet over 38 times every day and provided over 40% of the driving energy needs. This relatively high percentage results from the low relative battery energy and high relative energy consumption rate modeled for the compact PEV in this example scenario.

3.1.2 Wait Time Required

As previously mentioned, the “first come, first served” model is employed to help maintain a low median wait time. In this initial scenario, up to four PEVs are waiting for the two charge ports, but wait times rarely exceed 30 minutes (see Figure 6).

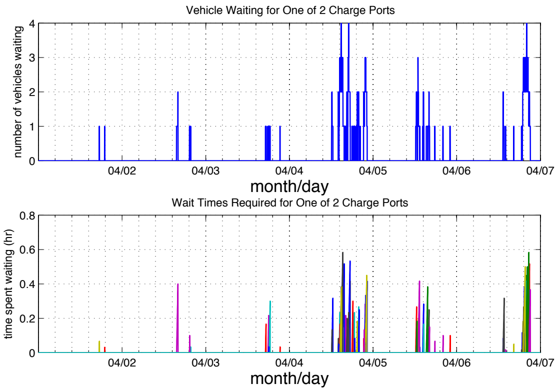

Figure 6: PEVs waiting for available charge port

Wait times typically grow as the day goes on, reflecting a stronger probability of fast charging required depending on the day’s travel and whether home charging occurred the night before.

3.1.3 System Interactions

The integrated simulation models the power exchange between the fleet, solar array, stationary battery, and utility. Power demand from fast charging the PEVs is supplied by the solar array, stationary battery, or grid depending on the availability of solar (time-of-day) and the stationary battery’s state-of-charge. A sample week is shown in Figure 7.
More detail is highlighted in the sample day shown in Figure 8. On this day, the solar array produced nearly peak output until the mid-afternoon where clouds likely attenuated the insolation.

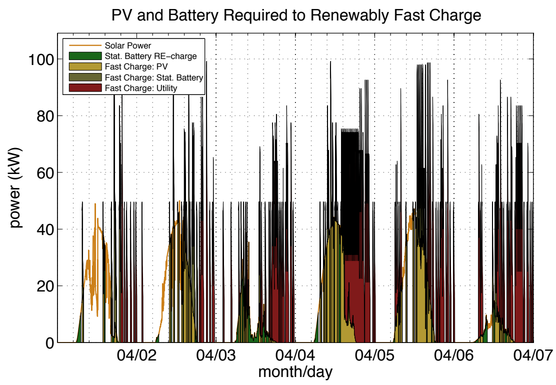

Figure 7: Sample week of station power exchange

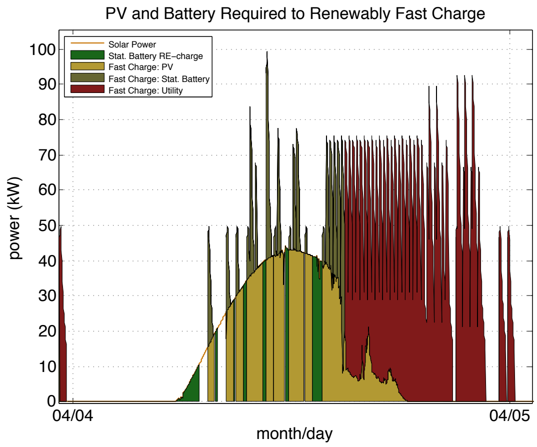

Figure 8: Close-up of a single sample day

Fast charges, indicated by brief spikes of 50 to 100 kW, signify one or two vehicles charging simultaneously. In between station usage, the solar array replenishes the battery until it is again full. Late in the afternoon, as more frequent fast charges are required, the battery empties and the station relies on the grid for nearly all of the charge power. The almost continuous fast charging occurring in the afternoon is a direct result of the small PEV battery size in this scenario relative to the trip distances travelled by this fleet.

3.1.4 Stationary Battery vs. Grid Use

Each day the solar array charges the stationary battery, but as the battery empties, the grid power ramps up to meet the fast charge demand. The high demand of fast charging in the afternoon combined with minimal solar production in the evening hours led to peak usage of the grid (Figure 9).

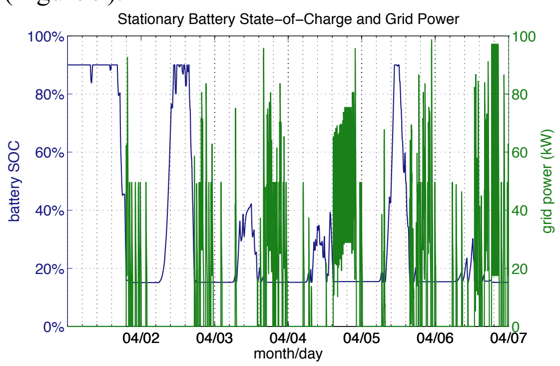

Figure 9: Comparison of Stationary Battery and Grid Energy Consumption for Fast Charging

3.2 Design of Experiments

Waiting 30 minutes for a 20-minute fast charge seems relatively short, but is much longer than typical waits at gas stations today. To more adequately address the wide array of possible usage patterns and station designs, a design-of-experiments was conducted, sweeping the parameters given in Table 1.

Table 1: Parameters swept in fast charge station design study

Parameter	Low Value	High Value
Number of PEVs in Fleet	100	400
PEV Battery Capacity (kWh)	16	40
Number of Charger Ports	1	4
Solar Array Size (kW)	0	100
Stationary Battery Capacity (kWh)	0	200

Initially a sweep of the five parameters was conducted at three levels each (minus a few incompatible cases), yielding a result set for 168 different scenarios. Although a more in-depth analysis is anticipated during the following phases of this research, early results using this new simulation tool point to a strong correlation of fast charger utilization with both the size of the fleet it serves and the battery capacity of the PEVs. The average number of uses each day and wait time required with four charger ports is summarized in Figure 10.

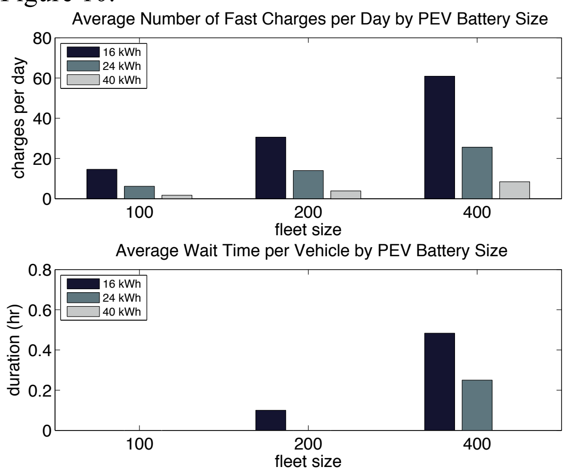

Figure 10: Average station utilization with four ports

4 Conclusion and Future Work

Depending upon the size and concentration of a local fleet of vehicles, fast charging stations may be in high demand. This study detailed a method of simulating potential use of fast chargers as well as the key information data sets and assumptions.

Several trends appeared in the data, including a strong demand for fast charges in the afternoon and early evening hours. This may guide a renewable station designer to orient solar panels towards the west to shift the peak output later in the day, coinciding with the charging load.
In addition, a large PV array and stationary battery are necessary to confidently offset grid load. However, with upwards of 40 charges per day, the extra investment may pay for itself in charging fees and electric bill reductions.
NREL plans to complete a more exhaustive design study of these trade-offs and their financial implications later this year.

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