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Vision for and Implementation of a National High Power DC Fast Charging Network

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Abstract

Affordable, long-range plug-in electric vehicles (PEVs or EVs for short) arrived on the North American market in late 2016 with the launch of the 238 mile (380 km) all-electric Chevrolet Bolt. Additional light-duty EVs with similar long ranges have also been announced for US market launch in 2017-2021. To drive long distances from city to city while meeting customers' expectations of a quick refueling time, charging power is also increasing from current power levels of 50 kW to 350 kW (or more) to be done at public multi-station high power DC fast charging plazas.

The work presented here outlines major considerations and some initial current strategies for effectively supporting the adoption of long range electric vehicles with DC fast charging.

Key words: plug-in electric vehicle, DC fast charging, high power, long range, charging network

1 Introduction

More than 633,000 plug-in electric vehicles have been sold in the US market as shown in Figure 1 below.[1]

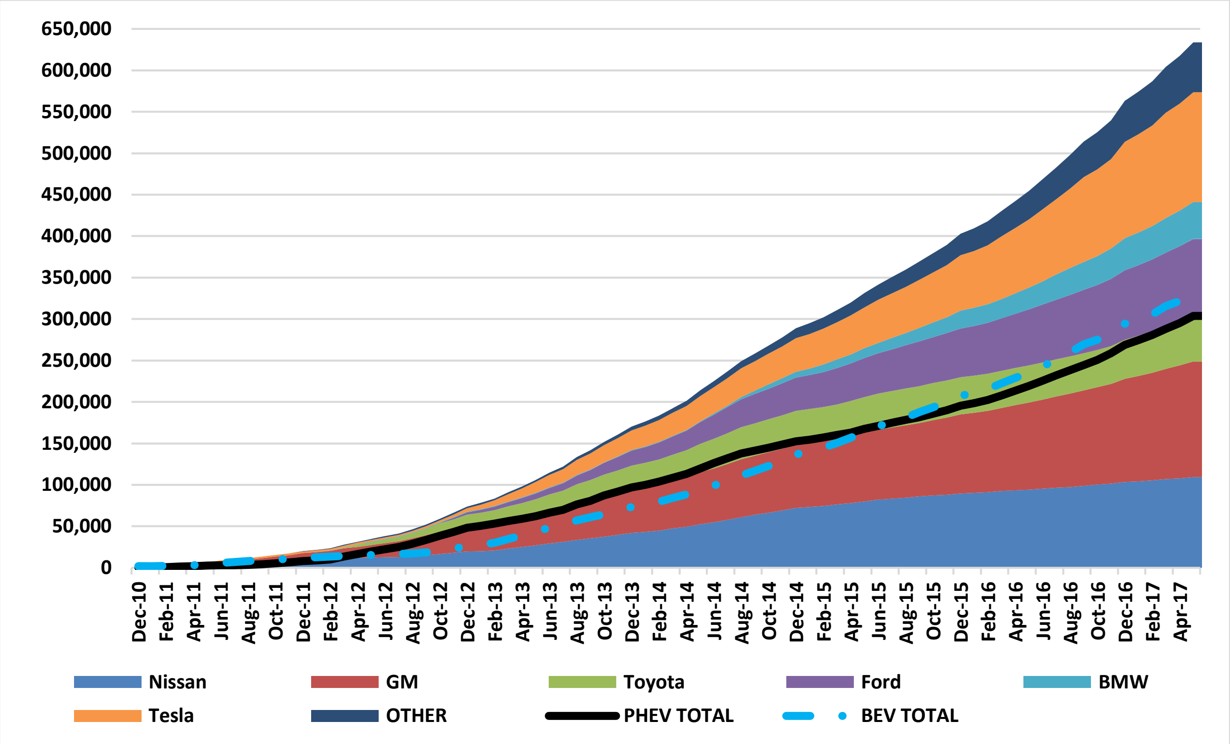

Figure 1: Plug-in electric vehicle sales in the US, December 2010 – May 2017

[1] EPRI research, US PEV sales through May 2017. Source: IHS/Polk.

While sales have been concentrated in urban and suburban population centers thus far, EVs have sold across the country as seen in Figure 2 below.[2]

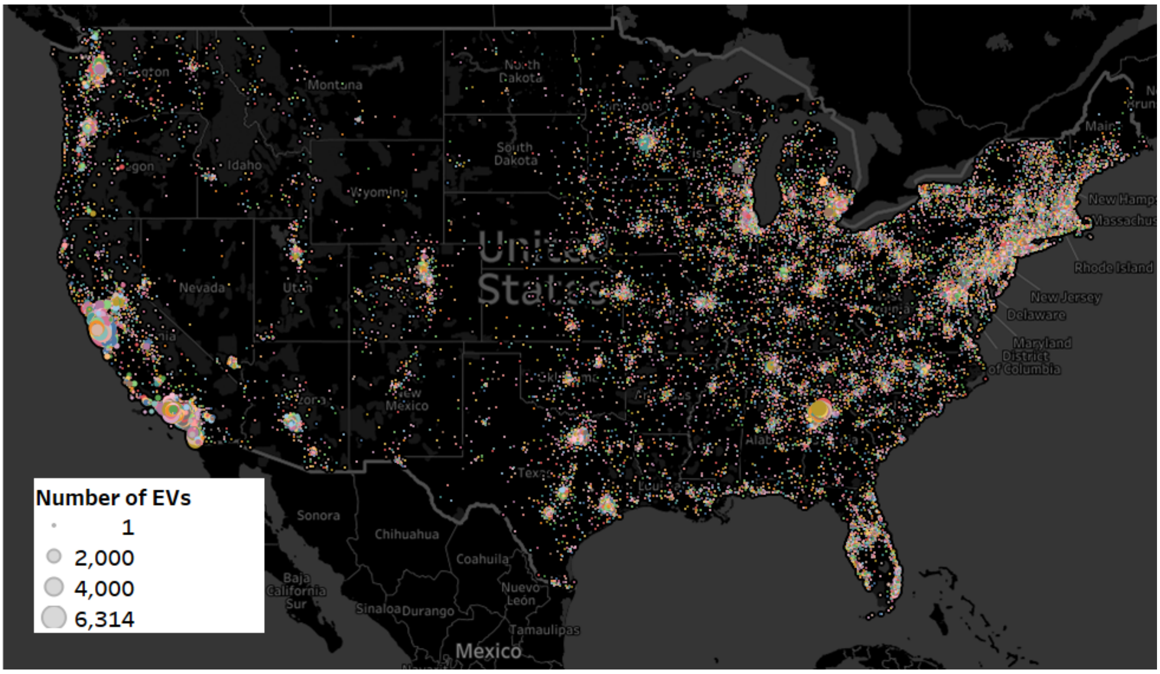

Figure 2: Plug-in electric vehicle sales location, May 2017

In addition, the automakers have announced more than 30 new or revised EVs set to hit the market through 2021, both plug-in hybrid and battery electric vehicles.[3] To meet consumer expectations, automakers today are introducing plug-in electric vehicles with longer range and announcing plans to dramatically increase range in the next several years. This is largely due to decreasing battery prices (see Figure 3 below)[4], and to a lesser extent, similar component cost and other cost reductions as the EV market starts to scale.

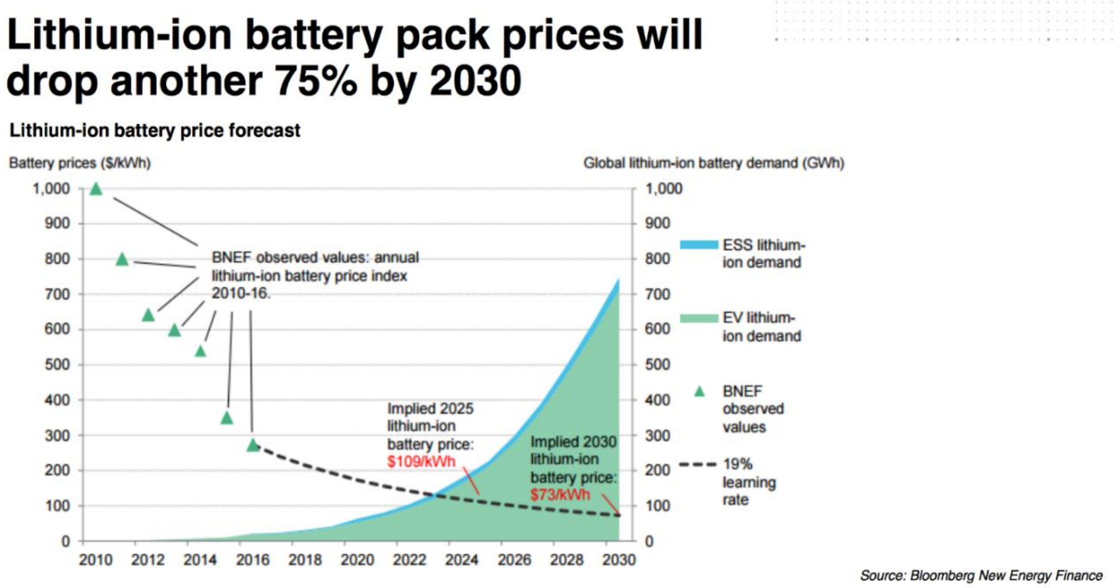

Figure 3: Decrease in lithium-ion battery prices

[2] EPRI internal research.
[3] EPRI internal research.
[4] Bloomberg New Energy Finance

1.1 Electric Vehicle Infrastructure and Grid Impacts

Most electric vehicle charging will occur at home, if available. Public charging infrastructure is necessary to support a fleet of electric vehicles, including charging at work, public charging at longer dwell locations such as airports, shopping malls, or schools, and DC fast charging or battery swapping to support long distance trips and EV drivers who do not have access to charging at home or at work.

A common initial question when consider a network is the number of public charging stations that are necessary in a certain region. The ideal ratio of public chargers to number of electric vehicles depends on several factors that may vary regionally such as battery size, the number of multi-unit dwellings, level of EV adoption, workplace charging and average driving statistics. A high estimate for EV infrastructure, using data collected from other areas with the modelled vehicle data, indicates that about one workplace and one public charger are needed for every three EVs, if no at-home charging exists. A significant availability of home charging infrastructure reduces the requirement for work and public infrastructure.

The grid impact of EV charging is low to start and grows slowly:

- In lighter-load periods like the spring and fall, peak electrical demand is about 700W per vehicle
- In higher-load periods like the summer and winter, peak electrical demand can increase to about 1700W per vehicle
- These peak demand numbers are for uncontrolled charging. The use of managed charging (e.g. ‘smart charging’) or implementation of off-peak rates will significantly reduce or even potentially eliminate these additions to peak demand.
- System level demand for battery swapping is typically below 700W per vehicle. The likely key challenge is ensuring sufficient capacity at each fast charging or battery exchange site (i.e. the facility service connection)
- There are significant grid modernization efforts underway at North American utilities for all aspects of the transmission and distribution system. Working with utility planners to help them understand current and future capacity needs can help ensure that grid upgrades will provide for current and future capacity for EV charging infrastructure installations.

While most charging will occur at home and/or work (see Figure 4 below), public charging infrastructure remains important – to serve the EVs who cannot charge at home or work, to extend electric miles for the driving days when the regional trip exceeds the electric range (e.g. running multiple errands on a weekend day), as well as to enable long-distance point-to-point use case. It is this third use case that high-power DC fast charging is best suited for.

Figure 4: Priority of charging locations (per EPRI charging guide). EV drivers mainly rely on home charging (~80% of the time), followed by workplace charging~15-20% of the time) and occasionally by public charging (~0-5%)[5]

Mass market, 200+ mile (300+ kilometer) range electric vehicles have already arrived on the US market, starting with the General Motors’ 238 mile Chevrolet Bolt which arrived in California and Oregon in late 2016. Tesla has received nearly 400,000 reservations (deposits) for its Model 3, which has been announced to arrive in Q3 2017 with an estimated 215-mile (345 kilometer) range. Porsche, Audi, BMW, Ford, Hyundai,

[5] A U.S. Consumer’s Guide to Electric Vehicle Charging. EPRI, Palo Alto, CA: 2016. 3002009442

Toyota and other automakers have also announced electric vehicles with 200-300 mile (300-450 kilometer) range set to hit the market by 2020.

Meeting these market expectations will likely require a combination of larger batteries and DC fast charging.

2 Research Overview

EPRI's multi-faceted work on high power DC fast charging aims to examine the following topics:

- Current and future market of plug-in electric vehicles (EVs)
- Justification for higher power (up to 350 kW) DC fast charging, specifically increased EV customer satisfaction, increased utility of EVs (more electric miles), support of electric trucks, buses, and other medium and heavy-duty electric vehicles, and increased utility load
- Lessons learned from existing DC charging plaza installations
- Key points of a national DC fast charging network
- Technical specifications of high power DC fast charging on a vehicle basis
- Technical specifications of high power DC charging plazas
- Installation and operational costs of high power DC charging plazas

For more than 25 years, EPRI's experience in electric transportation, including collaboration with the utility, automotive, and charging infrastructure industries as well as EPRI's deep expertise in grid infrastructure, operations, and impact are helping guide the research.

3 Initial results

As project work continues; a few key findings are emerging.

3.1 EV Market Evolution and Justification for Higher Charging Power

Battery capacities of light-duty EVs are expected to increase over the next several years from current the 20-33 kWh range to 60- 100kWh. Current DC fast-charging power levels range from 50kW (U.S., European, and Japanese OEMs) to 130kW (Tesla). Furthermore, several U.S. and European automakers, specifically Porsche, Audi, Ford, Hyundai, Nissan, and General Motors, have discussed – or released statements of – their intention to use higher power DC fast charging on future models, with some power levels approaching 350-400 kW as seen in Figure 5.

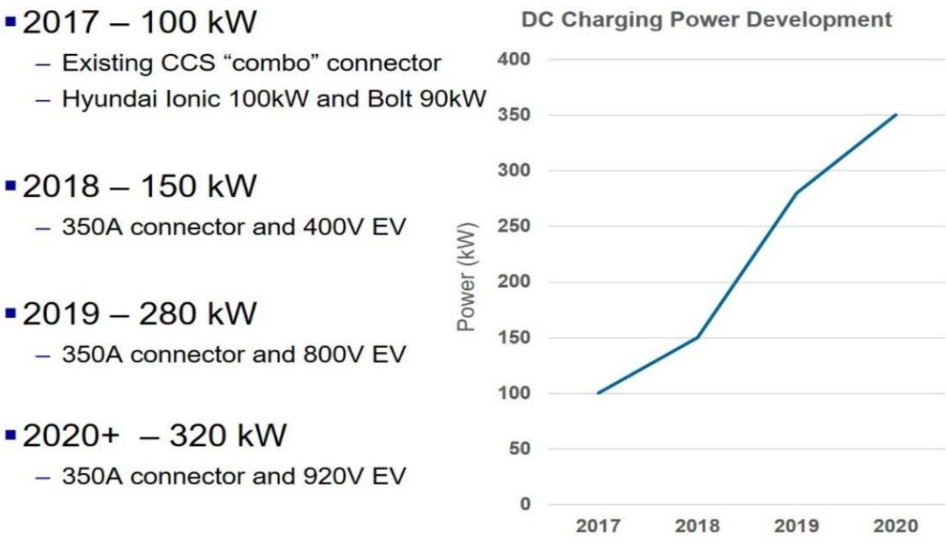

Figure 5: Progression of SAE charging standards and vehicle voltage, 2017-2021

As seen in Figure 6 below, an increasing variety and number of battery electric vehicles (pure electric) are hitting the market through 2021 which coincides with longer electric driving range. When not charging at home or work, DC fast charging will enable EV customers to drive and refuel their electric vehicle in similar fashion to the gasoline vehicle of today.

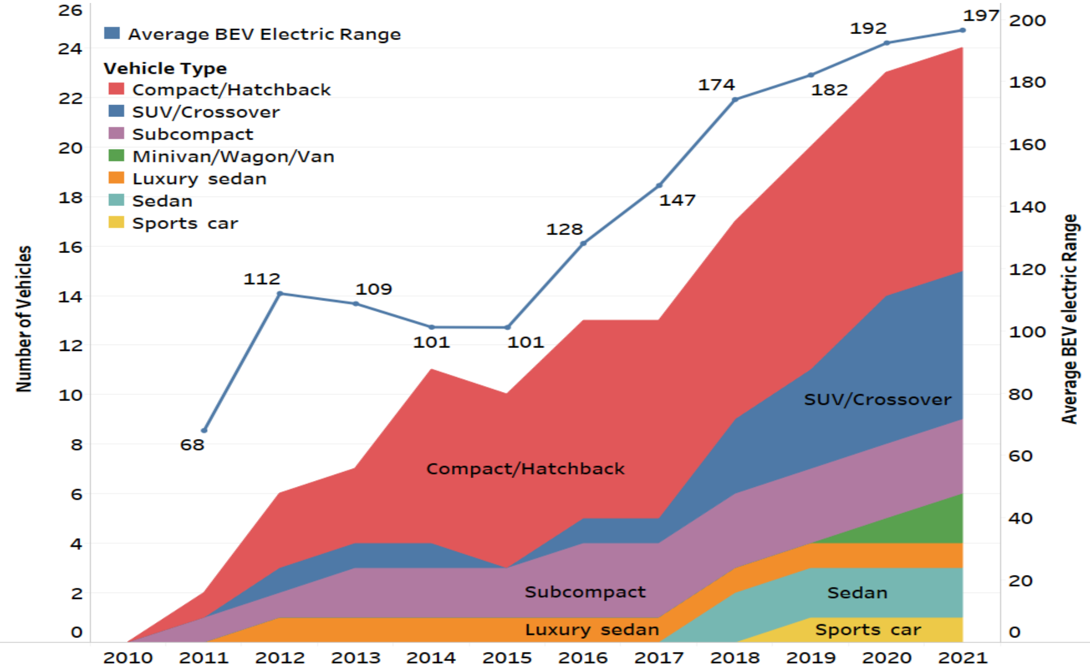

Figure 6: Battery electric vehicle market launch and electric driving range, 2010 - 2021

Plug-in versions of medium- and heavy-duty vehicles are also starting to be deployed. The use case of plug-in transit buses readily lends itself to high-power DC fast charging. Some bus manufacturers have designed charging systems to operate at power levels as high as 300kW. The SAE J3105 standard for Level 2 DC charging is examining charging rates of 1000 to 1500 kW.[6] Also, while the use cases between light-duty and medium- / heavy-duty are different, utilities, automakers, and other stakeholders can learn from the various applications of high power DC fast charging.

Table 1 shows the trend toward increased range and battery capacity for light-duty EVs. For the US market, the automotive OEMs seem to be focused on maintaining the ability to restore a significant portion of a vehicle's range (typically 80%) in under 30 minutes. Given the higher battery capacities, the only way to achieve the charging times is by increasing the power level of DC fast charging and making internal improvements in the PEV charging system, including moving from 400V to 800V EVs.

Vehicle	**Battery Capacity (kWh)**	**Range (Miles)**	**kWh per Mile**
2017 Nissan LEAF	24	84*	0.29
2017 Nissan LEAF	30	107*	0.28
2017 Chevy Bolt	60	238	0.25
Example 300 mile PEV	84	300	0.28

Table 1 – Actual and Estimated Vehicle Battery Capacities

[6] https://epri.azureedge.net/documents/Minutes-of-Bus-and-Truck-Charging-Interface-Group-Meeting-March-28-2017.pdf

3.2 Electric Vehicle Charging Infrastructure Options

There are four different options to charge electric vehicles (Table 2). They are listed by the amount of time it would take to charge a battery as well as by how expensive they are to install.

While Level 1 is the slowest option, it is also often the most cost effective and most convenient. Level 1 charging is often at home and can occur overnight. A simple electrical plug at home is sufficient for this charging option. DC Fast charging and battery swapping are the fastest options, but will also be more expensive. These options might be used during long trips or when there are no other charging options available at home or work.

Charge Type	Voltage	Power level	Ideal time constraints	Potential Locations	Time to charge (20% SOC 50kWh battery)
Level 1	120 V ac, 1 phase	0-3 kW	>8 hours	Home charging or long dwell places such as airports and overnight parking structures	~16 hours
Level 2	208-240V ac, 1 phase	3-19.2 kW	2-8 hours	Home or short dwell places. Workplace, shopping	~2-4 hours
DC Fast	200-500V dc (EVSE output)	150 kW max	<2 hours	Public fast charging to enable long trips.	~1 hour
Battery Swapping	NA*	NA*	<30 min	Public fast charging to enable long trips.	~10 minutes

Table 2: Electric vehicle charging types and characteristics

The costs to charge as the charging level often increases gets higher. The impacts to electrical infrastructure for a DC Fast charging station are much higher than those of a Level 1 or a Level 2 charger. If the cost to charge includes partial recovery of these costs, an EV driver will naturally chose the least-cost option that also meets their needs. Home charging if often the cheapest and most convenient, however it may not always be available. Here are two examples showing different charging scenarios using the different charging infrastructure:

Multi-unit dwellings

There are a few ways to charge an EV when home charging is not available as may be the case at a multi-unit dwelling such as an apartment, townhouse, or condominium. The most likely candidate is workplace charging. The electric vehicle owner can also charge weekly at a DC Fast charger (or battery swapping station if available) to fill their battery if their workplace does not have charging. The driver can also take advantage of charging (either Level 2 or DC Fast) while they are doing other things. There may be charging where they do shopping, at a park where they take their children, at a movie theater or at the library. The shorter the stay at the destination, the higher the power the charging station should have.

Long distance trips

For long distance trips where the round trip is greater than the range of the EV, plans need to be made to charge at the destination or at fast public charging along the way. Often after a couple hours driving, a stop to recharge may also be a welcome break from driving. When traveling with an electric vehicle, taking a break needs to coincide with a (DC fast) charging station or possibly a battery swapping station.

3.3 National Vision for High Power DC Fast Charging

The customer must be the center of any national fueling network. This network must be – from the customer's perspective – easy to use, easy to pay for, easy to find, safe, reliable, clean, transparent on pricing, and competitive.

As mentioned above, DC fast charging has multiple use cases, the first of which is to enable long-distance driving between cities, towns, and important destinations. A charging plaza may be like today's rest stop or service station, with a 4 to 12 DC fast charging stations ranging from 50 kW, to 200 kW, to 400 kW. Customer would pay more for higher power, just like customer today pay more for premium gas, or more similar, pay more for faster internet speeds. The initial phase of a national charging network uses an assumption of 75 miles between charging plazas. It follows the major east-west highways and major north-south freeways. This initial phase might look like this Figure 7, a proposed initial national DC fast charging map for the USA:

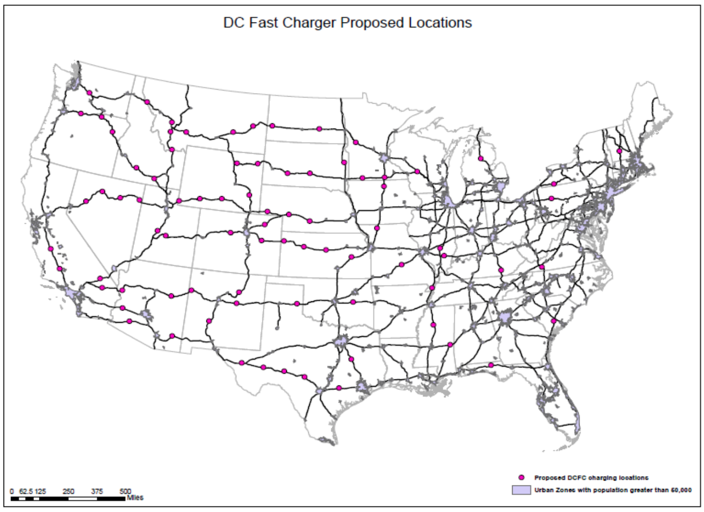

Figure 7: Proposed national DC fast charging network, outside urban areas with 75 miles spacing

3.4 Phasing of DC Fast Charging Stations

The phasing of the DC fast charging stations first addresses distance and then addresses areas with more usage. As more EVs are purchased, the charging infrastructure needs to increase. Figure 8 below shows the growth of DCFC stations over time as well as the number of EVs at the same period for each US state. While each state has different regulations and different proportions of charging infrastructure, it gives a general sense of the ratio of number of DC Fast connectors vs number of EVs by state.

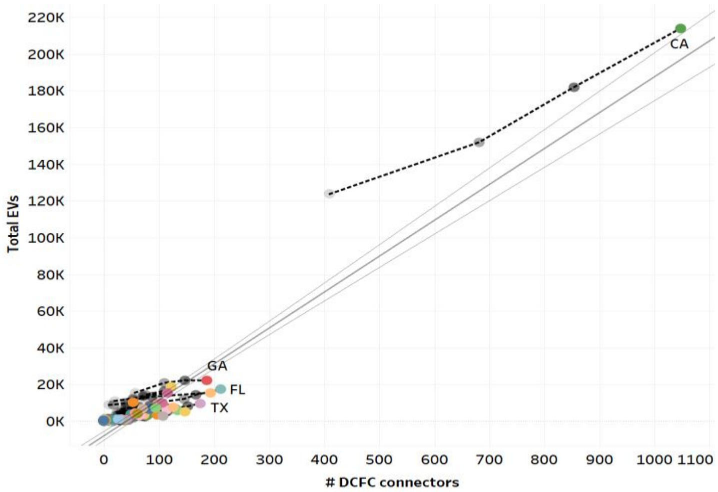

Figure 8. Number of DC Fast connectors vs number of EVs over time, grouped by US state.

This data indicates approximately 200 electric vehicles for every DC Fast charging connector.

3.5 Potential Utility Impacts

The prospect of widespread adoption of high-power DC fast charging presents potential opportunities and challenges, and raises questions for utilities and their customers.

A station of five to ten high-power DC fast chargers offers potential for increased utility load. As an example, ten 150kW DC fast chargers at a single site leads to a 1.5MW load. Eight 350kW DC fast chargers would be a 2.8MW load. While utilities are used to providing the necessary power and energy to reliably serve large loads to commercial and industrial customers, is a question of how to scale up as quickly and cost effectively as possible. Most DC charging plazas today are essentially one-off designs. Utility provides AC power, an AC meter, and rate (tariff). The site host adds the necessary electrical infrastructure including AC to DC convertors. Most of this equipment is not standardized, increasing costs and whose complexity potentially decreases site reliability. Some customers (automakers, host sites, or other stakeholders) may not know what to expect. Potential new customers and other stakeholders may be unfamiliar with both the utility process to set up such a charging site, timing, and expected costs. In addition, the various rate and technical options to help manage energy and demand costs vary with utilization. Looking at the costs and benefits of a single DC charging plaza at a single site may be much different than looking at all the stations as a portfolio serving the general motoring public.

One potential solution is for the utilities to off direct current (DC) as a service, letting this site host simply add DC-DC convertors and the DC fast charging equipment. This possible solution has many applications such as data centers, community solar, and other customer end uses and is currently being investigated by an EPRI-led public consortium of utilities, automakers, infrastructure companies, charging network companies, and other stakeholders. The goal is to understand what an end-to-end DC-as-a-service might look like, both on the utility side as well as on the site host side, and see how the installation and operational costs of a DC fast charging station served by DC-as-a-service compare to those costs of such a plaza service by the traditional AC service.

3.6 Alternatives to High Power DC Fast Charging

Battery swapping may be one alternative to high power DC fast charging. Although life-cycle battery management is important to effectively use this expensive asset, initial analysis indicates that the development of battery exchange stations is not economically prudent and a suite of charging solutions and integrated smart charging can provide the optimal solution to provide necessary refuelling capabilities to customers. This would include different power levels, technologies and potentially the integration of renewables to assist in balancing the electric power grid.

Battery swapping is not simple. Major modifications are required to the high voltage advanced traction batteries to safely interface to the vehicle. The normal batteries are designed to be structurally integrated into the vehicle, survive crash events, link into the electrical/control system and have sophisticated interconnects with a liquid-cooled thermal management system. These complexities create technical challenges for the fast battery exchange.

Battery swapping to provide extended range and quickly refuel EVs has been considered a novel concept in the industry. Trials have been conducted by both Better Place and Tesla over the last five years with neither currently operational. Better Place was an Israeli-based start-up located in Silicon Valley starting in 2007. Better Place attempted to operationalize the battery swapping concept to extend the range of EVs. To make the business model work, heavy subsidies favoring electric vehicles were applied in Israel and Denmark, the two launch markets. Customers in Denmark, for example, purchased the vehicle (an 80-mile range vehicle) for $37,000 less the battery and paid an additional $12,000 for a 4-year contract including charging and swapping privileges. Ultimately, Better Place went bankrupt after selling a few hundred vehicles and installing a few swapping stations.[7] Efforts to work with OEMs were not successful, with the mainstream manufacturers citing their desire to extend range by faster charging or on-board range extenders.

Better Place filed for bankruptcy in the spring of 2013 after nearly $1B in investment. Better Place's individual swapping stations cost about $2M and could exchange an empty battery with a fully charged one in about 5 minutes. For the concept to work, all the batteries must be the same size and shape to minimize both battery inventory and unique tools and fixtures. Customers paid $250 per month for Better Place using the Renault Fluence ZE electric car.

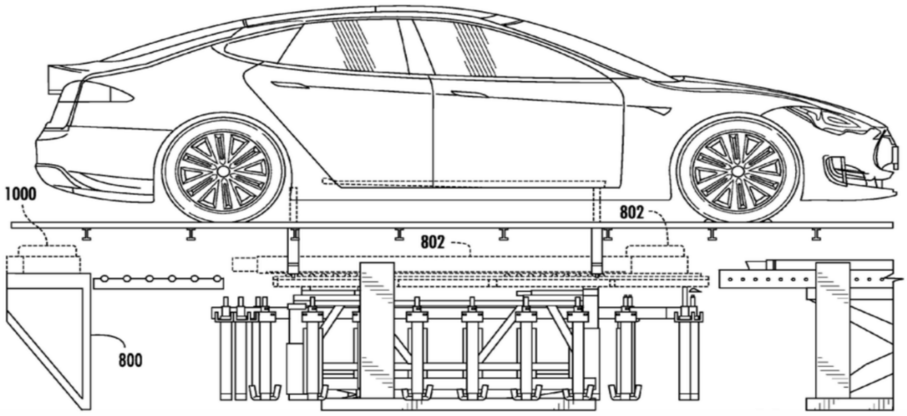

Figure 9, Tesla Patent for Swappable Battery Tooling

Tesla has also investigated battery swapping as an option by testing a swapping station in California. The price for a swap was $60 or over 5 times the cost of electricity. Tesla also received additional ZEV Zero Emission Vehicle credits for executing swaps. This trial was not intended to replace the Supercharger fast-charging network which continues to expand in the US and globally.

Figure 9 above highlights the mechanism required to execute a battery exchange. The process itself is quite complicated with significant investment required to automate the process. Elon Musk, Tesla CEO, has stated that there was not much interest from customers with a low take rate to battery exchange trial invitations (about 2%). Concerns were also raised on the condition of the batteries received as well as quality concerns. Battery swapping is no longer being pursued by Tesla which is now focusing entirely on Supercharging and as charging needs will increase with the launch of the Model 3 later in 2017.

For the battery swapping concept to potentially succeed, many enablers must be in place. First, a significant commitment to building the swapping station infrastructure (could exceed $100M investment) must exist. Advantageous subsidies must be in place vs. conventional vehicles. Careful site selection can focus on high travel routes and areas (perhaps a commercial trial with predictable routes), and support additional trips. Financial support for the working capital is necessary given the battery inventory that must be maintained for the specific batteries that can be switched. It should be noted that full charging infrastructure is required when employing battery swapping since each pack must be re-charged at the swapping station as well as necessary safety measures to store and maintain the battery inventory.

Although the industry has moved towards a fast charging network model for distance travel needs, battery swapping capability may still be quite useful for service and exploring life-cycle management business opportunities for the battery and back-up energy storage for the grid. It is unclear whether 5-minute charges can be achieved. Fast charging now offers 30-minute charging which gives nearly 80% of an EV's full range.

[7] https://www.fastcompany.com/3028159/a-broken-place-better-place

One advantage of battery swapping is that they can 'charge' a battery faster than a DC fast charger, approximately 10 minutes, which then can be recharged overnight when there is less load on the grid. However, assuming a battery swap takes 10 minutes, if a battery swapping location swaps batteries consistently for 12 hours, then numerous batteries must recharge overnight. If a 50-kWh battery is swapped out every 10 minutes for 12 hours, that leaves 72 batteries to be charged overnight, at a total of 3600 kWh. If these 3600 kWh can be spread over 12 hours creates a continuous load of 300 kW. The number of chargers needed to facilitate this charging is based on the charge level. At 20 kW AC Level 2, 15 charging connections would be needed.

Some of the variables to consider when considering a battery swapping station are:

- Battery swapping time
- Number of batteries that can be swapped at one time
- Number of hours in the day available for charging
- Station power limits
- Space for charging
- Trade-offs for battery inventory carrying costs versus desired customer service levels

Lastly, it is important to understand battery swapping's compatibility with existing automotive design and manufacturing norms. For a variety of competitive reasons, automotive manufacturers understandably prefer to make the battery packs unique; they simply are not interchangeable and interoperable. Similar, there are no standards that exist for EV battery packs to serve like common household batteries. In comparison, modern EVs are designed around battery packs tightly integrated into the overall vehicle architecture, making each vehicle battery pack unique in a variety of ways. This poses perhaps the greatest challenge in making battery swamping as a form of 'recharging' the EV batteries mainstream. This is unlikely to change in the next generation of EVs for at least a decade.

Fast Charging Infrastructure Considerations

DC fast charging (and battery swapping) are the most expensive to install and therefore need to be most strategic in terms of spacing. The remainder of the section focuses just on fast charging infrastructure (which can be either DC fast chargers or battery swapping).

As mentioned above, there are many charging levels as well as locations to charge an electric vehicle. Longer dwell locations such as home, work or at shopping centers are an easy way to let people charge while they continue to engage in the activities that they already do. However, to enable long distance trips for intercity or vacation driving, a fast charging infrastructure is needed. These chargers can also be used by those who do not have a convenient home or workplace charger.

Placing DC fast chargers at current gasoline stations, rest areas, or travel centers allows a new EV driver to visit a familiar place for charging. Furthermore, accompanying infrastructure such as washrooms, concessions and lighting is already in place. The minimal number of fast charger stations needed in each region is based solely on the range of the vehicle. This minimal spacing enables a vehicle to travel across an area. As more EVs enter the market, more and more charging connectors are needed to support them. Therefore, fast charging station placement has two phases; the first to enable long trips and the second to address areas where people are charging the most. For this second phase, additional DC fast chargers are needed in areas of high adoption and where there are not many home and workplace charging options.

4 Conclusions

Coinciding with the arrival of longer range (200 mile+) plug-in electric vehicles, higher power DC fast charging of electric vehicles is coming in the next few years, leading to 2-4 MW charging plazas. A vision as well as key learnings from existing DC fast charging stations are needed to swiftly and economically scale a national network of high power DC fast charging across North America.

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