EV Fast Charging, an Enabling Technology

by Charles Botsford and Andrea Edwards

What obstacles remain for mass adoption of electric vehicles (EVs)? If a portion of early EV buyers choose the high cost EV to obtain maximum driving range, and other EV buyers choose the lower cost EV and sacrifice driving range, what type of EV will auto manufacturers need to offer to capture the mainstream car buyer? The obvious answer is to offer an affordable EV that also solves the range issue. This paper looks at true fast charging as an enabling technology to accomplish this.

Introduction to the EV Driver State of Mind

The adoption of EVs from 2010 to the present has made great strides both in terms of vehicle sales and in terms of installation of charging infrastructure. The underlying reasons for the enhanced state of the EV market now versus the first incarnation of EVs in the 1990s, which was driven by air quality regulations (*e.g.*, California zero emissions vehicle mandate), are that in addition to the ZEV mandate, key drivers also include high fuel prices, the need for energy independence, and more stringent federal regulations (*e.g.*, the Corporate Average Fuel Economy, CAFE). Yet, questions remain regarding whether EV adoption can be sustained or whether the current EV market will stagnate or even decline.

What is necessary for a consumer to decide to buy an EV? The mainstream car driver has operated a regular gasoline-powered vehicle all her life and would happily continue doing that for as long as she can keep refilling her car's gas tank—affordably. That, of course, was one of the major EV market drivers after the scare of 2008 when the price of crude oil increased to $140/bbl. What happens if a driver has to pay a fortune for a gallon of gasoline?

In the 2011-14 time frame, the price of crude oil stabilized at $100/bbl and has recently declined to $60/bbl. Many forecasters project oil to remain at this low price level, possibly for several years. This will likely dampen the demand for EVs—until the next run up in crude oil prices. Price volatility and market uncertainty often drive the need for people to find alternatives.

EV Adoption Obstacles

Even with high crude oil prices, however, other obstacles remain in the path of widespread EV adoption. The two major obstacles are the price differential and limited range. For mainstream consumers to switch to EVs, they have to believe they are getting an upgrade from the gas-powered Ford, Toyota, or Chevy they have driven for years.

Early adopter EV owners have made allowances. They charge their vehicles overnight at their homes. They have secured a $199/month, three-year lease. They might have access to the West Coast Electric Highway (WCEH)[1] (Fig. 1) or Tesla's Supercharger network for fast charging. They may even charge their EVs at work to manage their long daily commutes.

Still, none of them can charge his EV in under ten minutes and then drive a hundred miles (ten miles per minute of charging). Tesla comes closest to this with their 125 kW Superchargers, which enable a bit over six miles per minute of charging. For thirty minutes parked at a Supercharger, the Tesla driver can drive about 180 miles. Is this enough to satisfy a regular car driver who is used to three minutes at a gas pump to travel 300 miles? Thirty minutes is a long time, considering the ten minutes required to exit the freeway and another ten minutes to get back on. The whole stop for a Tesla fast charge might be close to an hour.

That's the same on-and-off time for a regular car driver, by the way. The three-minute fill time is sandwiched between twenty minutes to get on and off the freeway, for a total potential stop time of twenty-five minutes. So a ten-minute EV charge time is a thirty-minute stop. This doesn't solve the range problem by a long shot, though, for those who want to hop in their car and drive 300 miles without stopping. Some have argued that a driver should stop every 100 miles, or an hour-and-a-half of driving time, just to take a break. The 300-mile driving-without-a-stop expectation might be mitigated with $5/gallon gasoline, but this is still an open issue.

Tesla currently serves a small subset of EV drivers who can afford large battery packs and the upfront payment for fast charging. While Tesla plans to pursue the mainstream driver, the price differential is certainly the other constraint they would need to solve to bring about widespread adoption of EVs.

Fast Charging as an Enabler to Overcome the Price and Range Obstacles

So, how do we solve the price differential and limited range problems?

Price Differential—The major EV cost component is the battery pack. Tesla currently offers large battery packs of 60 to 85 kWh to solve the range problem. An 85 kWh battery pack can allow an EV to travel up to 250 miles (assumes 75 kWh usable pack state of charge, SOC). The problems with a pack that large are weight, volume, and cost. Many other car companies have designed their EVs with 20 to 30 kWh packs. While this reduces the cost impact of the battery pack, it also results in a range of less than 100 miles. For example, a Nissan LEAF has a 24 kWh battery pack (18-20 kWh usable SOC) with a reported highway range on the order of 75 miles.

If 24 kWh is too small to satisfy the mainstream EV driver and 85 kWh is too expensive, what is a good compromise? Let's examine the characteristics of a 40 kWh battery pack. The usable state of charge is on the order of 32-34 kWh, which could result in a highway range of 120 miles, depending on vehicle weight, tires, aerodynamics, and other factors.

Battery pack price projections abound. In the early days of lithium batteries, a battery pack cost approximately $2,000/kWh. Thus, a 40 kWh battery pack would have cost $80,000. That was then. Some researchers project lithium cell costs declining to $100/kWh, but then you have to add pack structure and battery management system costs, which bring the total battery pack cost closer to $200/kWh. Thus, a 40 kWh battery pack would cost $8,000. This is expensive, but still consistent with cost models for producing affordable EVs in the $30K to $40K range.

Limited Range—What good is 120 miles of range if a driver wants to travel from Bellingham, Washington to Ashland, Oregon

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Fig. 1. *LEAF charging at Skyhomish, WA WCEH DC Fast Charging Station.*

(essentially Canada to California), which is 550 miles? EV drivers can now take that trip on the WCEH in a Nissan LEAF by stopping every 60 miles. The recharge time is about thirty minutes. Driving at 65 mph, the total trip time would be on the order of fourteen hours. The WCEH chargers are rated at 50 kW. To recharge the 34 kWh of a 40 kWh pack in ten minutes the chargers would need to be rated at 200 kW, or 60% more power than the Tesla Superchargers. The same trip with a 120-mile range EV recharging in ten minutes would take eleven hours. This is roughly the same time it would take a Tesla driver with an 85 kWh battery pack. The same driver in a gasoline car could do the same trip in about ten hours. (See Table I.)

Table I. 550-Mile Trip from Bellingham, WA to Ashland, OR

Gasoline	120-mile EV	Tesla	Leaf/WCEH
10-hours	11-hours	11-hours	14-hours

Overcoming the Remaining EV Adoption Obstacles

In addition to price and range, several additional obstacles remain. While no one can predict for sure how these issues will be resolved, it is important to highlight their significance.

Battery Technology—A significant technology advancement enabling faster direct current (DC) charging was the development of lithium titanate, a battery chemistry that allows for ten-minute fast charging. In 2007, Altairnano Technologies developed a 35 kWh lithium titanate battery pack, and was able to successfully demonstrate a ten-minute fast charge capability using a 250 kW high power DC charger (Fig. 2).

In 2011, Foothill Transit, which is a joint powers authority of 21 member cities in the San Gabriel and Pomona Valleys of California that operates a fixed-route bus public transit service in Greater Los Angeles, put EV buses into service. The buses, manufactured by Proterra, have 83 kWh lithium titanate battery packs, which are charged in ten minutes using 500 kW DC chargers. These buses remain in service today.

Today, existing EVs such as the Honda Fit and the Mitsubishi i-MiEV use the Toshiba version of the lithium titanate chemistry. This lithium chemistry is noted for its long cycle life on the order of 5,000 cycles at 100% depth of discharge, high charge and discharge power density (6c rates), excellent safety record, and long calendar life.

Grid Impacts—Utility concerns over DC fast chargers include voltage sag, poor power factor, and other issues. However, a study that examined four types of utility local distribution feeders, two at 13.2 kV and two at 26 kV show that even with multiple 250 kW DC fast chargers, grid impact could be minimal.[2] The proof of the validity of this study is in Tesla's implementation of their Supercharger network and the Foothill Transit 500 kW DC chargers.

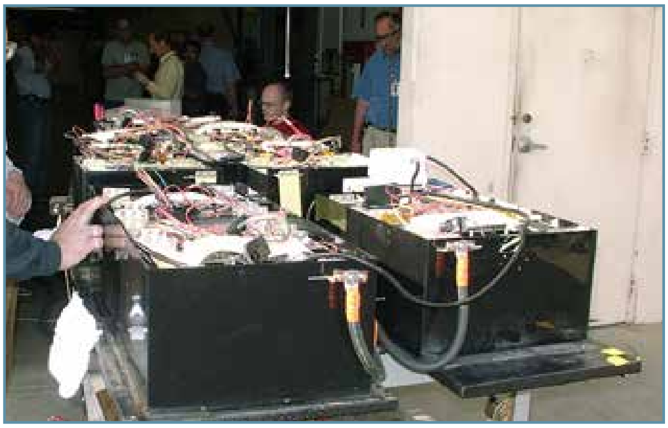

Fig. 2. *May 2007 10-minute fast charge demonstration.*

The study concluded that the effect of a proposed EV fast charging station at the 500 kW power level would be dependent on the utility system site, and that compensation techniques may be necessary. At lower levels, however, modeling showed almost negligible grid impacts for even low quality distribution circuits.

EV fast chargers typically ramp up power levels rather than supply instantaneous power. This alleviates short time scale grid shocks. They are also designed with the capability to communicate continuously with the grid. If a problem occurs with the distribution line, the utility could command the EV charger(s) to ramp down in power level, or shut down completely as a form of demand response.

For weak grid distribution lines, charging schemes that include battery storage between the grid and the charger bank, as detailed in a 2007-issued patent,[3] could provide a buffer to further reduce the potential for adverse grid impacts (Fig. 3). Indeed, utility control, coupled with a high peak use rate structure, is designed to modify consumer behavior and could minimize potential grid impacts from fast charging.

High Power Connectors—In the U.S., three high power charger connectors and their communication protocols are prominent: 1) CHAdeMO, 2) Tesla, and 3) the SAE combo. CHAdeMO, an organization that originated in Asia, now has 435 members in 26 countries. The CHAdeMO connector power level allows for charging up to 62 kW, but most chargers are 44 to 50 kW. In the U.S., the CHAdeMO chargers number over 800 as of the end of 2014. Tesla Superchargers are 90 and 125 kW in power level and number almost 350 stations with 1,900 ports in the U.S. The Society of Automotive Engineers (SAE) "combo" connectors allow for DC fast charging at up to 80 kW (typically 50 kW), combined with the SAE Level 2 connector. In the U.S., the SAE combo chargers numbered approximately 20 as of the end of 2014, according to Plugshare.[4] To charge at 200 kW or higher would require a different connector. A rumored high power DC connector from China could potentially work, but would have to gain acceptance through the standards committees.

Economics of DC Fast Charge Stations—Who would install high power DC fast charger stations? These stations are not highly profitable. A gasoline station could see $50 revenue from each three-minute fill up, times 50 fill ups per day per pump, times six pumps, or $15,000 of daily revenue. A DC fast charge station could see $7.50 per ten-minute charge, times 20 charge sessions per day, times two chargers, or $300 of daily revenue. Selling gasoline, however, is a low margin business, and the stations make money selling food and cigarettes. Adding value to the venue business model may be the real business case for DC fast chargers as well.

Today, government grants provide the bulk of funding for equipment and installation of DC fast charge stations with three notable exceptions: Tesla, Nissan, and NRG Energy (eVgo). Tesla

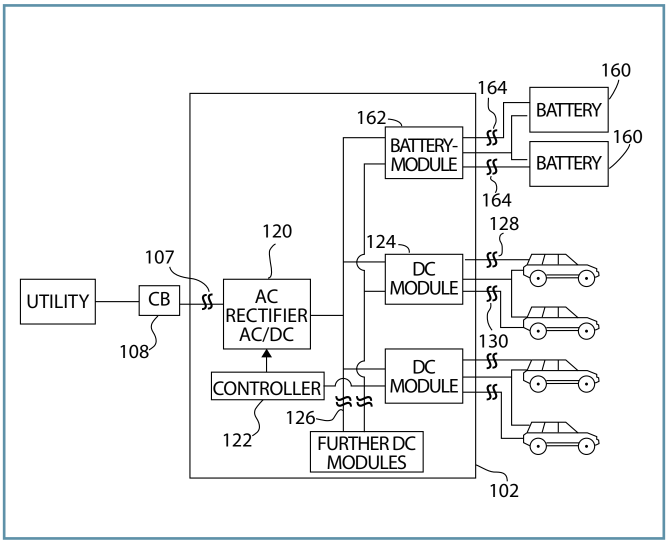

Fig. 3. *Illustration from a utility bi-directional EV charger patent.*[3]

has invested significant corporate funding and also includes fast charge access in the price of their vehicles to fund installation of their Supercharger station network. Nissan has also invested heavily in deploying DC fast chargers at their dealerships and other venues. In Texas and California, eVgo has installed significant numbers of DC fast charge stations.

Auto Manufacturers and Battery Chemistries—Switching to a fast charge lithium chemistry for some auto manufacturers will be an obstacle. Most auto manufacturers use either standard lithium chemistry (4.1 V) for their battery cells, or lithium iron phosphate (3.2 V). Typically, the higher the cell voltage, the higher the specific energy (kWh/kg). Thus, Tesla, Nissan, and many others use the higher voltage cells because they can minimize EV weight for a given kWh pack. In addition, the chemistry tends to cost less than the lower specific energy chemistries because less lithium is needed per kWh. Lithium titanate, which is a fast charge lithium chemistry, is a 2.6 V cell chemistry, which means it has low specific energy (higher pack weight). Though low in specific energy it has many other major advantages besides the ability to fast charge as mentioned above. Also mentioned above, several auto manufacturers (Honda, Mitsubishi, others) use lithium titanate for their EV packs, which means these auto manufacturers consider that the advantages outweigh the low specific energy disadvantage.

Conclusions

Widespread adoption of EVs faces many obstacles, most notably high costs when coupled with large battery packs, and limited range when coupled with small battery packs. One potential solution is to increase the traditional battery pack size to the 120-mile range, but use a lithium chemistry that allows ten-minute fast charging.

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