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July 2017

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

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U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance



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Abstract

To achieve a successful increase in the plug-in battery electric vehicle (BEV) market, it is anticipated that a significant improvement in battery performance is required to improve the range that BEVs can travel and the rate at which they can be recharged. While the range that BEVs can travel on a single recharge is improving, the recharging rate is still much slower than the refueling rate of conventional internal combustion engine vehicles. To achieve comparable recharge times, we explore the vehicle considerations of charge rates of at least 400 kW. Faster recharge is expected to significantly mitigate the perceived deficiencies for long-distance transportation, to provide alternative charging in densely populated areas where overnight charging at home may not be possible, and to reduce range anxiety for travel within a city when unplanned charging may be required. This substantial increase in ~~the~~ charging rate is expected to create technical issues in the design of the battery system and vehicle's electrical architecture that must be resolved. This work focuses on battery system thermal design and total recharge time to meet the goals of implementing higher charge rates and the impacts of the expected increase in system voltage on the components of the vehicle.

Keywords

Direct current fast charging (DCFC), battery electric vehicles (BEV), extreme fast charging (XFC), power electronics, long-distance travel

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1. Introduction

Presently, plug-in battery electric vehicles (BEVs) are not capable of charging at rates that allow for a recharging time similar to refueling conventional internal combustion engine vehicles (ICEVs). In addition, charging of BEVs at a higher power should enable more travel and allow the driver to take advantage of lower electric fuel costs, thus improving the economics of BEV ownership. This work will explore the vehicle design considerations that require research, development, and deployment (RD&D) activities to meet the challenge of providing BEVs with similar performance to that of ICEVs. This work will include analysis of the drivetrain and auxiliary components of the vehicle with the exception of the battery cell- and pack-level considerations, though the battery system capacity and system thermal performance will be explored. In addition to this article, battery cell and pack design RD&D are described in the companion articles “Enabling Fast Charging – A Battery Technology Gap Assessment” and “Enabling Fast Charging – A Battery Thermal Management Gap Assessment.” The economic and infrastructure challenges of charging stations to support these vehicles are discussed in “Enabling Fast Charging – Infrastructure and Economic Considerations

In the current market, Tesla vehicles offer the fastest recharge rates with 120 kW from most of its Supercharger stations [1], though it is believed that some of these chargers can support up to 145-kW charging [2]. Porsche has demonstrated the Mission E concept vehicle, which can support up to 350 kW from a d.c. fast charger (DCFC) that operates at a d.c. voltage of 800 V. Porsche has plans to go into production with a vehicle based on this concept in 2020 [3]. Other BEVs in today’s market, such as the Nissan Leaf and BMW i3 [4], have been designed around the prevailing 50-kW DCFC infrastructure [5]; however, the [Chevrolet Bolt is reported to extend this power up to 80-55 kW \[6\] utilizing a DCFC with 150 A capability \(or 60 kW rating](#)

at 400V). Meanwhile, BEVs are expected to continue supporting home and workplace charging with a.c. onboard chargers where DCFC infrastructure is expected to expand charging coverage and convenience for BEV drivers. It remains to be seen what the impacts, in terms of cost to the vehicle and battery system, would be incurred to exclusively provide DCFC for refueling.

However, to provide a refueling time comparable to that for an ICEV, it has been proposed that charging power will need to increase from the existing maximum of 120 kW to at least 400 kW, which we will refer to as extreme fast charging (XFC). This XFC will likely require an increased battery voltage rating from the existing 400 V consensus of passenger vehicles to reduce charging current and manage the cable size of the charger. A detailed discussion around this voltage change for the charging connector cable is included in the infrastructure and economics paper *Enabling Fast Charging – Infrastructure and Economic Considerations*. In this paper, we will consider an 800- to 1,000-V range as the design criterion for XFC. Table 1 defines future BEVs and compares differences between current or existing BEVs and future BEVs. The defined future BEV characteristics will be used for the analysis in this paper.

Table 1. Comparison between existing and future BEVs

	Existing BEVs	Future BEVs
d.c. charging power	50 - 120 kW	> 400 kW
Battery pack voltage	400 V for passenger vehicles [7] 800 V for some commercial vehicles [7,8]	800 – 1,000 V
Battery pack capacity	20 – 90 kWh	> 60 kWh
Vehicle range	80 – 300 miles	> 200 miles
Charging connector	SAE J1772 CCS, CHAdeMO, Tesla	Revised CCS and CHAdeMO or a new XFC connector

The objective of this work is to assess the impact to the vehicle due to the transitions of charging power, battery pack voltage, and battery pack capacity as proposed in Table 1. To assess this impact, the work will (1) evaluate the technical factors that limit XFC with respect to the BEV, (2) identify the factors that limit the operation of BEVs with respect to ICEVs, and (3) define key

areas where the U.S. Department of Energy can play an active role in performing RD&D support for advancing the implementation of XFC capability in BEVs. In addition to surveying literature and the expertise at the national laboratories, the team engaged industry to identify the key questions that need to be addressed to successfully implement XFC. These include understanding the XFC use cases and the effect on BEVs, how the BEV electrical architecture will be impacted by XFC, and finally understanding how XFC will impact the vehicle charging system design.

2. XFC Use Cases and Effect on BEVs

Primarily, existing BEVs are charged with low power (1.4 to 7.2 kW) level 1 and level 2 electric vehicle service equipment (EVSE) at home and in the workplace. However, XFC can be a supplement for unplanned trips or for daily charging in regions without home or workplace access to level 2 EVSE, such as multi-unit dwellings and dense urban environments [1]. Further, XFC can benefit other use cases such as long-distance travel or in taxi, commercial, and other shared fleets. We have identified the following design considerations that need to be addressed for XFC and will examine intercity travel impacts on battery capacity in the subsequent sections.

- How will these differing use cases (taxis, fleets, urban, rural, etc.) impact the frequency and duration of XFC events, and what effect will this have on vehicle design?
- How will the price of an XFC event affect whether drivers choose to charge at an XFC given no immediate travel need when level 2 EVSE is an alternative, and how does this impact vehicle design for battery life constraints and charging component design?
- Does XFC present an opportunity to allow a high level of electrification for autonomous vehicles and shared taxis?

- How can XFC handle regional differences such as electric vehicle (EV) credit, climate, and urban design in the Northeast, high commute miles in California, and rural applications?
- How does XFC affect the desired range and battery capacity of a BEV?

2.1. Intercity Travel Analysis for XFC

Intercity travel has been noted as the driving rationale for XFC as a means to enable BEV travel that is comparable to ICEV travel. The analysis in this section will examine the travel time of existing BEVs as illustrated in the example shown in Figure 1 for a trip from Salt Lake City, Utah, to Denver, Colorado. [The methodology used for determining the charging time required for each BEV scenario in this analysis will be detailed following the description of all travel scenarios which are summarized in Table 2.](#)

[As a baseline,](#) the trip is about 525 miles and takes about 8.4 hours by an ICEV with one refueling stop that lasts 15 minutes. This stop is assumed to take about 10 minutes for setup, which includes activities such as taking a detour to a fueling station, waiting in a queue, setting up the dispenser, and paying plus five minutes for fueling of the ICEV [9]. [The travel time for the ICEV and all BEV scenarios are calculated using an average travel speed of 65 mph.](#) If the same route is driven with a 200-mile BEV, at least two charging stops would be needed to account for the shorter range of the BEV.

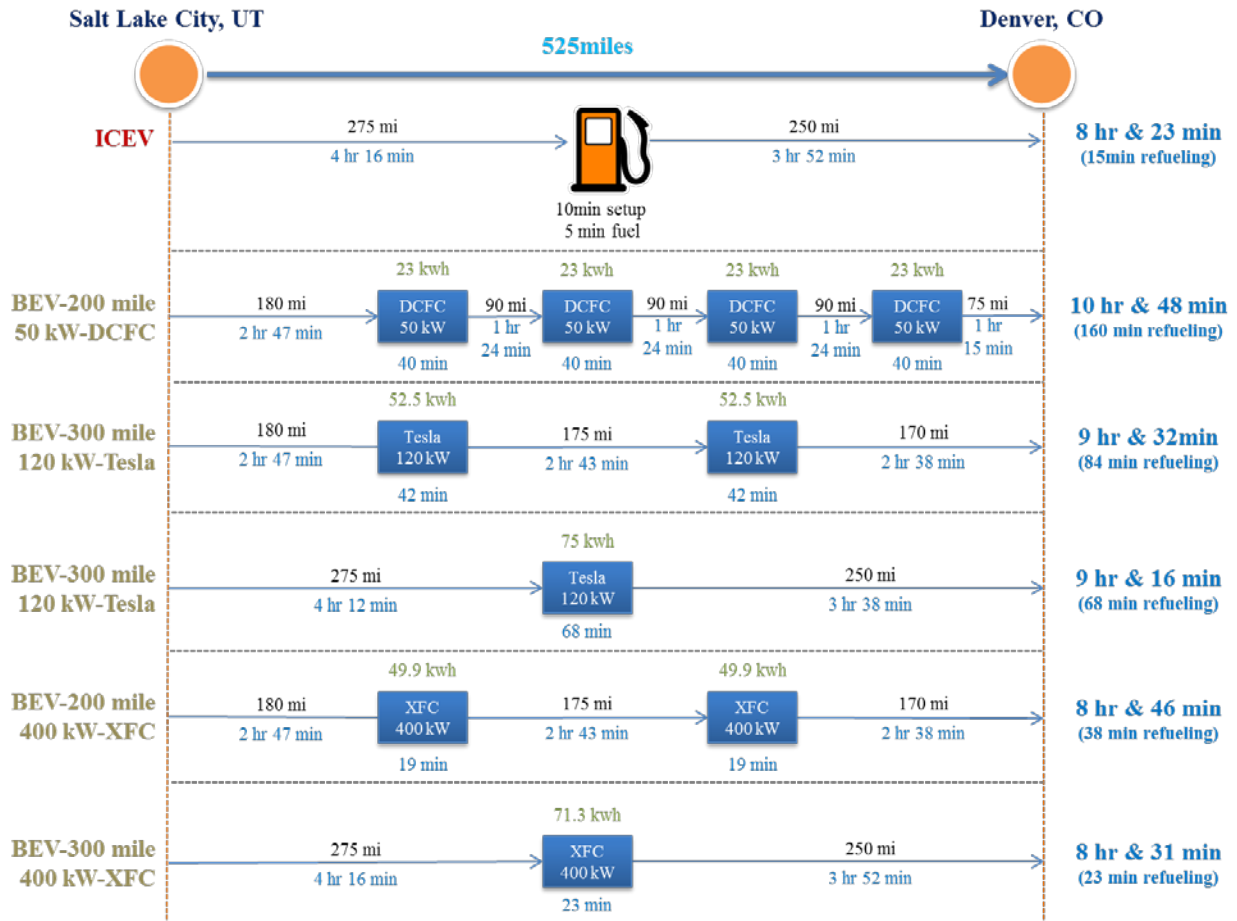


Figure 1. Intercity travel from Salt Lake City to Denver

Starting with the 50-kW DCFC and 200-mile BEV scenario, it will take more than one hour to fully recharge a nearly empty battery. This is generally not acceptable to drivers on long trips where there is an expectation to keep moving. Therefore, we adopt a 30-minute charge with an additional 10-minute penalty for setup in this analysis. The DCFC replenishes only 90 miles of range, and so there would need to be four charging stops. The driving time between successive recharging events is 1 hour and 24 minutes, which is much less than the expected driving time for ICEVs. The limited recharge capability of the 50-kW DCFC and this vehicle range impact the average driving speed over the entire route drastically. The total charging time would be 2 hours and 40 minutes, which requires 28.8% more time to travel the same route than in the ICEV

case. The following example is of a 300-mile BEV that can charge at 120 kW using the Tesla DCFC but maintains a 200-mile range for comparison to the 200-mile BEV. The 175-mile recharge, which takes 32 minutes, allows for two recharge stops and would result in the trip finishing in 9 hours and 24 minutes. The total travel time would be about 13.7% longer for the Tesla DCFC solution than with an ICEV. However, if the 300-mile BEV were to use its full range for only one recharge stop, as shown in the next example, then the total trip time is reduced to 9 hours and 8 minutes with a total charging stop time of 68 minutes. This results in a modest improvement of 16 minutes in travel time over the 200-mile range case or about 10.5% longer than the travel time with an ICEV.

The proposed 400-kW XFC would allow for a 200-mile BEV to reduce the travel time even further, but would still require two recharge stops. These stops would take about 19 minutes for the same 175-mile refuel as the Tesla DCFC but with 9 minutes of charging instead of 32 minutes. The total travel time becomes 8 hours and 46 minutes which is 4.6% longer than the ICEV. A higher BEV range is required to reduce the number of charging stops and further decrease the total travel time as the time penalty for exiting the travel path and starting the charge becomes a greater proportion of the total refueling stop time. A 300-mile BEV requires one recharge stop in this example and is expected to replenish 250 miles in 13 minutes of charging. The travel time would be 8 minutes longer than the ICEV or about 1.6% longer. Table 2 summarizes the parameters used in this analysis of intercity travel as well as some travel results.

Table 2. Summary of Intercity Travel Analysis

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Vehicle Type	Drive Efficiency (Wh/mi)	Range Charged (mi)	Charge Event Time (min)	Charged Capacity (kWh)	Capacity Charged (% of rated)	Time Driving (% of total)	Travel Time (% increase)	Total Travel Time (h:m)
ICEV	N/A	300	5	N/A	N/A	97.0	0.0	8:23
DCFC BEV 200	256	90	30	23.0	38.3	75.3	28.8%	10:48
Tesla BEV 200	300	175	32	52.5	58.3	85.3	13.7	9:32
Tesla BEV 300	300	250	58	75.0	83.3	87.8	10.5	9:16
XFC BEV 200	285	175	9	49.9	76.7	92.8	4.6	8:46
XFC BEV 300	285	250	13	71.3	75.0	95.5	1.6	8:31

[Charging times for the DCFC BEV and Tesla BEVs used in t](#)This example trip from Salt Lake City to Denver has [been](#) calculated based on the published charging time for the Chevrolet Bolt [10,11] and Tesla 90D [12] by the manufacturers. These [published](#) charging times [and recharge ranges](#) have been translated into stored energy [using the vehicle efficiency](#) [13,14] and compared against the total energy transfer possible at the maximum rated power of the DCFC equipment for both vehicles as illustrated in Figure 2. ~~In addition~~[For comparison](#), charging times for the Kia Soul EV [15], Chevrolet Spark EV [16], and Volkswagen eGolf EV [17] have been included to represent the performance of existing 80-mile BEVs [with 50kW DCFC capability](#). [This data has been collected for multiple vehicles of each model utilizing a 50 kW DCFC rated at 100 A of d.c. current and with charging tests that start from a low SOC \(3-8%\) after the vehicle has rested in a controlled 25°C soak condition.](#)

The triangle markers indicate the selected charge time and energy transfer for each stop in the analysis above. These charge times are greater than that indicated by the dashed lines, which

specify the energy that could be transferred at the respective 50-, 120-, and 400-kW constant power rates. This increase in charge time is expected based on battery charge rate limitations, ~~and~~ battery charge efficiency, battery thermal constraints, and d.c. current limitations of the DCFC. Lithium chemistries are restricted by an upper voltage limit to prevent oxidation of the electrolyte solvents which can occur at high cathode over-potentials. Exceeding this over-potential can lead to further oxidative side-reactions that may involve gas generation and overpressure of the cell. As a result, the vehicle battery management system will control the DCFC to modify the charge current and avoid these conditions. Charge control methods are devised by the vehicle manufacturer and more detail on the many aspects of the possible methodologies are found in [18–22]. A combination of these limits explains The effect of this control is ~~an~~ the upward bend in stored energy versus charge time from the constant power line when as each vehicle model reaches the end of its charge as shown in Figure 2.

The power ~~rating~~ of the chargers in the analysis above are indicated at 50 kW for the DCFC and 120 kW for the Tesla DCFC instead of the DCFC-rating of 6080 kW and 145 kW as the charging time curves in Figure 2 show that the charging times of the Chevrolet Bolt and Tesla 90D are more consistent with these lower constant power rates. Theis difference difference between the constant power level and rated power-illustrates the potential for a mismatch-that the time-averaged charging capability between-the will be less than DCFC capability; which areare typically based-on maximumdefined by the maximum charging current but using a voltage beyond the typical charge voltage of a connected vehicle,-and the connected vehicle charge capability. However, ~~may can~~ vehicle manufacturers may recommend charging with a higher power-rated DCFC; as seen in the Chevrolet Bolt user manual with an 80 kW DCFC[11], in

order to ensure sufficient d.c. charging current during the beginning of the charge when charging voltages are lower.

Charging times of 9 and 13 minutes have been adopted for the hypothetical XFC 200-mile and 300-mile BEVs based on an assumed 20-mile per minute charge capability target for these vehicles. This equates to an average charged energy of 5.7 kWh per minute, which is effectively a 342-kW charge rate. This is a significant improvement over the Tesla vehicle, which achieved an average charged energy of 1.6 kWh per minute (98.4 kW) for the 175-mile recharge and an average charged energy of 1.3 kWh per minute (77.6 kW) for the 250-mile recharge. It is expected that an XFC vehicle will not be capable of charging at the full rated 400-kW power for the entire charge period due to battery life and thermal limitations. However, calculation of the exact limitations will require additional work to understand the battery chemistry and thermal cooling performance for the battery systems in these future XFC vehicles. Further, the XFC infrastructure design has been proposed to this point as a current-limited device at 350 A with a peak of 400 A. This means that it will only be able to transfer the full power rating at the 1,000-V maximum rating and will have reduced power transfer performance based on the inherent voltage window of the battery system unless higher current ratings are considered.

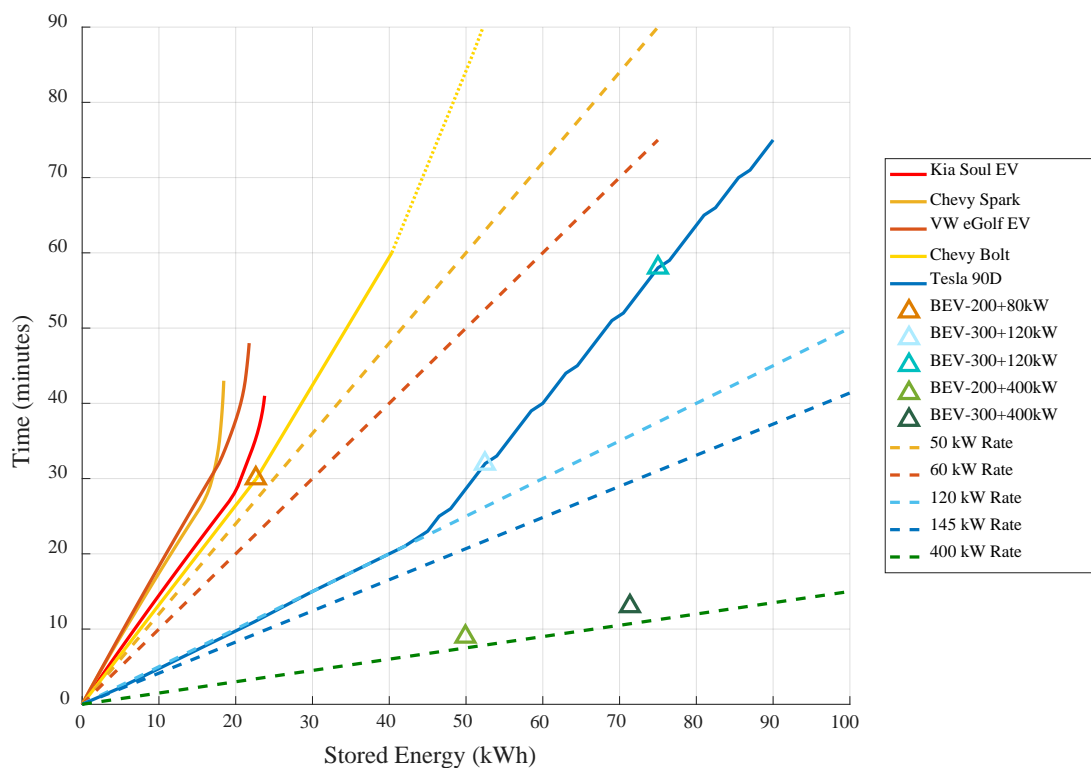


Figure 2. Charging time and energy comparison [2,10–17,23]

2.2. Range and Battery Capacity for XFC Vehicles

There is tradeoff between maximum charging rate and battery capacity as alluded to in the intercity travel example. Assuming that XFC at 400 kW is available; driving on highway corridors can be estimated to be as described below. BEVs with various battery sizes (30 kWh, 60 kWh, 90 kWh and 140 kWh with 85% usable energy) are considered on the 525-mile corridor. They may need one or more stops for charging during this trip.

As a more conservative approach than the scenario presented in the previous section, we adopt travel at 80 mph which results in a midsize BEV consuming approximately 35 kW power. For a BEV with 30-kWh battery pack with 85% usable state-of-charge (SOC) window, the effective range will be approximately 60 miles, before which the vehicle will have to stop traveling to

recharge. Similar to the previous example, we assume a 10-minute penalty for activities such as taking a detour to a charging station, paying, waiting, and setting up the charger. Once connected, we assume that the charger can charge the vehicle at a constant rate of 400 kW. For the sake of comparing the effect of energy capacity on a BEV, this analysis assumes that there is no limitation from the battery or thermal system that prevents charging at the full power rate of the XFC infrastructure. For a relatively small (30 kWh) EV battery pack, this would mean a full charge in a little over 3 minutes and a charge rate in excess of an 12 C-rate. Although it achieves a very quick charge, the distance that can be driven with a full charge also is smaller with smaller battery pack. A BEV with a 30-kWh pack will have to stop for charging again after another 45 minutes of driving. Apart from the inconvenience of frequent stops, this adds to the overall driving time as shown in Figure 3. Further, as the battery pack size increases, the frequency of charging decreases along with the overall time taken by the trip.

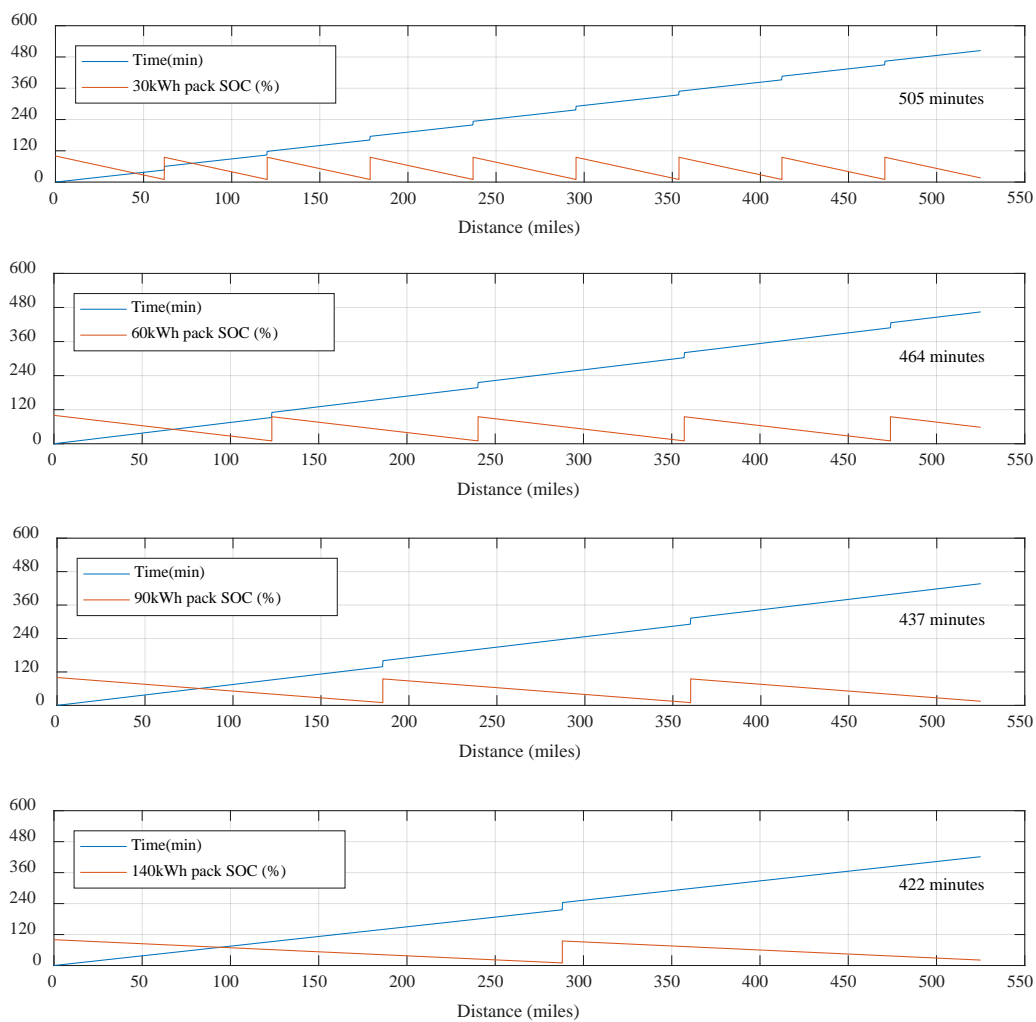


Figure 3. Battery capacity and travel distance simulation

From the feedback received during the XFC meeting with industry representatives, it is believed that for extended travel with a BEV that a stop after every 2 hours might be an acceptable limitation. This 2-hour minimum points to the need for a battery size greater than 60 kWh. However with the price differences in battery, gasoline and charging costs, we might also see changes in the consumer behavior.

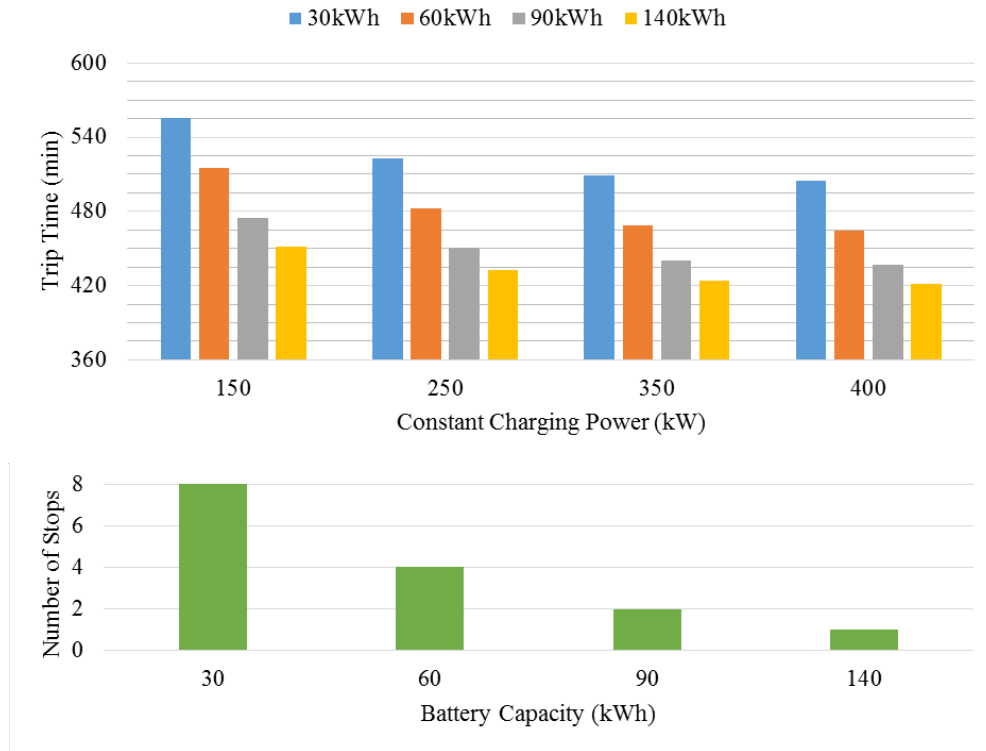


Figure 4. Estimated 525-mile trip at 80mph for different capacity and charging power

As we see in Figure 4, the increase in battery size and higher charging power can bring down the overall trip time. This lowered trip time is achieved by reducing either the number of charging events or the duration of such events. The 140 kWh pack needs only one stop for charging, but the 30 kWh pack will need as many as 8 stops for charging. If the charging is planned to end the drive with a fully depleted battery, we might be able to reduce the overall charging time a little bit for all vehicles, but the penalty associated with stopping for charging remains the same.

If we measure long distance driving by the trip time alone, then a BEV with a 140 kWh battery pack capable of charging at a 150 kW could be comparable to one with a 90 kWh battery pack with a 250 kW charging capability. Similarly, a BEV with the same 140 kWh battery capable of charging at 250 kW achieved a 5 minute advantage to one with a 90 kWh battery pack with a 400 kW charging capability.

The battery size selection will vary based on the assumptions. If we assume a lower driving speed 65mph, and an electrical power consumption of 285 Wh (mile)⁻¹ to be consistent with a more moderate driving requirement, the driving time for the same 525 mile drive will be different. Figure 5 shows the estimated trip time with these assumptions. It is interesting to note that if the vehicle energy consumption is lower, both 90 kWh pack and 140 kWh pack can complete the trip with just one stop for charging. The larger pack takes longer to charge, hence this results in a slightly longer trip time. While 90 kWh pack finishes the trip almost fully depleted, 140 kWh pack will still be almost full. Based on the assumptions made for vehicle usage, performance, component cost and convenience costs an optimum choice could be made for the battery size.

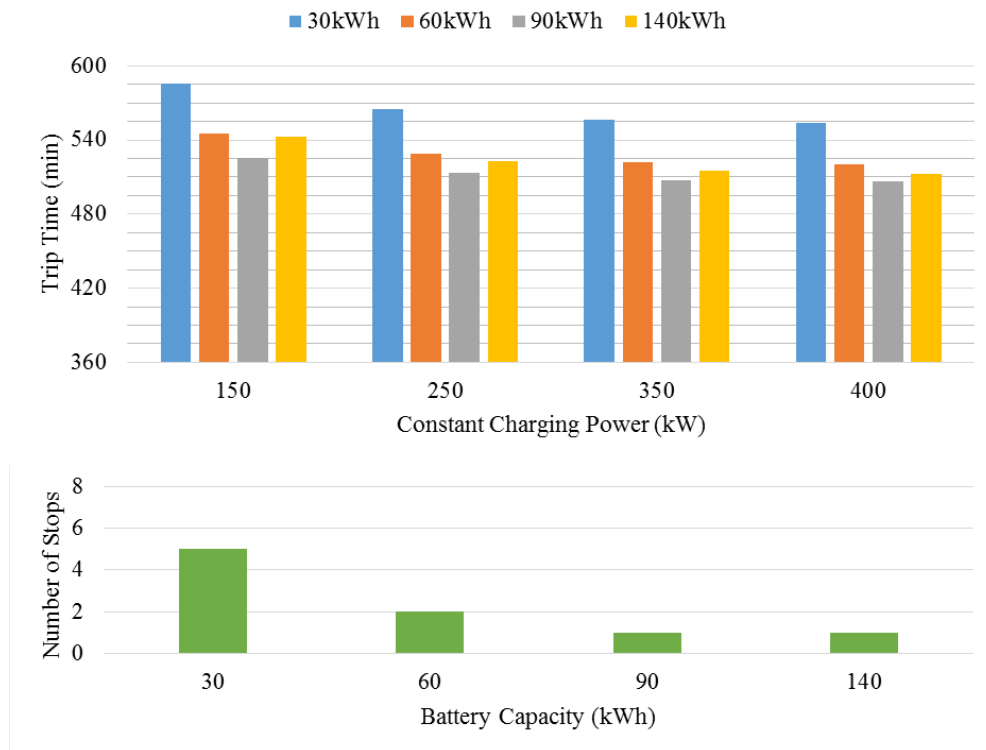


Figure 5. Estimated 525-mile trip at 65mph for different capacity and charging power

An economically optimum choice could be found with the right sized battery and charge rate, once more is understood for estimated cost of XFC at these power levels and cost of advanced batteries. The analysis presented here assumes the battery capacity and charging rate are independent of each other for simplicity. However, the maximum charging rate for a given battery will have some dependence on the battery capacity. This may result in a situation where larger capacity vehicles are a byproduct of designing battery systems to meet the high power rating of the charging infrastructure.

3. BEV Electrical System Impacts for XFC

Electrified vehicles ~~in~~ for the light-duty passenger vehicles market have powertrain systems with voltages in two stratified regions: that of relatively low 12- to 48-V systems for mild or “start-stop” hybrids, and around 400 V for full hybrid EVs and BEVs [7,8]. These voltage ranges have been driven by the relative power level required of the powertrain. XFC has the potential of creating an additional voltage class for EVs in the 800- to 1,000-V range, in this case based on the need to reduce current for charging the battery. However, this increase in voltage may benefit the application of BEVs in the light-duty truck class of passenger vehicles with increased power capability, which is an area that BEVs have seen limited exposure. We have identified the following considerations that will need to be addressed for XFC. The subsequent sections will examine electrical architecture approaches and the impact on power electronic components.

- What are the impacts of higher battery voltage on powertrain component volume, mass, efficiency, and cost given the duty cycle of the vehicle?
- Does increased voltage impact considerations of personal safety and first response and are the existing design approaches sufficient to mitigate these concerns?

- What are the impacts to hybrid EVs, plug-in hybrid EVs, and existing BEVs that use a lower voltage than new XFC-enabled vehicles?

3.1. Electrical Architectures to Support XFC

A higher charging voltage will reduce the cable size between the charger and the vehicle; however, this requires an innovative power electronics architecture and component changes inside the XFC-capable BEV. There are at least four options for XFC voltage-capable BEV architectures as shown in Figure 6. For simplicity, the 800- to 1,000-V range considered in this work will be shown at the system maximum of 1,000 V.

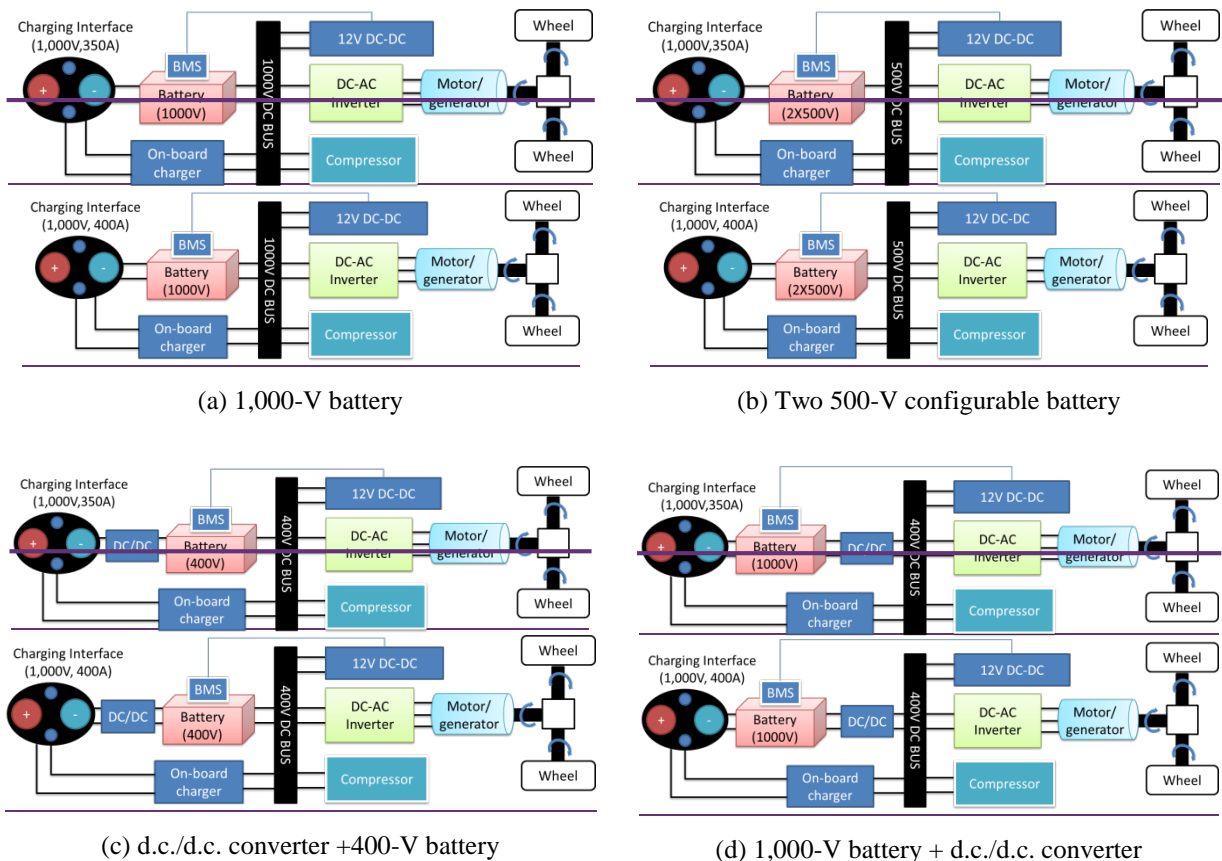


Figure 6. Options for 1,000 V BEV Architectures

The first option as shown in Figure 6(a) adopts the existing BEV architecture, but upgrades each component to support 1,000-V and 400-kW charging. A discussion of the impact to the power electronic component design for this voltage change is included in the following section.

The second option, shown in Figure 6(b), is to design a configurable battery that can connect in series to provide 1,000 V for charging and connect in parallel to provide a 500-V d.c. bus for driving. This architecture requires a complex battery management system and electronics to flexibly convert the battery connection from series to parallel and vice versa. Implementing a flexible series and parallel connection can be challenging as two series battery strings will have different impedance and temperature condition, which could result in SOC imbalances. Charge imbalances might appear while the vehicle is being driven in the parallel configuration and while it is charged in the series configuration. After a charge event, the series-to-parallel configuration change would require balancing of each string before the vehicle is ready to be driven. This will require development in a novel battery integration, control, and management method to make this architecture feasible[24,25].

The third design, in Figure 6(c), is to add an additional d.c./d.c. converter between the charge interface and the battery to allow for existing 400-V power electronic components. The converter between the charge port and the battery would need to be capable of 400 kW to maximize the benefit of XFC infrastructure. A converter of this rating would likely negate the benefits of XFC in that the vehicle would be burdened with the additional volume, mass, and cost constraints of a converter that only provides benefit for use with XFC infrastructure.

The final design, in Figure 6(d), is to add an additional d.c./d.c. converter between a 1,000-V battery and the 400-V d.c. bus to allow for the power electronic components to remain at their

existing rating. This concept would allow for a reduced peak power rating of the converter to be around 150 to 200 kW for a typical non-performance car BEV. However, this design adds additional conversion inefficiencies that would impact total range and vehicle efficiency. A variant of this architecture where the traction inverter is rated at 1,000 V and directly tied to the battery but the auxiliary components reside on a second 400-V bus formed by a converter that is rated at a lower power level may be more realistic. This variant would allow for continued use of common auxiliary components across a manufacturer's hybrid EV, plug-in hybrid EV, and BEV vehicle models.

While these four design options of BEV architectures will have many advantages and disadvantages that make it unclear at first approach which is the best option, the first option is the most similar approach to existing design practices. Further, options 6(a), 6(c), and 6(d) require the use of 1,000-V power electronics hardware on the vehicle; therefore, in the following paragraphs we use the first option (Figure 6(a)) as an example to identify the potential challenges for the design of power electronics and other components in the electrical system.

- Existing power electronics at the 1,000-V level have proven industry-standard components and technologies; however, there is limited exposure to automotive applications in this work.
- Increased voltage will require increased insulation and creepage requirements [26] that may add volume and mass to the vehicles' electrical components, cabling, and connectors.
- Higher battery voltage will require a battery pack with more cells connected in series. This will require additional sensing and balancing circuits to monitor and balance the battery pack.

- Fusing in the vehicle from the main pack line to the sensing lines will require increased clearing ratings. This may require new materials and fuse designs to meet the low resistance requirements for high-accuracy measurements.
- Charging power of 400 kW will require battery management systems that have been designed to support high current charging while maintaining accurate SOC prediction. Further, the balancing circuit design may need to change to better manage more cells connected in series and greater imbalances due to the higher charging and discharging rates.

System voltage levels will have different impacts depending on the use case and performance level of the BEV. For example, a high-performance BEV with the associated high power levels during driving could greatly benefit from a higher overall system voltage given that energy moves into and out of the battery at high power levels more often. A common 1,000-V rating throughout the BEV will likely offer lower overall weight because lighter and smaller cables are sufficient for the higher power transport and counter the greater insulation requirements. At higher power levels, optimized 1,000-V power electronics architecture may offer improved driving efficiency by providing a much larger reduction in typical operating current. However, this will be specific to the use and duty cycle of the BEV. Similarly, BEV designs for more typical commuting and slower travel through cities may not see as much benefit from the higher voltage throughout the vehicle design. Analysis is needed to understand which electrical architecture and corresponding component design will provide the most effective design that enhances the value of XFC charging and driving efficiency given the use of the vehicle.

3.2. XFC Voltage Impacts on Power Electronics and Electric Machines

A higher XFC voltage rating will impact the design of the internal electronics for inverters which support the traction motor and refrigerant compressor as well as for the converters that support the 14-V electrical, on-board charger, and battery management systems. Switches for these devices could be replaced by 1,700-V insulated gate bipolar transistors or 1,700-V silicon-carbide metal-oxide-semiconductor field-effect transistors which are both available. However, the maturity of the metal-oxide-semiconductor field-effect transistors is not as far along as the insulated gate bipolar transistors. Further, film capacitors for the d.c. bus also exist in the 1,400- to 1,700-V range and could be substituted for existing components. However, the design of gate drivers and other sensing and control components would need to be modified to account for the higher isolation requirements.

The higher voltage in these power electronic components should reduce conduction loss of the switch, but the higher voltage could result in higher switching loss in the entire operating region. This could result in a situation where the higher switching loss cancels the benefit of lower conduction loss, but this effect will be dependent on the type of switches chosen, operating frequency, and the type of design for the converter or inverter. Overall it is possible that the efficiency of the drive inverter could be improved due to lower current levels for the same power level. However, the efficiency of the on-board charger and 14-V d.c./d.c. would likely decrease due to the higher turns ratio for an isolated transformer design.

Similarly the design of the electric machines in the vehicle would need to change as a result of higher operating voltages. This would impact the traction motor design and refrigerant compressors motor depending on the auxiliary component design for the BEV. These motor designs would need new insulation, winding, and magnetics designs to account for the higher system voltage. The higher voltage should improve power density of the motor and allow for

higher base speed operation in their design. However, changes to the insulation material or thickness could impact the thermal performance of the motor, which may lead to lower power density to achieve adequate cooling performance.

Higher voltage is expected to allow better utilization of silicon-carbide devices, and they should outperform current state-of-the-art silicon devices. Effort is needed in applying these devices to automotive systems. Specifically, package stack thermal resistance may increase, leading to reduced heat transfer and increase the need in research for thermal management and thermal reliability to meet quality and life targets. Research into materials, packaging, thermal management for the reliability of inverters, converters, and motors is needed for systems operating at these higher voltages.

4. XFC Impact on BEV Charging System Design

XFC has the potential to provide a significant improvement in the flexibility of charging to alleviate travel uncertainty issues with the long charging duration of existing BEVs. However, this places new constraints on how XFC is incorporated into the design of vehicles to account for the diversity of charging capabilities of both XFC EVSE and vehicles. Coordination will be needed to remove consumer uncertainty around charging type, duration of an event, and other factors. We have identified the following considerations that will need to be addressed for XFC in the design of a BEV charging system. The subsequent sections will examine vehicle thermal system impacts, charging interface considerations for existing and XFC BEVs, and the cybersecurity implications for XFC.

- How should the charging rate of XFC be managed based on the environment and condition of the vehicle?

- What standards are needed to enable an XFC EVSE to share in the calculation of charge rate and charge duration? What is the need for certification of pairing process and function due to too much uncertainty in both d.c. and a.c. charging today?
- Are additional standards needed to enable a BEV/battery management system to share control signals and provide display data to the station and driver?
- Will the design of an interface to support XFC allow for automated refueling?
- Could cooling on the infrastructure connector eliminate the need for cooling on the vehicle inlet? Will new material development be needed to cool down connector pin temperatures?

4.1. Vehicle Thermal System Impacts of XFC

Implementation of XFC is expected to have a significant impact on the vehicle thermal system design. Existing EV thermal systems must meet many design criteria, including requirements for the thermal management of the traction battery, power electronics, and electric motor, all under dramatically varying environmental conditions. Thermal system architectures vary in their complexity, from numerous independent thermal subsystems to a fully integrated combined system. Representative EV thermal systems use a vapor compression cycle and chiller combined with a water/ethylene glycol secondary loop to perform the critical functions of traction battery, power electronics, electric motor, and vehicle cabin thermal management. Existing design capacities for these systems are based on peak power electronics, electric motor, and battery heat rejection demands. At 70%–90% charging efficiency for the XFC event, depending on the battery cell type selected, thermal losses and subsequent battery cooling demands are expected to far exceed existing design capacities. Therefore, to meet the cooling demands of the XFC event, either the onboard thermal system capacity will need to increase significantly or an independent

cooling system associated with the XFC charging infrastructure will be necessary. Modifications to the thermal system design or incorporation of an external independent cooling system will be driven by the battery selection and associated thermal management needs.

If thermal management of XFC can be accomplished through an onboard thermal system, increased capacity will be necessary for the radiator and air conditioning compressor, as well as the battery thermal subcircuit. For the battery thermal design alone, the elevated heat rejection requirements could force implementation of direct refrigerant-based cooling of the traction battery, replacing existing water/ethylene glycol cooling designs. Alternatively, if thermal management of XFC requires an independent cooling system, it will have to function alongside the normal battery thermal management system. Therefore, redundant or shared systems would be necessary, which would require significant changes to design and control strategies.

While XFC will require changing the thermal system design and either increasing onboard or adding independent cooling capacity, intelligent thermal system design provides an opportunity to recover charging losses during the XFC event. During cold weather conditions, EV range reduction due to cabin heating can be over 50% due to the need to operate a resistive heater with the traction battery. However, stored thermal energy in the battery during and after an XFC event could be used for cabin heating with a thermal system design that utilizes this heat through a heat pump. As an example, for a 300-kg battery with heat capacity of $800 \text{ J (kg-K)}^{-1}$, a 20°C increase in battery temperature above the target operating temperature from the XFC event displaces the equivalent of 16 minutes of continuous operation of a 5-kW vehicle cabin resistive heater that would otherwise be powered from the battery, increasing the effective range of the vehicle. Additional intelligent thermal system design could enhance XFC performance, including opportunistic preconditioning of the thermal circuit prior to the XFC event. Further research on a

thermal management system incorporating XFC is necessary to incorporate the unique demand while meeting existing component requirements and optimizing the system for varying operating conditions.

4.2. Charging Interface for Existing and XFC BEVs

There is a need to select appropriate cables and connectors to support 1,000-V and 350-A XFC.

The connector shapes should be standardized to assure interoperability with new and existing BEVs. The existing connectors that manufacturers are offering have a maximum current rating of 250 A with convective cooling and cannot support 400-A XFC [27]. One option is to integrate a cooling circuit into the cables and connectors as a new liquid-cooled cable system [28,29]. The integrated cooling controller allows the system to detect when cooling is needed and activates the system as necessary. With liquid-cooled cables and connector system, charging current of 350 A and short-term events up to 400 A d.c. maximum are possible while still providing a flexible, small-diameter and low-weight cable solution [3]. Manufacturers of these cables are developing prototypes of CCS-2 (1,000 V) and CHAdeMO (500 V) cables [28,29]. A summary of the existing and proposed connectors with voltage and current ranges is included in Figure 7.

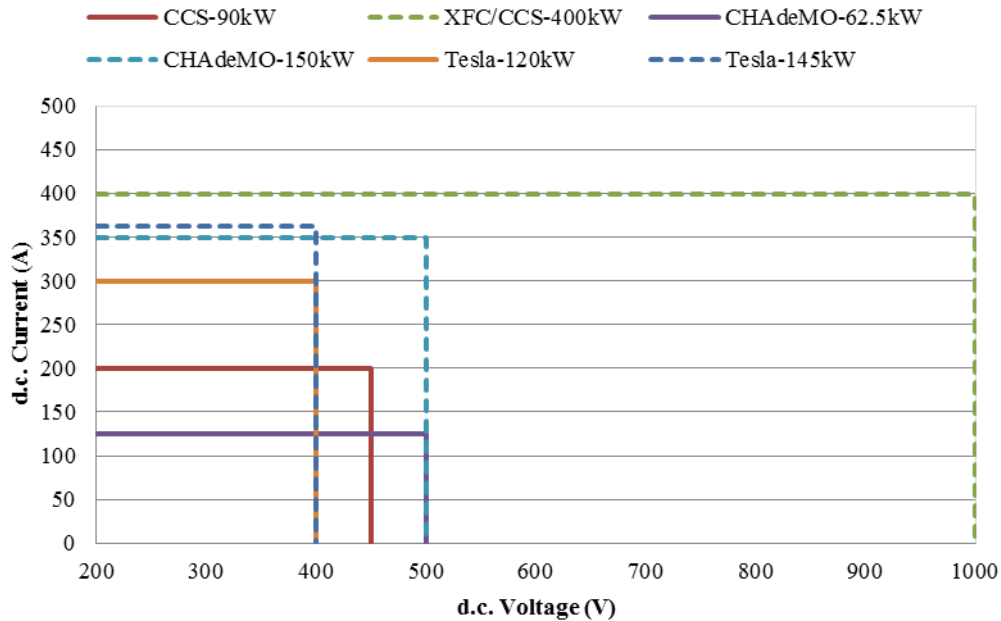


Figure 7. Charging connector voltage and current range for new and existing vehicles

Further research is needed to develop new materials to reduce the cable and connector sizes, cool the cables and connectors with liquid or other technologies, and to develop a safe and light charging cable and connector for XFC. The existing cable and material design for temperature rise of these cables may result in heavy and difficult-to-use connector solutions. Further, it may be an option to use automatic docking, where a robot arm can automatically connect and disconnect the charger to the vehicle charge interface with no input required from the driver, making it easier to operate and potentially safer. Automatic charging solutions via overhead connections have been considered in electric bus applications with charging power rates at 500 to 600 kW [30,31]. Further complicating the design of the charging connector is the concept of the extreme DCFC infrastructure providing cooling to the vehicle during charging.

Since each BEV model has a unique battery chemistry, battery pack size, and rated voltage, each BEV model will require a unique charging method. Even if the BEV models are the same, different battery SOC, states of [health](#), [health](#), and battery temperatures require different

charging rates and charging voltages. Future charging infrastructure will need to be more flexible than existing chargers in terms of the voltage and current to meet both new and existing vehicles as shown in Figure 7. A requirement for new XFC EVSE will be interoperability with existing BEVs to allow them to initiate and properly control charging voltage and current. This will require that the power electronics of the new XFC EVSE operate in the existing voltage and current range and that the communication methods remain the same.

Further, BEVs should allow the EVSE to negotiate and respond to changes in the charging power level to allow for charging to be effectively and efficiently shared at an XFC charging depot. The unused power from one vehicle can be dispensed to charge other vehicles. On the other hand, allowing power level negotiation also enables charging depots to respond to charging demand to reduce, and perhaps avoid, peak demand charges. While this may increase overall charging time, the upstream utility cost will be affected, and thus the business model for XFC charging may challenge the notion of constant fuel prices throughout a refueling event or during a business day.

4.3. Cybersecurity of BEV for XFC

XFC and existing d.c. charging require critical communication between a BEV and the charging infrastructure to coordinate charging voltage and current. Unlike a.c. charging, this creates a vulnerability in that the onboard charge controller must communicate important battery constraints to the off-board battery charger. Enabling BEVs to support 1,000-V and 400-kW XFC charging could give hackers an enticing vulnerability to exploit. The higher power level could be used more easily to impact the grid than with other components. Further, if XFC allows for a larger portion of the transportation fleet to become electrified, then a larger disruption to the transportation system could be affected by attacking this infrastructure.

Effective deployment of XFC will require that the new infrastructure is capable of charging existing vehicles. This means that the new XFC infrastructure, which is capable of applying higher voltage and current to charge new XFC-capable BEVs, will interact with less capable existing BEVs. This represents a scenario in which the existing vehicle could be exploited to request the XFC infrastructure to apply more power than it is capable of receiving. This may result in damage to the vehicle and potentially the XFC infrastructure. XFC vehicles would also be subject to the same sort of vulnerability in which the compromised XFC BEV may request power for longer than it is capable of supporting a higher XFC charge rate. Other vulnerabilities from the vehicle side exist such as the locking mechanism, which could be vulnerable to erroneously unlocking while charging the vehicle. If the user then tried removing the connector, he or she could be exposed to a shock or arc flash hazard.

The nature of XFC and existing d.c. fast chargers where vehicles may move from one charger to the next creates an interesting cybersecurity situation. As has been suggested in [32] it may be possible for a vehicle infected with malicious code to infect a charger that then proceeds to infect other vehicles. The drivers of these newly infected vehicles could then unknowingly spread the malicious code to other chargers and infect the d.c. charging network. Therefore, there is a critical need for consistent security for BEVs to ensure safe, secure, and resilient d.c. charging. The point where the vulnerabilities could be used to gain access and exploit infrastructure beyond that of the BEVs to XFC should be identified. Cybersecurity must be built into the BEV architecture, battery management systems, and XFC infrastructure.

5. RD&D Considerations for XFC BEVs

Driven by a push toward both higher-power XFC and higher battery voltage, both new and existing BEVs are facing new technical challenges and technical development opportunities. The

success of this transition will be heavily dependent on their interoperability to bridge the gap between BEVs and EVSE in terms of charging voltage and current ratings. Securing this interoperability is essential to succeed in promoting adoption of BEVs and XFC.

Existing energy-dense battery technology supports charging at a 1.5 to 2.0 C-rate. BEVs charge with a power of 50 kW for most BEVs and 120 kW for Tesla BEVs. There are two fundamental methods to transition the voltage rating of BEV architecture from 400 to 1,000 V. The first approach is to upgrade the BEV charging voltage directly to 1,000 V, but gradually increase the allowed charging current based on the battery technology. Another approach is to move to a 400-A system charging current, but to step up the BEV system voltage with the change in battery technology. There are advantages and disadvantages to each approach for the BEV architecture; however, new EVSE design to accommodate both approaches can be the same as show in Figure 8.

Charger Voltage	400V	400 - 1000V		
Charge Inlet	CHAdeMO, SAE J1772 CCS, Tesla	XFC Designed Inlet (s) for 1000V@400A		
Vehicle	400V, 125A, 50kW 400V, 350A, 140kW	600V, 400A, 240kW	800V, 400A, 320kW	1000V,400A,400kW
Battery Rate	1.5-2C	3C	4C	5C
	Today			Future

Figure 8. Timeline of BEV and battery to support XFC

Identification and prioritization of research and design challenges and opportunities have the potential to lead to more rapid generation of subsequent research to address those gaps. Table 3 summarizes the challenges of BEVs and EVSE to support 400-kW XFC and higher battery voltage.

The main challenge is how to provide interoperable BEVs and EVSE given their different voltage and current ratings. To resolve these challenges, research opportunities lie in developing new power electronic architecture, components, and interoperable interfaces to bridge BEVs and EVSEs together. Innovative system optimization methods are also needed to effectively integrate all components together to improve charging and driving efficiency. Data sharing methodologies and cybersecurity strategy should also be developed to protect the drivers' privacy and ensure safe operation of BEVs and XFC.

Table 3. Challenges and opportunities to support XFC

		New BEVs	Existing BEVs
Extreme Fast d.c. Charging	Challenge	<ul style="list-style-type: none"> • Durability of high current inlet and cable in a range of environments • Higher system voltage design may impact the mass and volume of vehicle hardware • Development of a new inlet/connector standard that is backward compatible • Cybersecurity and safety risks may increase with higher voltage • High cost of XFC may result in a large discrepancy in charging rate within the market, leading to consumer confusion • Vehicle thermal design for XFC may be costly while rarely used for some cases • Battery charge estimation and cell balance management could be more difficult 	<ul style="list-style-type: none"> • Interface interoperability issues could require software updates • Low battery voltage requires greater XFC range • Cybersecurity and safety concerns may increase with higher voltage/current and exposure
	Opportunity	<ul style="list-style-type: none"> • New material and methodology for designing high current cable and connectors • High voltage power electronics may improve vehicle efficiency • Integrated cabin and vehicle thermal designs may improve on-road efficiency • A new charging method for XFC could be automated to improve accessibility and help with automated vehicles 	<ul style="list-style-type: none"> • Higher current capability could be exploited on older vehicles • Increased infrastructure if backward compatible would increase utility of existing vehicles
Existing d.c. Fast	Challenge	<ul style="list-style-type: none"> • The d.c. voltage operating range of DCFC is likely too low for new XFC vehicles • New charge interface may not be backward compatible and may strand existing infrastructure 	
	Opportunity	<ul style="list-style-type: none"> • Existing equipment voltage range could be upgraded with lower installation costs • Some vehicle electrical architectures could allow for voltage compatibility 	
Existing a.c. Charging	Challenge	<ul style="list-style-type: none"> • Higher d.c. voltage will impact onboard charger design • Larger battery capacity may take too long to charge, especially with Level 1, though Level 2 may still be a challenge 	
	Opportunity	<ul style="list-style-type: none"> • XFC could spur increased a.c. infrastructure as more vehicles are introduced into the market • New material and cooling technology development may benefit a.c. charging 	

6. Conclusions

If BEVs are to make a significant increase in the market share of passenger vehicles it is expected that XFC will be needed to improve the range that BEVs can travel and to allow these vehicles to be charged with as much convenience as an ICEV. This faster recharge will require significant changes in the design of BEVs to increase their charging power to at least 400 kW to allow 200 miles of charging in a time of 10 minutes to be consistent with the 5 minutes in which an ICEV can refuel. The changes required to meet this challenge for the vehicle design necessitate RD&D to address the following:

- Battery charging power density must be increased while maintaining energy-dense cells such that long distance travel does not require excessive recharge events.
- The desired use cases for XFC, whether primarily for intercity travel or for everyday refueling, should be understood as it will impact the tradeoffs for BEV design.
- Increased system voltage will impact the design of power electronics and electrical architecture designs. This could increase the volume, mass, and cost of components and should be optimized in conjunction with vehicle duty cycle.
- Interoperability of XFC charging systems with vehicles will be required to provide consistent charging experiences for BEV owners. Charging capabilities of different vehicle models and charging infrastructure should be classified in a way that allows XFC to be commonly understood by the public.

While it is expected that the design changes to support the challenges of XFC represent a significant shift in the design of the vehicle electrical architecture and battery system. The benefits of XFC on the operation of BEVs should bring these vehicles much closer to accepted refueling norms and increase the adoption of BEVs in the market.

Acronyms

a.c.	alternating current
BEV	plug-in battery electric vehicle, includes both battery and plug-in hybrid electric vehicles
CCS	combined charging system, also called combo coupler
d.c.	direct current
DCFC	d.c. fast charger or d.c. fast charging
EV	electric vehicle
EVSE	electric vehicle service equipment
ICEV	internal combustion engine vehicle
RD&D	research, development and deployment
SOC	state of charge
XFC	extreme fast charging (20 mile / minute recharge)

Acknowledgements

This work was performed under the auspices of the US Department of Energy, Office of Vehicle Technologies, under Contract Nos. DE-AC02-06CH11357 (Argonne National Laboratory), DE-AC07-05ID14517 (Idaho National Laboratory), and DE-AC36-08GO28308 (National Renewable Energy Laboratory). The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

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