R&D Insights for Extreme Fast Charging of Medium- and Heavy-Duty Vehicles

Insights from the NREL Commercial Vehicles and
Extreme Fast Charging Research Needs Workshop,
August 27–28, 2019

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R&D Insights for Extreme Fast Charging of Medium- and Heavy-Duty Vehicles

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List of Acronyms

BEV	battery electric vehicle
DCaaS	direct current as a service
DER	distributed energy resources
DOE	Department of Energy
EV	electric vehicle
EVSE	electric vehicle supply equipment
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
MDHD	medium- and heavy-duty
NMC	nickel manganese cobalt
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PV	photovoltaics
R&D	research and development
ROI	return on investment
TCO	total cost of ownership
UL	Underwriters Laboratories
V2G	vehicle-to-grid
XFC	extreme fast charging

Table of Contents

1 Introduction 1

2 OEMs and Fleets 2

2.1 Panel Discussion 2

2.1.1 Discussion Topics 2

2.1.2 R&D Gaps and Opportunities 2

2.2 Charging Interface Technology and Approaches Breakout Session 3

2.2.1 Discussion Topics 3

2.2.2 R&D Gaps and Opportunities 4

2.3 Logistics, Operations, and Use Breakout Session 4

2.3.1 Discussion Topics 4

2.3.2 R&D Gaps and Opportunities 5

2.4 Electric Vehicle Components and Subsystems Breakout Session 6

2.4.1 Discussion Topics 6

2.4.2 R&D Gaps and Opportunities 7

3 Infrastructure and Utilities 8

3.1 Panel Discussion 8

3.1.1 Discussion Topics 8

3.1.2 R&D Gaps and Opportunities 9

3.2 Siting and Interconnection Breakout Session 9

3.2.1 Discussion Topics 9

3.2.2 R&D Gaps and Opportunities 10

3.3 Onsite Energy Technologies: Distributed Energy Resources, Behind-the-Meter Storage Breakout Session 10

3.3.1 Discussion Topics 10

3.3.2 R&D Gaps and Opportunities 11

3.4 Charging and Power Conversion Equipment Breakout Session 11

3.4.1 Discussion Topics 11

3.4.2 R&D Gaps and Opportunities 13

Appendix 1: Meeting Agenda 14

Appendix 2: Attendee List 16

Introduction

As battery costs have declined and battery performance has improved, the applicability of vehicle electrification has expanded beyond passenger cars to the commercial vehicle sector. However, due to the larger batteries that would be needed for the medium- and heavy-duty (MDHD) sector, the electric charging capabilities to serve these larger commercial vehicles will need to be substantially more powerful than light-duty chargers. More specifically, such "extreme fast charging" (XFC) will likely need to reach the megawatt scale to provide a full charge in less than 30 minutes in some applications. In addition, the combined cost of electrified vehicles and charging must be competitive with the costs of petroleum-based technologies and other alternatives to encourage widespread adoption of battery electric vehicles (BEVs) among MDHD fleets. Most of these fleets have a commercial mission and demand low total cost of ownership (TCO) (which motivates minimal refueling times) and high performance from their vehicles.

Research and development (R&D) on safe, efficient, and cost-effective XFC is needed now to mitigate technical barriers in time to coincide with the anticipated large-scale adoption of MDHD electrified vehicles across numerous commercial applications. Technological areas of interest include connectors, contactors, solid-state transformers, grid interface devices, power transfer mechanisms, charging control systems, XFC-capable energy storage, and automated charging. Methods to analyze costs and performance from both the vehicle and infrastructure perspectives must be developed. Logistical systems for optimization of commercial vehicle charging and operation need to be created. A viable XFC system must be capable of integrating with the electric grid, renewable energy generators like solar and wind, and stationary energy storage without any adverse impacts. The collaboration among stakeholders—such as MDHD original equipment manufacturers (OEMs), component manufacturers, fleets, truck stop owners, and utilities—will also be essential.

The early stages of MDHD vehicle electrification have suggested a potential role for XFC R&D that would help resolve the "chicken and egg" dilemma: how can XFC and MW+ charging-infrastructure capital investments be made before vehicle adoption is widespread, and how can vehicle adoption become widespread before a highly developed and cost-effective charging infrastructure is available? To help guide potential U.S. Department of Energy (DOE) activities in this area, DOE's National Renewable Energy Laboratory (NREL) convened a Commercial Vehicles and Extreme Fast-Charging Research Needs Workshop on August 27 and 28, 2019, in Golden, Colorado. Participants included DOE and NREL personnel as well as over 40 representatives from OEMs, commercial fleets, technology developers, utilities, infrastructure developers, and consultants. Attendees participated in two panel discussions (organized around "OEMs and Fleets" and "Infrastructure and Utilities") as well as six breakout sessions on subtopics within those two areas to discuss the current state of XFC, identify common barriers to widespread implementation, and suggest R&D needs that might be addressed with the help of DOE and national laboratory resources. This report summarizes the workshop findings.

2 OEMs and Fleets

2.1 Panel Discussion

2.1.1 Discussion Topics

The following key discussion topics emerged during this panel discussion:

Standardization – The CharIN High-Power Charging for Commercial Vehicles Task Force is developing a global standard for charging commercial MDHD BEVs, focusing on high-power DC charging (above 350 kW). The current emphasis is on a manually operated connector that will meet the necessary codes and standards (existing and anticipated in the future).

XFC needs – XFC can improve end-user flexibility and promote MDHD BEV adoption. Flexibility is reduced if customers must access a limited XFC charging network.

Factors needed for successful fleet BEV adoption – Factors include parts availability; service; evaluation of range, routes, and tradeoffs around opportunity charging (including charging at the depot, overnight, inductively, and XFC); battery weight impacts on available freight capacity; battery costs; TCO assessment; collaboration with utilities to potentially upgrade onsite infrastructure; and education and training.

Integrating charging infrastructure into existing facilities – Important practical considerations for all facilities include cable management and parking configuration (cord limitations, cord size and length, liquid cooling, location of charge port) and the need for "behind the fence" (private) charging (owing to the need for safety and maintenance, exclusion of competitors, and a strategic network). Some examples from fleets considered solar power for facilities, but the return on investment (ROI) and roof space were inadequate for vehicle charging. One fleet aims to transform a plant into a near-zero-emissions freight facility, including photovoltaics (PV) with battery storage; electric yard tractors, box trucks, tractors, and forklifts; and low-NOx renewable compressed natural gas tractors and fueling.

Key challenges for fleet electrification – Key challenges include limited vehicle availability, high vehicle cost, impact of battery weight and large wheelbase on commercial vehicle performance, lack of charging standards (e.g., location of charging ports on trucks), electricity rate structures, and the need for infrastructure upgrades in front of and behind the meter.

2.1.2 R&D Gaps and Opportunities

The following R&D gaps and opportunities were identified through this panel discussion:

- Aggregating and analyzing data on use cases for various applications
- Developing a battery capable of 3–4C-rate charging with good energy density, low cost, and the ability to support 4,000 charge cycles
    - Nickel manganese cobalt (NMC) can support a continuous 0.7–1C rate, but cannot be used with XFC
    - Lithium-Titanate Oxide can support a higher charge rate but has low energy density and is expensive
    - Power-oriented NMC may work but at a higher cost and lower energy density
    - High C-rate charge cycles accompanied by significant internal heating have negative impacts on battery life.

- Developing a high-fidelity TCO model accounting for large variations in time horizon, technology options, fuel/energy prices, weather, and other impacts such as drive cycles and road grade, infrastructure costs, vehicle costs, degradation and salvage value, and facility grid integration. Model validation using real-world electric fleet/XFC demonstration data would be valuable.

2.2 Charging Interface Technology and Approaches Breakout Session

2.2.1 Discussion Topics

The following key discussion topics emerged during this breakout session:

Connection point on vehicle – The electric vehicle supply equipment (EVSE) connector port location on the vehicle and the EVSE location relative to the parking space would determine the vehicle's parking orientation and/or cord set requirements during charging within a facility. Locating the EVSE in the front of a vehicle parking space would require a charge port in the front of the vehicle and possibly require front pull-in parking, which may contradict current industry practices. If EVSE was at the front of the stall and vehicles were backed in, this would require longer cables (about 18–24 ft) to reach the front port. Coordination and specification of the EVSE location and charge port location will be required for commercial vehicle deployments and could vary by customer/location.

Connector durability – As connector and cable sizes increase due to higher power levels, forces on the connector may cause damage over time. Currently CharIN aims for a 100-N maximum force in its connector standard. If a connector fails, there is a possibility that the entire connector (and sometimes cord set) must be replaced, which could be costly. Current EVSE connectors are not necessarily designed for repair, and there are a limited number of manufacturers. Currently, the force required for EVSE connector insertion makes it a one-person operation, but large connectors may require mechanical support/assistance in the future. The example of airline fueling connections (which already provide mechanical support for large fuel lines) could be a valuable model for a similar EVSE solution. Alternate connection options include pantographs and wireless power transfer systems, but both have cost, packaging, and efficiency challenges. Fleets should consider what is best for them, but additional cost and installation information would be valuable.

Power delivery – The choice between AC and DC power supply to charging units is important and needs to be considered for each application. For example, some early-adopter delivery trucks will be both AC and DC compatible, most charging at approximately 30–50 kW; future vehicles might only be DC compatible due to higher power needed and the need for cost reduction on board the vehicle. AC EVSE charging requires an onboard charger, which adds unnecessary weight and volume to the vehicle but possibly less facility infrastructure. DC charging requires more onsite equipment. A rectifier (typically integral to EVSE) is needed to convert AC to DC. A larger onsite rectifier could be employed to supply a high-voltage DC bus, and then DC rectifiers could also supply power to other conventional non-vehicle 480-V AC loads (once replaced with DC equipment), but might also more readily enable other DC energy sources on the DC bus. Ground-fault protection equipment is necessary but lacking for high-voltage DC power systems. Manufacturers and fleets are leaning toward DC-only charging to reduce the amount of onboard charging equipment.

Utility vs. fleet-owned equipment: Direct current as a service (DCaaS) could place the necessary and additional infrastructure burden on utilities. Fleets do not want to necessarily own power-conversion hardware, but utilities have a good business model for such a service: they already own this type of equipment (transformers), and their business is designed for installing, managing, and paying off infrastructure costs. The utility regulatory process could delay new rate structures or service changes because such processes sometimes take 2–3 years. In addition, current DC meters (for DCaaS) do not meet utility requirements. The Electric Power Research Institute (EPRI) has a DCaaS working group to work on these issues.

AC voltages and power levels for EVSE will continue to use standard distribution levels: 120-, 208-, 240-, and 480-V AC. DC voltages are less standardized. The building standard is around 380–480-V DC. Europe (International Electrotechnical Commission) is standardizing on 350-, 750-, and 1,500-V DC. Safety is a primary concern for high voltages. Personal protective and electrical service equipment required for installations above 1,000 V will add to complexity and reduce the general availability of equipment.

2.2.2 R&D Gaps and Opportunities

The following R&D gaps and opportunities were identified through this breakout session:

- Performing TCO analysis of charging approaches for typical installation scenarios
    - Specifying vehicle-side charging type/configuration: AC vs. DC, overhead, wireless, etc.
    - Considering rectifier, transformer, and metering placement (e.g., on vehicle, in EVSE, onsite, owned by utility)
    - Analyzing charging levels vs. cost (AC and DC voltage bus)
    - Clarifying how current electricity rates influence infrastructure and how new rates could be introduced
    - Using managed charging and/or distributed energy resources (DER) to minimize TCO of infrastructure and vehicle investments
    - Analyzing route data and energy requirements to predict power demand at different levels of EVSE penetration.
- Developing a utility-approved managed charging tool that could help specify and ultimately mitigate equipment upgrades through utility-owned and/or managed charging solutions.

2.3 Logistics, Operations, and Use Breakout Session

2.3.1 Discussion Topics

The following key discussion topics emerged during this breakout session:

Charging infrastructure access – Large private fleets and parcel delivery fleets are leading much of the initial electrification efforts and maintaining control of their infrastructure "behind the fence" at warehouses or depots, which enables them to design access and ensure availability. Factors driving private infrastructure access include the need for high infrastructure utilization to minimize costs, the need for schedule control, high vehicle utilization, limited yard space for outdoor parking with very close vehicle parking, the need for nighttime and daytime charging, negotiated fuel or electricity rates, competitive positions relative to other potential users, seasonal issues (when scheduling becomes even tighter), and facility (non-vehicle) power demand, grid capacity, and use charges. High utilization leverages charging hardware investment and minimizes charging costs for fleets with private infrastructure but has limited availability to other potential users. However, some operators (e.g., leased fleets) may have regular times with lower utilization that might provide access opportunities. Suggested solutions to access and space availability include developing "platinum" customer relationships with noncompeting fleets, installing infrastructure at properties separate from loading or plant operations where charging time or vehicle downtime is high enough to not impact schedules, and/or using overhead charging where outdoor charging is acceptable.

Public infrastructure – Most carriers are fleets of 100 vehicles or fewer that would need reliable access to public charging, including truck stop charging for highway trips. The National Association of Truck Stop Operators formed an Alternative Fuels Council to assist members with infrastructure advice, regulatory compliance, and incentives, and to facilitate relationships with suppliers. However, past financial losses from failed electrification for overnight idling projects likely will make truck stop owners less willing to participate. Truck stop owners need tools to help them evaluate charging infrastructure propositions (see Section 2.3.2). For public charging beyond long-haul trucking, many transit and logistics companies are concentrated in areas that could indicate good locations for infrastructure and become service center hubs. Such charging depots would require substantial power; potential sites include brownfield sites at former manufacturing facilities because they already have power availability.

Use cases and geospatial issues – Truck movements under 100 miles are expected to be the first electrification applications, possibly covering 80% of customers; such trucks would charge at depots at lower power levels and would not need XFC. High-mileage applications would realize greater benefits from electrification but require larger, more expensive batteries and higher-cost charging infrastructure. Data collection and analysis would help inform the tradeoffs related to various use cases and geospatial situations (see Section 2.3.2). There is a need to think beyond the vehicle and integrate larger trends, such as urbanization and growth in logistics due to e-commerce.

Issues of scale – Several participants expressed concern over issues arising when electrification is scaled up: would rapid vehicle deployment outpace the infrastructure and utilities? In some cases, the electrical power needed at truck stops could equal the power requirements of entire towns. Some rural locations do not even have three-phase power. Cost recovery could take 30–40 years. On the fleet and facility level, the easiest applications are the first to be electrified, but scaling up quickly becomes nonlinear. Capital costs are high, and total operational costs are not transparent. There are issues related to land use, real estate costs, parking, and existing building infrastructure. Cost models built on press releases and grant awards do not include actual or final costs and create unrealistic expectations. Maintenance costs for mature BEVs are unknown. Existing TCO tools may be inadequate for future projections. Many fleets find a need for greater than a one-to-one BEV replacement for each diesel vehicle because of range and route flexibility concerns. Costs for electrifying its entire fleet prompted at least one transit agency to investigate hydrogen fuel cells.

Charge management – Understanding charge time, availability, and projected battery energy capacity requires more fleet data to design a charge management system that factors facility loads over time, vehicle routing plans, and energy consumption. Suggested approaches include using reliability requirements to inform the value of "downtime" for charging. Total TCO models may not capture all complexities; fleets must consider whether electric vehicles make sense for given applications, routes, and operational specifics. Many companies use logistics systems to plan routes, and these systems might form the basis of charge management systems. This integration of the facility and fleet—with facility managers becoming fuel/energy managers—has been challenging for some private fleets experimenting with electrification. Needs for fleet tools were discussed (see Section 2.3.2).

Cost and utilization – High charger utilization rates are key to offsetting infrastructure costs. Demand charges must be built into the business plan, and the first charger in a corridor takes a huge hit. Demand charges become less of an issue as utilization increases. However, the load curve is not uniform/consistent, so the optimal utilization is unclear. Facility managers must consider whether to build a few XFC ports or a larger number of lower-power chargers. Vehicle automation might change utilization if vehicles can move themselves for charging.

Emissions, policy, and standards – Sustainability concerns may drive electrification more than economics. Better understanding is needed of renewable portfolio standard economics and policy, carbon taxes, and internalization of costs due to diesel emissions. Other policies and practices gaining momentum are no-diesel or zero-emissions zones and businesses that limit using fleets whose trucks do not meet CO2 goals. With regard to standards, OEMs and equipment providers need an agreement on the software side and requirements for the vehicle.

Clarification of XFC – Definitions of XFC can vary, but XFC may enable electrification for some MDHD applications. Backward compatibility would enable vehicles with slower charging capability to use the XFC infrastructure. Some OEMs may be looking to fuel cells for heavier vehicles with longer range requirements; DOE's R&D portfolio considers that scenario.

2.3.2 R&D Gaps and Opportunities

The following R&D gaps and opportunities were identified through this breakout session:

- Developing a tool to analyze truck stop charging infrastructure, addressing issues such as:
    - Sufficiency of electric distribution feeders at specific truck stop locations
    - Potential market for public truck charging at specific locations
    - Number of plugs required.

- Analyzing the timing needs and business models for installing truck stop charging
- Collecting data on and analyzing heavy-duty vehicle charging use cases
    - Over-the-road vs. regional hub-and-spoke duty cycles
    - Detailed vehicle mission profiles
    - Geographic variations accounting for traffic volume, weather, evolving e-commerce and delivery practices (e.g., distribution centers sited away from dense urban areas), and so forth.
- Developing more detailed TCO models
- Analyzing charge-management systems for optimizing utilization and reducing demand charges while meeting operational requirements
- Developing tools to help fleets determine optimal charging sites and schedules
- Developing tools to help fleets optimize decarbonization investments in the context of emerging sustainability policies.

2.4 Electric Vehicle Components and Subsystems Breakout Session

2.4.1 Discussion Topics

The following key discussion topics emerged during this breakout session:

Battery economics – The residual value of batteries is an important and unknown aspect of BEV TCO calculations. Some participants paid $3/kg to recycle batteries at end of life, which could equate to $4,000–$5,000 for an MDHD vehicle. This negative residual value must be considered in purchase decisions, and it should be mitigated through battery lifecycle design or second-life opportunities. Second-life considerations meriting investigation include the applicability of vehicle batteries to stationary applications, challenges and costs related to using batteries from different vehicles and years and opportunities for standardization, the impact of cooling method (e.g., liquid cooling), comparisons of repurposed current batteries vs. future battery technology, the prevalence of vehicles outlasting their batteries, the ability of automotive batteries to meet stationary battery standards, and battery data and associated battery-life predictions. Because no MDHD propulsion battery-salvage market exists today, a future market cannot be assumed; work is needed to establish the foundations for such a market.

Battery life – Accurately predicting battery life will contribute to battery sizing, cost, viability of grid service opportunities, and second-life considerations. It will require sufficient battery-life data, robust life models, and consistent battery operation tracking. Standardization of battery operational data tracking and state of health would be helpful for the industry and should include the unique and diverse duty cycles expected for the MDHD market.

Battery swapping – This concept remains interesting despite past challenges and was discussed in this forum. It is unclear whether failures of the past are intrinsic to the approach or result from the light-duty market and prior technology. Commercial vehicles may present unique opportunities and challenges for battery swapping. Commercial vehicles are more cost driven than passenger cars, and the economic tradeoffs of battery swapping must be quantified. Many truck applications today operate 24/7 using "slip seating" and rarely turning their engines off. Battery swapping could add value in applications that must avoid downtime while mitigating XFC challenges. Challenges related to battery standardization, cooling systems, and a wide range of vehicle types across many manufacturers could be very difficult to overcome. However, companies have demonstrated technical feasibility (e.g., Better Place, Tesla, and others), and battery swaps are already being done in Poland and China and in niche applications such as material handling equipment.

Bidirectional power electronics – There is significant uncertainty about the viability and value of bidirectional vehicle-to-grid (V2G) applications for MDHD vehicles. V2G could be use case dependent. School buses are a potential near-term application, but utility or third-party financing would be needed. Some areas such as Hawaii, where batteries or the ability to reduce curtailed solar are needed, present another good opportunity. Some current demand response programs are designed to reduce peak power, such as a Minnesota pilot aimed at renewable energy integration.

Thermal challenges – Thermal challenges for cables, traction drive systems (including power electronics and batteries), and cabins require further investigation and standardization. Cooling will likely be needed to enable XFC cables with manageable weight, sufficient flexibility, and reasonable cost. The charging heat and close proximity of traction-drive components—vehicle-side cables, connectors, power electronics, and battery—make thermal management challenging and call for R&D on design and technologies such as high-temperature components, thermal storage, and advanced cooling strategies. Cabin heating and cooling are important, particularly for transit buses, where high cabin loads and low operational speeds have large impacts on battery size and range. Fleets often do not have the resources to investigate these impacts on their own. Advanced thermal system technologies such as localized climate control, air curtains, thermal storage, and heat pump systems merit investigation to mitigate battery impacts. Communication standardization could also help with preconditioning strategies.

Standardization – There seems to be a need to standardize telematics and vehicle charger communication, including options between the electric vehicle (EV) and EVSE using power-line communication and between the EVSE and the site/grid such as Open Charge Point Protocol and others. Two committees are examining adding BEV considerations to J1939 Controller Area Network communication, and industry is moving toward ethernet communication. Standardizing the high-voltage bus would help across several areas, including vehicle subsystem design and secondary upfitter integration.
Data integration and analysis – Work on data collection, integration, and analysis is needed to understand the very diverse MDHD vehicle market, quantify vehicle demands, enable better vehicle design, and increase adoption opportunities. This would help OEMs and fleets. Currently, telematics data come in many different forms, and each OEM uses different standards. FleetDNA is a good example of how data can come in many different forms. Helping to integrate these data is a good role for national laboratories.

2.4.2 R&D Gaps and Opportunities

The following R&D gaps and opportunities were identified through this breakout session:

- Performing R&D on battery design, life (testing, modeling, and robustness), second use (residual value and recycling costs), grid services opportunities, and standardization opportunities
- Researching the value of bidirectional (V2G) capability for applications beyond buses and vocational applications
- Researching thermal challenges in the areas of cables, power electronics, and batteries, as well as driver/occupant comfort systems
- Standardizing communication, telematics, the charging interface, and battery requirements (voltage)
- Integrating and analyzing data along with understanding the subclassification of vehicles in the diverse market
- Determining whether the MDHD vehicle battery-swapping scenario is different from past light-duty battery-swapping efforts.

3 Infrastructure and Utilities

3.1 Panel Discussion

3.1.1 Discussion Topics

The following key discussion topics emerged during this panel discussion:

Challenges to charging station installation – Challenges to station installation encountered in Europe include long, labor-intensive permitting processes applied to unique site configurations (limiting transfer of lessons learned between sites); small existing site footprints; novelty/uniqueness of DC metering; and complex electrical grounding considerations. American projects have also encountered long design and interconnection processes. Overall, high costs to customers and utilities, as well as a lack of regulations and standards, present challenges to station installation.

Station planning and design – A modular electrical design approach can include prioritizing station sites; developing roadmaps for network capacity and site deployments; integrating with utility planning processes; planning for distributed energy and resilience; planning for electrical infrastructure ahead of fleet ramp-up in each location; understanding opportunities for power sharing with buildings and other vehicle types, as well as the role of "behind-the-meter" energy storage; considering and developing plans to reduce risks; and reducing the costs of energy, storage, and renewable integration. It is important to pilot small-scale charging at a site while planning for larger scale. Early engagement and utility coordination at account and engineering levels facilitates understanding of requirements and feasible power delivery schedules. Utilities generally will not release site-specific power delivery capabilities without expressed or formal intent to develop a location. When a site is being developed, it is important to have onsite staff and contractors.
Technical barriers – Technical barriers on the vehicle side include the need for battery packs to handle fast charging (C rate must rise to 3C and 4C) and the need to mitigate battery degradation, especially if batteries are used in V2G applications or for other grid services. On the infrastructure side, barriers include the need to develop higher-voltage architectures, improve designs for safety, and implement automation and thermal management strategies.

Energy storage – As battery prices keep dropping, energy storage becomes a more attractive option. Considerations include choosing between grid integration and dedicated energy storage generation, evaluating available incentives for compatibility with energy storage, weighing size-related constraints and economics, and assessing the cost of integrating an energy storage project with existing resources. Avoiding demand charges due to energy storage charging is also important and management systems are needed.

DCaaS – Potential benefits of DCaaS include moving the AC/DC converters upstream to the utility-owned infrastructure, which reduces upfront costs to customers, reduces the equipment footprint, and enables the utility to depreciate the cost over time.

Safety – Recommendations for improving XFC station safety include developing a specific standard for XFC equipment (many architectures) and investigating the potential safety benefits of the DCaaS model.

Demand charges – Utility demand charges can present a challenge to station economics and are a concern.
Grid hosting capacity – Utilities can work with charging providers to identify locations on the grid that have suitable capacity for charging stations, but such an analysis requires considerable effort.

Site- and feeder-level controls – Site- and feeder-level controls could reduce energy costs and facilitate use of resiliency assets. Potential users of distributed controllable loads include utilities, load aggregators, and virtual power plants, with value coming from coordination of grid-service-enabled assets.

3.1.2 R&D Gaps and Opportunities

The following R&D gaps and opportunities were identified through this panel discussion:

- Modeling is needed to match energy supply and demand with lower-carbon options
- Analyzing energy storage opportunities in the context of enabling MW-level charging power and energy demand for vehicles
- Analyzing renewable energy integration challenges, including reviewing best practices among utilities
- Developing tools that provide stakeholder-specific estimates of long-term electrification costs and benefits
- Analyzing business cases for DCaaS and if it should be utility-owned or fleet-owned assets
- Analyzing safety benefits or concerns related to XFC.

3.2 Siting and Interconnection Breakout Session

3.2.1 Discussion Topics

The following key discussion topics emerged during this breakout session:

Peak demand – Utilities commonly (but not consistently across all service territories) place a peak limit of 2.5 MW for each interconnection point owing to a common maximum size of pad-mounted transformers for secondary service. Today's BEV loads typically do not add significant loads to existing facility loads, but future applications might as the BEV loads increase. Facility vs BEV load ratios can vary depending on the application. For example, facility loads with refrigerated goods could already have MW-level peak demand, whereas those limited to package handling require basic service in the tens of kW range but added BEV loads could increase these facilities to MW-level peak demands also. EV truck loads have differences and similarities with multi-megawatt data-center loads. Unlike charging loads, data centers have a steady demand curve all day while EV truck loads could be more intermittent. However, both applications require extensive, long-term land acquisition and infrastructure/utility planning. The "land grab" that has taken place in the data-center industry could be mirrored in the truck-charging industry, although data-center development is typically "greenfield," whereas truck-charging development will likely be "brownfield" (or using existing land/facilities). Transit agencies currently have small loads served by 25-kVA transformers; expanding the load to supply 20–30 buses could require 2.5 MW or more, and local feeders may not have capacity to serve such loads. Demand charges are a concern when peak demand increases. Some facilities have built diesel generators to reduce demand charges due to EVSE peaks, illustrating the need for more environmentally friendly peak-demand mitigation solutions. Some sites currently under development could be planning for peaks of 30 MW or more. These larger sites should not expect for this level of power to already be readily in place. Additional utility development will be required for a dedicated feeder of 8–40 MW.

Interconnection process – Location determines interconnection feasibility; sites far from the distribution substation (or subtransmission) will require expensive interconnection. Local distribution feeders may require significant upgrades to serve these loads, potentially including a dedicated feeder for larger loads. Interconnection processes vary among utilities, and processes to determine a site's hosting capacity are often longer than a fleet may anticipate. Development of maps could be used to highlight potential sites with capacity, as is being done in California; such an effort requires close collaboration with utilities. CALSTART is working on corridor planning by providing "heat maps" of the corridor grid, looking at current demand and demand 5–10 years out. Electrify America has noted drastic differences in EVSE barriers across the country, including permitting processes that vary by jurisdiction and interconnection processes that vary by utility—similar to initial issues with PV interconnection. An Illinois task force was successful in implementing a standardized permitting process for renewables. Hawaii developed a task force with NREL to streamline PV permitting/interconnection in collaboration with stakeholder groups including utilities, state agencies, and the public utilities commission. Products included permitting guidebooks and online tools.

Miscellaneous comments – Lessons from Tesla's experience include the importance of considering charging use cases and utilization/fleet requirements, the need for trucks to have immediate access to charging (which may require energy storage to mitigate demand charges), and the relationship between low EVSE utilization and high demand charges.

Fleet owners do not want to be in the business of owning transformers. Utilities will continue to be the primary owner of service equipment. Secondary voltage service will be preferred over primary voltage.

Billing requirements and rate structures vary greatly between utilities. Fleets with operations in many service territories have different ROI calculations.

Additional regulations or compelling business cases may drive utility engagement. Utilities will require funding support to develop tools.

3.2.2 R&D Gaps and Opportunities

The following R&D gaps and opportunities were identified through this breakout session:

- Collaborating with utilities to develop "heat maps" of available grid capacity to highlight locations that could serve large EVSE deployments—helping utilities mitigate equipment upgrades and helping fleets simplify the interconnection request process
- Investigating how to provide substantial electric power to remote truck stops
- Addressing peak demand concerns where local grids cannot supply peak power, moving away from onsite gas/diesel generation toward solutions such as charge management, storage, and PV/wind generation
- Developing a cost-optimization tool to consider different cost curves for all solutions.

3.3 Onsite Energy Technologies: Distributed Energy Resources, Behind-the-Meter Storage Breakout Session

3.3.1 Discussion Topics

The following key discussion topics emerged during this breakout session:

Variable charging economics – Because truck drivers are paid by the mile, electric truck charging time presents an economic barrier; one metric for evaluating XFC is miles per minute of delivered energy. Only large fleet operators can afford expensive private charging stations, so many small fleet operators could be left behind. Many fleets have fewer than 500 trucks. Public-access charging stations could serve these small fleets if they had fast-charging capabilities.

Vehicle-to-grid considerations – The high utilization of commercial vehicles excludes many MDHD fleets from V2G participation, except perhaps vehicles such as school bus fleets, which are commonly idle for 10 hours each day. Some believe V2G will never make sense from a business perspective, only for emergencies (e.g., for hospitals needing power during a hurricane) or possibly for the most challenging grid hours each year, although truck economics and logistics would still make this challenging. The impact of V2G use on battery life and performance remains unclear. The charging rate—especially the heat generated by fast charging—affects battery life.

Infrastructure installation barriers – Utilities are experiencing difficulties installing charging infrastructure. For example, Santa Monica's current infrastructure was built in the 1950s, and the distribution infrastructure needs a complete revamp in many places. In many situations, the California Public Utilities Commission is assigning the costs of infrastructure upgrades to customers, making it difficult for fleet operators to change their vehicle to be electric and build the necessary charging infrastructure.

Electrification tradeoffs by vehicle type and duty cycle – The ROI for vehicles that travel 24/7 will be highest, but electrifying these trucks will require high-power fast charging to minimize downtime. Charging for relatively short-range vehicles that return to a depot each day (e.g., Class 6 delivery trucks with 100 miles of range) is easiest to implement, but the ROI is lower. The need for fast charging presents a challenge to electrifying Class 8 delivery trucks. Still, companies like UPS are trying to purchase electric Class 8 trucks. UPS currently has 125 Tesla trucks on order and is discussing purchases with other OEMs.

Vehicle-ownership challenges – Convoluted truck ownership strategies (e.g., companies making lease payments on drivers' behalf) would get even more complicated with electric trucks due to changing cost models.

Vehicle-side barriers to fast charging – Thermal issues are very challenging on the vehicle side. Most contactors and current components for automotive applications are only rated for 400 A, not 2,000 A. Charging at very fast rates may be possible on the infrastructure side, but vehicles are not rated for these loads or, in general, the durability demands of MDHD vehicles.

3.3.2 R&D Gaps and Opportunities

The following R&D gaps and opportunities were identified through this breakout session:

- Analyzing U.S. fleet sizes, vehicle types and locations, routes, duty cycles, driver behaviors, etc. to analyze charging infrastructure needs—accounting for existing and emerging trends such as:
  - Driver break times, including potential to charge vehicles within daily driver hours-of-service limits
  - Driver preferences (e.g., increasing driver desire to work near home, regional routing)
  - Home charging of fixed-route vehicles
  - Autonomous vehicle charging.
- Analyzing current and potential future utility approaches to infrastructure challenges associated with growing EV charging demand
- Developing research facilities for testing high-power charging hardware/products to enable heavy-duty vehicle charging
- Identifying needed standards for extreme fast charging and behind-the-meter storage to mitigate barriers complicated by the proprietary nature of charging and storage protocols
- Clarifying current and potential future installation and interconnection costs.
  - Initially start with public transit projects, which have more transparent cost information; include projects award costs, change orders, and utility fees.

3.4 Charging and Power Conversion Equipment Breakout Session

3.4.1 Discussion Topics

The following key discussion topics emerged during this breakout session:

Charging levels – 50 kW was once considered fast for light duty but could be on the low end for overnight charging in some applications of large commercial vehicle batteries. Bus depots may have many 50-kW charge ports or fewer higher-power charging ports, all of which might result in peak site loads of over 1 MW. How do you scale up to this while minimizing costs to provide cost-effective electricity to fleets but consider the evolving charging ecosystem? Multiple types of power-conversion equipment might be considered for multiple vehicle types and charge levels to reduce costs. Some delivery fleets currently pay large amounts of parking fines owing to lack of available parking spaces in urban areas; dedicated charge locations could help reduce this cost if there were dedicated high-power charging locations. Onboard AC charging for smaller-capacity vehicles might be a solution for some applications and drive an AC infrastructure in a facility. Electromagnetic interference and/or electromagnetic compatibility from high voltage and high current is mostly unexplored and might be a need and suitable role for national laboratories.

Type of power/electricity – DC distribution systems might enable DCaaS and would require highly modular/scalable power supplies to meet demands from 50 kW to 1 MW or more. There is a need for some standardization for potentially highly variable power-level requirements. Variability in charging scenarios might drive the need for modularity. For example, depot charging could vary between 50 and 500 kW and maximize charge time flexibility or to enable "midday" charging of vehicles that might return to depots during the day. High-power chargers could also enable coordination of charging with driver break times. A "fast" charge during the day and "slow" charging overnight could also be a solution. A DC microgrid approach is desirable but cost prohibitive: at least two orders of magnitude more expensive, with $1/W typical for AC transformer use but $50–$75/W for DC solid-state transformers used today. Life and reliability are also unknown for solid-state transformers, as are standardized interconnection, breakers, and service procedures; a change to this technology would require new service training. Also, DC metering might be an issue for high-power DC systems (not typical today).

Charging locations – Corridor charging to enable 30-minute fast charges for 200–300 miles would require MW+ of charging power per port. Coordination with or changing of driver regulations could enable more "fast-charge" scenarios. Real estate and overhead space might be a problem for high-power charging, as well as in-ground footprint and underground space needs.

Charge and energy management systems – The International Organization for Standardization (ISO) 15118 communication protocol between EVSE and controller might enable better integration of DER and/or onsite storage. Open Charge Point Protocol is currently only open to energy management systems and does not accommodate onsite storage systems. Standards are needed to improve these issues and enable optimal site operation. Some companies offer renewable resources or battery integration solutions to help manage and optimize energy management onsite. Software is needed to accomplish this, but it is unclear who will do the controls at the vehicle, charger, site level, etc. Site controls need to be optimized for electricity delivery owners/operators.

Power conversion hardware technologies – Traditional or current charging hardware is currently at the 480-V level, but this might not be the optimal solution for many scenarios including integrated facility equipment (BEVs, PV, storage, and lights). DCaaS might drive hardware configurations and also opens the question of who would own hardware. The need for safety equipment and circuit breakers is currently a cost issue, and equipment is sometimes overdesigned due to maximum power ratings (even though maximum power may never happen); National Electrical Code and Underwriters Laboratories (UL) standards will force expensive solutions that might not be needed with solid-state devices. There are no UL standards for cooling solutions yet; this could be a role for laboratories. Higher voltages (now above 950 V) limit the use of silicon devices, and costs go up (as well as switching losses). Equipment with 1,200 V is the current status quo for mass market, and sometimes involves "stacking" the power electronics to deliver higher voltage, but this should not be done above 13.8 kV. Bidirectional V2G capabilities for Institute of Electrical and Electronics Engineers (IEEE) 1547 need to be adapted for BEV distributed resources. Marine (shore power) applications should be assessed and analyzed for feasibility.

Battery swapping approach – Discussion on battery swapping included questions around limitations/advantages to moving energy storage to the trailers on tractor-trailer combinations, which included safety, additional connections, cooling strategies, power electronics to interface with tractors (standardization of connector issue), and compatibility of using trailers with multiple tractors. One solution discussed entails a trailer with a separate drive unit, but this adds 2,000 lb of batteries on the trailer, which could prove difficult for axle weight limits, along with the challenge of moving and handling heavy packs (which requires special equipment). The ratio of trailers to tractors, ownership models, locations (charging and use), and utilization rates of trailers are challenges. BEV vs. diesel-powered refrigerated trailer units (reefers) could be a solution.

Telematics and data for charging – Data integration for fleets could prove important to help manage energy use and recharging. Integrated GPS, fuel use, and geographic information from telematics systems could help improve overall system design by informing across multiple platforms and operating environments (informing better battery design, tracking, etc.).

Connectors/cables – There are questions about whether DC will work for all applications or if AC is needed. OEMs prefer to get to DC systems to eliminate onboard hardware needs, but there would be benefits to leveraging what has been done with Level 2 charging infrastructure (AC). Automotive cabling (likely at 4/0 for discussed charging power) might be a challenge. Standards and testing are needed to increase current carrying capability of 2/0 wire with cooling capabilities. Also discussed was how to protect multiple wires and protect the charge-side equipment. Charging with overhead/catenary systems is done today (600 kW), and a similar ground-side or lateral-side location might be considered for high-power "connectorless" systems to avoid plug/connector issues at high power levels. Overhead charging is in use for buses, but it might be difficult for other applications with less roof space. Cooling solutions are being investigated, but they need dielectric, noncaustic, biodegradable, safe solutions; aircraft solutions should be examined.

Bidirectional/grid services hardware – Discussion included opportunities for emergency/resiliency management. Battery (and vehicle) manufacturers are resistant to warrantying drive batteries that might be used for grid services because life impacts are not well enough understood. Some startups have tried a different battery ownership model, but it has not taken off yet. Investigation and assessment of battery life, secondary use, and grid services for commercial vehicle batteries are good roles for national laboratories. Demand response with vehicle batteries has no clear standard now (OpenADR).

3.4.2 R&D Gaps and Opportunities

- Developing cost-effective power-conversion equipment that can accommodate various power and voltage levels to improve:
    - DCaaS
    - Standardization for various power levels
    - Life and reliability concerns for new or reconfigured equipment
    - Compact high-current revenue-grade DC metering.
- Developing communication and energy management systems to enable cost-effective site control (with DER):
    - ISO 15118 enhancement for improved control across DER and storage
    - Development of better standards to enable onsite storage
    - Optimization of site controllers including use of improved telematics to enable better predictive control
    - Enabling bidirectional capability for IEEE 1547 to enable vehicle-to-everything.
- Improving cabling and connectors to accommodate increased thermal loads
- Investigating integrated energy management and grid services:
    - Resiliency opportunities
    - Battery life, secondary use, and grid-services opportunities.

Appendix 1: Meeting Agenda

Tuesday, August 27

1:00 p.m.	Meeting Welcome & Agenda Overview John Farrell, NREL
1:10 p.m.	Introductions and Overview Steven Boyd and Lee Slezak, U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Office
1:20 p.m.	NREL and Workshop Introduction Kevin Walkowicz, NREL
1:35 p.m.	Panel Introduction Ken Kelly, NREL
1:40 p.m.	OEM and Fleet – Panel Presentations *Daimler, Cummins, Penske, and PepsiCo* Rustam Kocher (Daimler), John Kresse (Cummins), Sean Yentsch (Penske), Keshav Sondhi (PepsiCo)
2:40 p.m.	Panel Discussion Ken Kelly, NREL (facilitator)
3:10 p.m.	Break
3:25 p.m.	Introduction to Breakout Sessions Jason Lustbader, NREL
3:30 p.m.	Breakout 1*
3:55 p.m.	Break
4:00 p.m.	Breakout 2*
4:25 p.m.	Break
4:30 p.m.	Breakout 3*
4:55–5:00 p.m.	Wrap-Up Kevin Walkowicz, NREL

*Day 1 Rotating Breakout Topics:

- Charging interface technology and approaches
- Logistics/operations/use
- Electric vehicle components/sub-systems

Wednesday, August 28

8:30 a.m.	Welcome and Day 1 Recap John Farrell, NREL
8:45 a.m.	Panel Introduction Andrew Meintz, NREL
8:50 a.m.	Infrastructure and Utilities – Panel Presentation *Tritium, Xcel Energy, Black and Veatch, and Eaton* James Kennedy (Tritium), Beth Chacon (Xcel Energy), Paul Stith (Black and Veatch), David Ganger (Eaton)
9:50 a.m.	Panel Discussion Andrew Meintz, NREL (facilitator)
10:20 a.m.	Break
10:25 a.m.	Introduction to Breakout Sessions Jason Lustbader, NREL
10:30 a.m.	Breakout 1**
10:55 a.m.	Break
11:00 a.m.	Breakout 2**
11:25 a.m.	Break
11:30 a.m.	Breakout 3**
11:55 a.m.–12:00 p.m.	Wrap-Up Kevin Walkowicz, NREL

**Day 2 Rotating Breakout Topics:

- Siting and interconnection
- Onsite energy technologies (DER, Behind-the-Meter Storage)
- Charging and power-conversion equipment

Appendix 2: Attendee List

First name	Last name	Company
Emrah	Arslanturk	Cummins Inc.
Jesse	Bennett	NREL
Kevin	Bennion	NREL
Vijay	Bhavaraju	Eaton
Alicia	Birky	NREL
Daniel	Black	Volvo Trucks
Andrew	Bouthilet	Eaton
Steven	Boyd	U.S. DOE EERE Vehicle Technologies Office
Grant	Brummels	Exelon
Anthony	Calabro	Momentum Dynamics
Beth	Chacon	Xcel Energy
Madhu	Chinthavali	Oak Ridge National Laboratory
Joe	Colett	Portland General Electric
Watson	Collins	EPRI
Mike	Coop	ThinkSmartGrid/Argonne National Laboratory
Michael	Corona	Nikola
John	Deboer	Siemens
Dan	Dobrzynski	Argonne National Laboratory
John	Farrell	NREL
Summer	Ferreira	Sandia National Laboratories
John	Furtado	Daimler Trucks North America
David	Ganger	Eaton
Shibani	Ghosh	NREL
Alycia	Gilde	CALSTART
Madeline	Gilleran	NREL
Gary	Gloceri	Rivian
Keith	Hardy	Argonne National Laboratory
Bobby	Hill	BYD Motors, Inc.
Rob	Hovsapian	NREL
Birk	Jones	Sandia National Laboratory
Perry	Jones	Oak Ridge National Laboratory
Kenneth	Kelly	NREL
James	Kennedy	Tritium
Michael	King	Colorado Department of Transportation
Rustam	Kocher	DTNA
John	Kresse	Cummins Inc.
Matthew	Lave	Sandia National Laboratories

First name	Last name	Company
Sandra	Loi	NREL
Steve	Lommele	NREL
Jessie	Lund	Rocky Mountain Institute
Jason	Lustbader	NREL
Margaret	Mann	NREL
Michael	Masquelier	WAVE
Jacob	Mathews	Ford Motor Company
Michael	McDonald	United Parcel Service
Francis (Frank)	McMahon	Momentum Dynamics
Russ	McNear	Army Applications Lab
Andrew	Meintz	NREL
Manish	Mohanpurkar	U.S. DOE EERE Vehicle Technologies Office
Matteo	Muratori	NREL
Chris	Nelder	Rocky Mountain Institute
Kathleen	Nelson Romans	Eaton
Christopher	Neuman	NREL
Roger	Nounou	GE Power Conversion
Jonathan	Oakley	ABB Inc.
Zach	Owens	Colorado Energy Office
Mike	Rowand	Duke Energy
Anuj	Sanghvi	NREL
Sophie	Shulman	Colorado Department of Transportation
Namit	Singh	Microgrid Labs Inc.
Lee	Slezak	U.S. DOE EERE Vehicle Technologies Office
Mark	Smith	U.S. DOE
Julie	Sodano	NREL
Keshav	Sondhi	PepsiCo
Jon	Stec	Rivian
Paul	Stith	Black & Veatch
George	Survant	1950
Martha	Symko-Davies	NREL
Ron	Thompson	Eaton
Jasna	Tomic	CALSTART
Francesca	Wahl	Tesla
Kevin	Walkowicz	NREL
Zachary	Wozniak	Allison Transmission
Sean	Yentsch	Penske Truck Leasing
Regan	Zane	Utah State University

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