EPRI

2023 TECHNICAL UPDATE

Tier 1 Supplier and Original Equipment Manufacturer (OEM) Company Perspectives on High-Power Charging

Electric Truck Research and Utilization Center (eTRUC) Project (Task 3.2)

CALSTART

eTRUC

Tier 1 Supplier and Original Equipment Manufacturer (OEM) Company Perspectives on High-Power Charging

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ABSTRACT

The Electric Truck Research and Utilization Center (eTRUC) seeks to accelerate the commercial adoption of a high-power combined charging system (CCS) and megawatt-level technologies in medium- and heavy-duty drayage trucks.

The goal of eTRUC project Task 3.2 is to assess the maturity of truck technology for high-power charging capable of adding at least 100 miles of range every 10 minutes. As part of Task 3.2, a series of interviews with leading Tier 1 suppliers and original equipment manufacturers (OEMs) was performed to understand the current technology capabilities and the expected path to support megawatt charging.

Tier 1 companies provided detailed insights on the limits of today's technology due to vehicle voltage, current, and battery life limitations. Perspectives included detailed discussions on the status and development of technology to support megawatt-level charging. Comments covered technology, charging infrastructure, and business case readiness for charging up to 1 MW and beyond.

OEMs surveyed provided key insights on the current Class 7 and Class 8 battery electric vehicle offerings in the United States and assessed the future readiness for megawatt-level charging. Interviews included discussions on battery capacity, grid integration, and costs associated with equipment compatible with megawatt-level charging.

Combining the OEM and Tier 1 survey reports provides a clear and coherent picture of the state of heavy-duty vehicles and vehicle componentry readiness to accept a megawatt charge in the coming years. OEMs and Tier 1 component suppliers interviewed highlighted their intentions to roll the Megawatt Charging System (MCS) out in the near future, with initial prototype versions of extreme high-power charging systems that could be commercially available in the next 2–3 years. Planners and public investment should be ready for this as it will significantly impact the market in general and trucks in specific.

Keywords

Heavy-duty drayage trucks
eTRUC
Charging infrastructure
Battery electric vehicles
Megawatt charging
EVSE

ACRONYM/TERM LIST

Acronym/Term	Meaning
BEV	Battery Electric Vehicle
CEC	California Energy Commission
EVSE	Electric Vehicle Supply Equipment
HD	Heavy Duty
HVIP	California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ITAC	Industry Technology Advisory Committee
kW	Kilowatt
kWh	Kilowatt-hour
MCS	Megawatt Charging System
MD	Medium Duty
MW	Megawatt
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
VPPs	Virtual power plants
ZE	Zero Emissions

EXECUTIVE SUMMARY

As part of the stakeholder engagement portion of the California's Electric Truck Utilization Center's (eTRUC) goal of developing, advancing, and deploying innovative heavy-duty (HD) high-power charging infrastructure along key freight corridors to promote the adoption of Class 7 and 8 battery electric zero-emission (ZE) trucks, industry outreach interviews were conducted with vehicle Original Equipment Manufacturers (OEMs), Tier 1 suppliers, EVSE vendors, and fleets to gain an understanding of current high-power charging technology, specifications, manufacturer market plans, protocols, standards, cost impacts, and industry coordination activities. This report presents the results of interviews with Tier 1 suppliers and OEMs. Tier 1 supplier interviews took place between January and May 2023. OEM interviews were conducted between January and March 2023.

Note: due to the sensitive nature of the information obtained during the interviews, the interview team committed to keep all responses anonymous and to share only aggregated data publicly.

Introduction

As the transportation industry accelerates the marketplace for commercial zero-emission vehicles (ZEVs), EPRI and CALSTART are teaming up to create California's Electric Truck Research and Utilization Center (eTRUC) for the CEC's $13 Million premier research hub for electric technologies in truck applications program.

eTRUC is a stakeholder-driven consortium of industry, government, academia, and community partners committed to the development, advancement, and deployment of innovative heavy-duty (HD) high-power charging infrastructure along key freight corridors that promote the adoption of Class 7 and 8 battery electric zero-emission (ZE) trucks. This project is intended to support planning, research, design, and deployment of innovative high power public corridor charging strategies that will extend the range and increase the operational flexibility of heavy-duty battery electric trucks beginning with an initial focus on drayage operations[1]. For the purposes of this project, "high-power charging" refers to charging power levels over 1 MW.

Tier 1 and OEM interview questions were developed jointly by EPRI, Oberon Insights, CALSTART, Paul International, and the eTRUC Industry Technical Advisory Committee (ITAC) and related specifically to high-power commercial electric vehicle charging systems.

Tier 1 interview participants included suppliers of major components, such as electric propulsion motors, electric axles, motor and e-axle controllers, vehicle controllers, power electronics, battery packs and battery management systems, on-board chargers, junction

[1] eTRUC, California's Research Hub for Electric Technologies in Truck Applications, Project Overview, https://etruc.org/

boxes, thermal management systems (for motors, cables, junction boxes, power electronics), inverters, and converters.

OEM interview participants included Heavy-Duty electric truck manufacturers in the United States, such as Class 7 and Class 8 electric trucks, with a focus on their day cab tractor and straight truck offerings.

OEM Interviews Key Insights and Take-Aways

Current Status: The nine original equipment manufacturers (OEMs) that our team spoke with currently offer thirteen heavy-duty battery electric truck models (nine Class 8 and four Class 7) for the U.S. market. Of these thirteen models, only one is currently capable of accepting a charge above 1 megawatt (MW). That model uses a proprietary connector. the maximum charge power accepted by the remaining twelve trucks ranges from 125-450 kilowatts (kW).

Technology readiness: CCS1 is the connector type used by all today, though this is expected to transition to MCS. Although most customers are not yet requesting higher-power charging or MCS, two-thirds of OEMs interviewed (representing over 96 percent of the current North American heavy-duty truck market) plan to integrate MCS into their trucks by 2030.

Costs: The cost to integrate MCS into a truck is not yet well understood, though it is expected to add less than $5,000 overall as long as system voltage remains below 1000 volts.

Tier 1 Supplier Interviews Key Insights and Take-Aways

Current Status: All of the Tier 1 suppliers included in the industry outreach surveys are monitoring or developing systems capable of MW-level charging. Although the MCS standard offers the benefit of interoperability, there are alternative high-power charging solutions, including multi-port connectors and automated charging. Initial deployments of EVSE and HD commercial electric trucks are likely to have current limits of 1,000 amps and up to 1,000 volts, which implies up to 1 MW. The actual power will depend upon vehicle architecture operating voltage. The next step in charging power is expected to be 1,500 amps at 1,000 volts (i.e., up to 1.5 MW). Due to the additional costs and technical complications, it is expected that moving to 1.5 MW charging will not occur for on-highway vehicles in the US until after 2030. Moving to the full MCS target of 3,000 amps and 1,250 volts (= 3.75 MW) is appropriate for specialty applications (mining, industrial, off-highway, agricultural, marine) where the costs and technical challenges can more readily be resolved. For on-highway, a move to the higher power level presents additional issues to address, such as limits imposed by power electronics components, cooling requirements, and battery limitations. In addition, it remains to define power requirements related to HD commercial electric vehicle duty cycles. The results of an extensive study by one of the major Tier 1 suppliers indicated that long haul Class 8 trucks are expected to adopt 800kWh batteries as a compromise between range, battery weight and cost. This would indicate charging power levels of 800kW currently and 1.2MW in future (1.5C with improved thermal management).

Market: The electric truck industry today is in early stages of deployment with only a few thousand heavy duty electric trucks and buses operating in North America. The lack of market demand has delayed development of high-power charging systems. This is expected to rapidly change, with the Tier 1 Industry projecting component sales for electric trucks to be 20% - 45% of company revenue by 2030 and major OEMs are introducing new vehicle platforms over the next two years. Due to the limited experience with electric trucks so far, there is significant uncertainty on the complete operational needs of fleets. Hence, views on component and vehicle needs vary across the industry.

Technology: Most Tier 1 suppliers rely on the OEMs to define electric powertrain component specifications. The interview participants were unanimous in predicting that vehicle architectures will not exceed 1000 volts prior to 2030 but will subsequently move above 1000 volts. Advances in power electronic components are required to increase operation voltages beyond 850 V. This includes transistors, capacitors, substrates, connectors, contactors, and junction boxes. The high-power charging levels will require several technical and operational advancements:

- Current battery chemistry limits charging power to around 1.5x the battery energy (1.5 C rate). Some manufacturers place a limit of 0.8 C for continuous charging and 1.5 C peak to optimize life of batteries utilizing currently available chemistries.
- Future battery chemistries may enable higher C rate charging, but these are likely several years away and will require advances in battery thermal management.
- Thermal management becomes a greater challenge since the battery and vehicle electrical systems will need to be kept cool, and the heat generated becomes hard to dissipate when the vehicle is stationary.
- Development of and compliance with safety standards.
- Some HD trucks and perhaps all medium-duty (MD) trucks may be fitted with CCS (if requested by fleets) and this may limit adoption of MCS.
- Higher vehicle voltages will require redesign of other components such as HVAC, power steering, actuators, water pumps, and fans.
- Concerns over ownership and control of the MCS charging system, including the roles of the customer and the electric utility company, and 2) concerns on operation and maintenance of the equipment.

Costs: Many of the Tier 1s expressed concern regarding the elevated cost of the infrastructure for high-power charging and how these costs will be amortized. Reducing electric demand rates for high power charging will have to be addressed. This could involve local energy storage systems.

The increase in charging station costs for MCS compared to CCS is expected to range from $1,000 to $3,000. The increase in on-board vehicle costs for MCS compared to CCS is predicted to range from $3,000 to $10,000, with power electronics, junction boxes, high-voltage high-current cables, power electronics, and liquid cooling systems representing significant portions of these costs.

Combined Key Takeaways

Combining the OEM and Tier 1 survey results allows us to present a holistic picture of the current and future MCS needs in the Heavy-Duty Commercial Vehicle sector. OEM respondents account for over 96% of North American heavy-duty truck sales and over 97% of North American heavy-duty zero-emission truck sales. The combined annual revenue from sales of electric vehicle components (light duty, medium duty, and heavy duty) of Tier 1 respondents accounts for US $5.2 billion.

Key takeaways on the future readiness for megawatt-level charging highlight the Original Equipment Manufacturers and Tier 1 component suppliers' intentions to roll Megawatt Charging Systems (MCS) out in the near future, with two-thirds of OEMs interviewed planning to integrate MCS into their trucks by 2030. Additionally, all Tier 1 suppliers included in the industry outreach surveys are monitoring or developing systems capable of MW-level charging.

Planning for future MCS deployment needs is essential when assessing the scale of transformation needed to meet potential Heavy Duty Vehicle electric charging needs. MCS will need to be rolled out at scale and require significant amounts of power and investment to meet this anticipated demand.

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Interviewees

Due to the nature of this project, we interviewed nine OEMs that currently manufacture heavy-duty (Class 7 and 8) battery electric trucks available for sale in the U.S.

Collectively, the OEMs interviewed account for over 96% of North American heavy-duty truck sales and over 97% of North American heavy-duty zero-emission truck sales.[2] Due to the sensitive nature of this information, we committed to keep all responses anonymous and to only share aggregated data publicly.

No significant differences in responses were observed between conventional OEMs and "Born Zero-Emission" OEMs.

Methodology

Most of the responses were gleaned from live interviews with key OEM staff, though a few OEMs preferred to respond to a written questionnaire, which we accommodated. Interviews were conducted between January and March 2023.

The project team drafted a list of key interview questions related to this topic. The eTRUC Industry Technology Advisory Committee (ITAC) reviewed this draft and provided feedback, which was incorporated into the final list of questions that was asked of participating OEMs. Volvo and Navistar are members of the ITAC.

Due to the sensitive nature of this information, not all OEMs were able to respond to each question.

Interview questions addressed topics ranging from current model offerings and architecture to future plans for enabling higher-power charging.

[2] Buysse, Claire. *Zero-emission bus and truck market in the United States and Canada: A 2021 update.* ICCT. 2022. https://theicct.org/publication/update-ze-truck-bus-market-us-can-sept22/ [theicct.org]

2 RESULTS

Current Vehicle Offerings

Although some of the OEMs also offer heavy-duty electric refuse trucks, bucket trucks, and/or terminal tractors, the interviews focused on their day cab tractor and straight truck offerings. Each OEM generally has one tractor model currently on the market, though some are available with different specifications (e.g., battery capacity and range, max charging power, etc.).

Class 8 Trucks

Nikola Tre BEV
Image source: CALSTART

Freightliner eCascadia
Image source: CALSTART

Lion Lion8 Tractor
Image source: CALSTART

Xos HDXT
Image source: CALSTART

BYD 8TT
Image source: CALSTART

Volvo VNR Electric
Image source: CALSTART

Peterbilt 579EV
Image source: CALSTART

Kenworth T680E
Image source: CALSTART

Tesla Semi
Image source: EPRI

Figure 1. Available Class 8 Battery Electric Trucks in the United States

Class 7 Trucks

Peterbilt 220EV
Image source: CALSTART

Kenworth 370E
Image source: CALSTART

International eMV
Image source: CALSTART

Freightliner eM2
Image source: CALSTART

Figure 2. Available Class 7 Battery Electric Trucks in the United States

Some of these models are available for delivery today, while some have a wait time of approximately one year (similar to diesel trucks).

Cost

The upfront cost of these trucks ranges from approximately $250,000 to $550,000, with an average price of $375,000. This is approximately two to three times the price of a comparable diesel tractor, though incentives are available for most of these models through California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) program. Class 8 tractors qualify for $120,000 in HVIP incentives, while the straight trucks qualify for $85,000. Additional funding is available for fleets that operate in disadvantaged communities (DACs). Due to fleet size adjustments new to HVIP in 2023, private fleets with more than 100 medium-and heavy-duty vehicles (MDHD) will receive less funding per vehicle (20-50% less), and those with 500+ M/HDVs must meet bulk purchase requirements in order to qualify for incentives.

Battery Capacity

One of the Class 8 trucks has a battery capacity of just under 1 megawatt-hour (MWh). The remaining Class 8 trucks have a battery capacity between 291 kilowatt-hours (kWh) to 733 kWh, with an average of 500-kWh.

The Class 7 trucks have a battery capacity between 141 kWh to 291 kWh, with an average of 231 kWh.

Fuel Economy

Based on manufacturer-states specs, the Class 8 trucks have an average fuel economy of 2.2 kilowatt-hours per mile (kWh/mile), while the Class 7 trucks achieve an average fuel economy of 1.4 kWh.

Production

Less than 3,000 of these electric trucks are expected to be produced (nationwide) in 2023. However, multiple manufacturers shared that they have the ability to ramp up production quite quickly based on market demand.

System Voltage

Currently, the battery system voltage of the trucks described above ranges from 400 to 1000, with an average of 729 volts.

Maximum Charging Power

One truck model is capable at charging at power levels over 1 MW. The maximum power that the twelve remaining trucks can continuously charge at ranges from 125 to 450 kilowatts (kW), with an average of 264 kW.

Charge Port Types

One truck model uses a proprietary technology for its charge port connection. All other trucks are available with Combined Charging Standard 1 (CCS1) charge ports, though some manufacturers also offer simply J1772 ports. One manufacturer is currently testing sample MCS connectors.

Protocols

All but one of these electric trucks are compatible with the Open Charge Point Protocol (OCPP) communication standard, though some are only compliant with OCPP 1.6, the most recent predecessor to the current 2.0 version.

About half of the vehicles are compliant with ISO 15118, a vehicle to grid (V2G) communication interface.

None of the vehicles are compliant with the Institute of Electrical and Electronics Engineers (IEEE) 2030.5 Smart Energy Profile Application Protocol, and some of the manufacturers were not even familiar with this standard.

Vehicle-Grid Integration (V2X)

Thanks to their OCPP connections, the trucks enable customers to take advantage of managed charging software – typically on the charger side - to plan and schedule charging, mitigate demand charges, and in certain cases even respond to utility signals (demand response). Many manufacturers noted that fleet customers are not interested in vehicle-to-grid (V2G) power export offerings. Moreover, trucks are generally not a good fit for V2G because their trips are not discretionary, nor do they often have long dwell periods during peak times for electricity demand (like school buses). However, refuse was noted as a segment that may eventually make sense for V2G. One manufacturer expressed an interest in offering aggregated grid services such as virtual power plants (VPPs).

Future Charging Plans

Although OEMs are generally not hearing from customers much about this issue, 56 percent of the OEMs we spoke with said they plan to increase the maximum power their vehicles can accept within the next five years. 33 percent have no plans to increase the acceptable max power, and 11 percent are unsure, though the unsure OEM already enables trucks to accept 350 or above kW. Developments in liquid cooled cable technology and high-voltage regulations were cited as considerations. For example, manufacturers shared that OSHA regulations change beyond 400-volts, which may be a challenge.

There was no agreement among interviewees with respect to how charge ports would evolve in order to enable this higher-power charging. For example, while most agreed that single-port MCS will prevail in the long-term for the heavy-duty truck market, many felt that CCS would be around far beyond 2030. In fact, many pointed out that even once MCS is standard for long-haul trucking and other duty cycles requiring faster charges, many heavy-duty trucks such as those performing urban deliveries, regional haul, or drayage will not require MCS and would therefore still be offered with CCS ports. 25 percent of OEMs see a future for (or are already offering) dual-port CCS charging, though most agreed that dual-port CCS was unlikely to be popular because of the additional cost, operational complexity, and space constraints presented by having two chargers and two cords per truck.

MCS Integration

The majority of OEMs are involved in CharIN's MCS Task Force, including some who have no plans to integrate MCS into their vehicles.

67 percent of OEMs interviewed (representing over 96 percent of the current North American heavy-duty truck market) plan to integrate MCS into their trucks by 2030. Of these, one plans to integrate MCS as early as next year. The remaining 33 percent weren't willing to share whether they plan to integrate MCS or have no plans to integrate MCS because their customers aren't requesting it and/or they believe fuel cell trucks will prevail as the preferred zero-emission technology for the long-haul heavy-duty truck market.

Much uncertainty exists around the cost to enable trucks for MCS, though most OEMs expect the new charging system components to add somewhere between $3,000 and $5,000 to the purchase price of a truck. And significant price reductions for necessary equipment are expected as production increases. A few OEMs noted that additional upgrades such as thermal management will need to be made to the vehicle architecture to enable charging at 1 MW and above, particularly once voltages exceed 1000, and that these costs are likely to be significant.

Components that OEMs expect will require upgrading include:

- Thermal management/cooling
- Charging port
- Battery management system (BMS)
- Busbars, conductors, and wiring
- Battery
- Power distribution units (PDUs)

When asked to rank how important it is to their company to offer trucks capable of charging using 1 MW+ chargers, using a scale of 1 to 10, with 1 being not at all a priority and 10 being the top priority, 67 percent of OEMs ranked it a 7 or above. 11 percent ranked it a 5, and the remaining 22 percent ranked it a 1.

OEMs also noted that charging power will be limited not only by what the trucks are capable of accepting, but increasingly by what utilities and the electrical grid can support.

Customer Perspectives

OEMs are ahead of end-user customers when it comes to high-power charging. Many – including those who expressed near-term plans to integrate MCS – shared that customers are not yet asking for vehicles that can accept higher power charging. None are specifically requesting MCS. Most customers seem satisfied with currently available charging capabilities, especially those with single-shift depot charging.

However, some – including independent operators, smaller fleets, and others with shared charging or no parking space – are interested in higher power charging. Some vocational customers that "slip seat" their vehicles are also interested in higher power and therefore faster charging to enable them to charge during shift changes (though they are not necessarily specifying new standards or power levels).

Some OEMs noted that fleets with operational constraints that would require higher power charging are not yet electric truck customers for exactly this reason. And so, although they are not hearing this desire expressed from customers (because they have essentially self-selected out of the market), they acknowledge that high-power charging will be needed for mass adoption of electric trucks and to achieve regulatory requirements (e.g., Advanced Clean Fleets). OEMs expect much of this high-power charging to be built out at public truck stops along key freight corridors.

In addition to public truck stop charging, "opportunity charging" (e.g., at or near ports) will also be important as it enables fleets to utilize their truck (an expensive asset) more, thereby deriving the maximum savings benefit from the vehicle's reduced fuel cost per mile and reduced maintenance costs.

Other High-Power Charging Standards and Technologies

Beyond MCS, a few additional high-power charging options were mentioned, including:

- Tesla's proprietary 1MW+ charging cables, which use an immersion cooling technology
- Wireless MW charging
  - WAVE currently offers wireless charging >500 kW
  - May make sense for niche markets like unionized shops that prevent drivers from plugging in a cable (e.g., ports)
  - Other examples from other heavy-duty industries such as mining (e.g., proprietary technology >500-kW being used to charge Caterpillar's electric mining truck)
- Robotic charging connections

Future Battery Chemistries and Charge Rates

To enable faster charging, many OEMs expect to see average charging rates increase from approximately 1.5C today to between 2 and 3C in the future. Potential battery chemistries mentioned by OEMs that may help achieve these higher charge rates include:

- Lithium-iron
  - Lithium Iron Phosphate (LFP)
  - Nickel Manganese Cobalt (NMC)

- Nickel oxide hydroxide – getting use in railways
- Nickel-hydrogen – testing in ferries
- Lithium sulfur
- Other solid state and lithium metal solutions

Safety, weight, and cost will continue to be important factors for selecting the right battery chemistry for electric trucks.

There was general consensus from OEMs that future trucks would have a system voltage of 900-1200 volts. As noted above, there is an anticipated cost barrier to exceeding 1000 to 1200 volts.

High-Power Charging Benefits

The primary benefit of enabling high-power charging for trucks is obvious: enabling faster charging times. As noted above, this is particularly important for being able to electrify more challenging operations like: long-haul, slip-seating/multi-shift, fleets without return-to-base operations that allow for overnight charging, and smaller fleets and owner-operators who may not have the ability to invest in charging infrastructure themselves. Faster charging also enables fleets to keep trucks running more, thereby maximizing the operational savings and environmental benefits of these assets.

OEMs also expect to see the following benefits from high-power charging:

- Not needing as many batteries on-board the vehicle (which helps reduce cost and alleviate challenges around the weight "penalty" of electric vehicles, allowing for more payload per trip).
- Higher utilization of charging infrastructure (vehicles can cycle faster, enabling more trucks to use each charger throughout the day, and thereby requiring fewer charger installations overall).
- Another noted benefit of the MCS standard in particular is its requirement of which side of the truck to put the charging port on. This is particularly helpful as the U.S. begins to build out public charging for electric M/HDVs.

High-Power Charging Challenges

OEMs noted the following challenges with respect to enabling high-power charging capable trucks:

- Cost (though noted truck sitting idle while charging is also costly)
- Grid constraints such as distribution circuit capacity (may further exacerbate challenges)

- Potential for reduced maintenance savings (because adding more parts to the vehicle)
- Interoperability
- Leaks from liquid cooled charging cables

Implications for eTRUC and Future Projects

Higher power charging is coming quickly to the trucking sector. If battery electric technology is to be able to meet the needs of long-haul, multi-shift, and other non-return-to-base operations, ensuring a speedy and seamless recharging process is necessary. Critical questions remain about what components will need to be upgraded in order to enable standardized 1 MW charging and how much cost this will add to the overall vehicle price. Regulatory considerations such as OSHA requirements may also impact how and to what extent high-power charging is enabled on the vehicle side. Luckily, OEMs are generally in agreement that MCS will be the standard of the future. Therefore, lessons learned via eTRUC's MCS test sites will be critical to advancing this technology and achieving mass adoption of electric trucks, regardless of duty cycle.

3 TIER 1 COMPANY INTERVIEWS FOR eTRUC PROGRAM

The Tier 1 Interview Process

Various fleets can benefit from availability of a network of fast charging stations specifically for trucks. This has led to the proposed standard for the Megawatt Charging System to provide charging power up to 3.75 MW compared to the up to 350kW for Combined Charging System. In principle high power charging can allow heavy duty trucks to charge within several minutes.

The eTRUC program goal is to understand the status and potential for high power truck charging to support fleet operations in California. A key element to this will be a vehicle industry view on the development roadmap for trucks to be ready for high power, megawatt charging. The intent is to have an industry view on the current status and the expected schedule for reducing charging time.

This Tier 1 survey is intended to be a starting point for the perspective by mapping current status and expected developments. The survey is intended to be anonymous to facilitate candid and detailed answers. The replies were aggregated and the aggregated survey results are included in this report.

The interview questions were developed by Oberon Insights, EPRI, CALSTART, Paul International and the eTRUC Industry Technical Advisory Committee. The question evolved as the interviews progressed and additional information became available.

Each interview included one interviewer/facilitator and one note taker.

Interviewees

Six interviews were conducted with Tier 1 component suppliers. These suppliers provide vehicle components and charging equipment to LD, MD, and HD electric vehicles. The combined annual revenue for these six companies is US $142.3 billion[2], with $5.2 billion from sales of electric vehicle components (light duty, medium duty, and heavy duty).

Each Tier 1 organization included in the interviews was represented by one or more technical management level employees.

Due to the sensitive nature of this information, we committed to keep all responses anonymous and to only share aggregated data publicly.

[2] Based on 2022 company annual reports.

Key Components Being Supplied

One of the objectives of the Tier 1 supplier interviews was to understand the key components being supplied to the vehicle OEMs, including current production volumes and engineering/production investments for the future.

The Tier 1 suppliers included in the industry outreach interviews collectively supply the following key components to the MD and HD commercial electric vehicle market:

- Electric propulsion motors
- Electric axles (includes electric propulsion motor, gearbox, and, in some cases, inverter) sets up power required by battery; battery power levels set by charging infrastructure. Need junction boxes to distribute power within vehicle which is at lower power level.
- Motor and e-axle controllers, vehicle controllers
- Power electronics
- Battery packs and battery management systems
- On-Board chargers
- Junction Boxes[3]
- Thermal management systems for motors, cables, junction boxes, power electronics
- Inverters and converters

Examples of these components are shown in Figure 3 through Figure 10.

[3] The junction box controls the high-voltage connections for the charging system, inverter/motor, and battery pack.

Figure 3. HD Electric Propulsion Motor

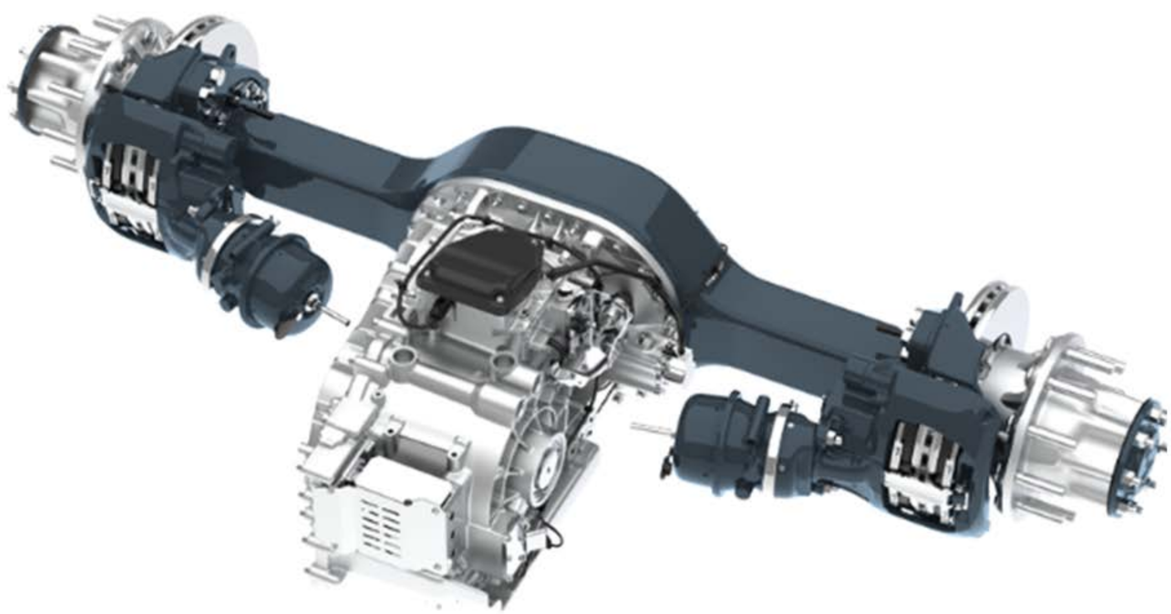

Figure 4. Electric Axle for Truck Applications

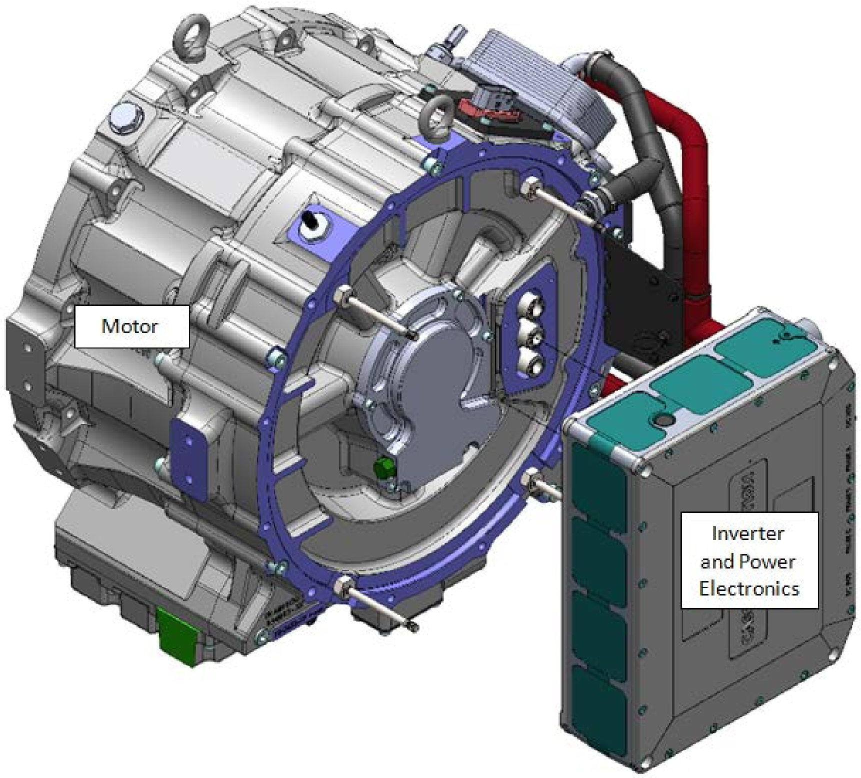

Figure 5. Electric Truck Moto, Inverter, Controller, and Power Electronics

Figure 6. Battery Packs Mounted in Semi-Tractor Chassis

Figure 7. On-Board Charger

Figure 8. High Voltage Truck Junction Box and Power Distribution Unit

Figure 9. Electric Drive Components Thermal Management System

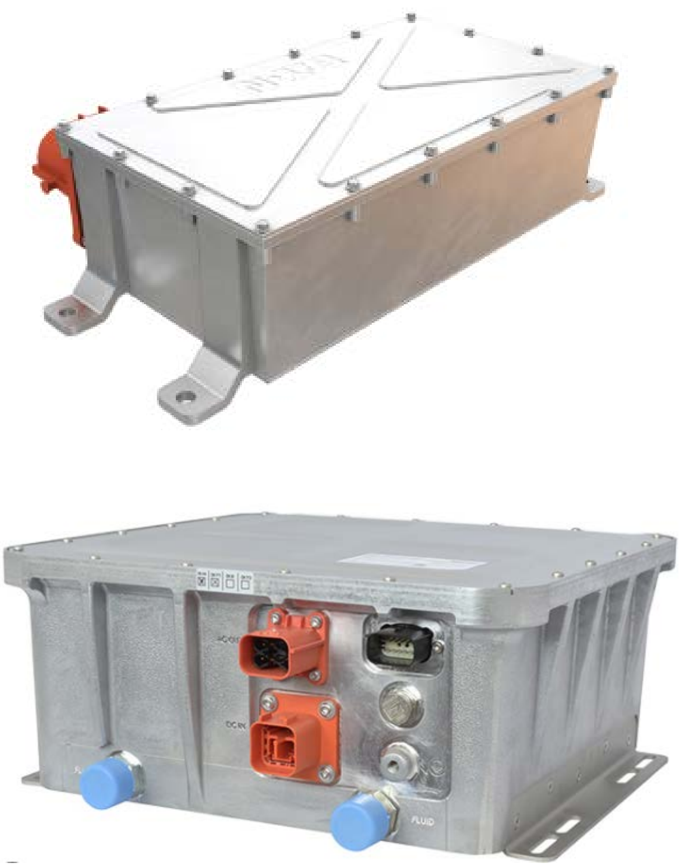

Figure 10. High Voltage DC/DC Converter (top) and Inverter (bottom)

Key Component Production Volumes

Electric vehicle component production volumes are governed by vehicle sales. Since MW charging is appropriate for MD and HD vehicles, including buses, the current populations and projected growth rates were examined to identify the upper bounds of electric vehicle component demand.

The population of MD and HD electric commercial vehicles is currently a small percentage of the total registered MD and HD vehicles in operation. For example, in California, the number of registered MD and HD vehicles is over 1 million[4], while the number of MD and HD zero tailpipe emissions vehicles (battery electric and fuel cell electric) is 1,943 (at end of last reporting period, Quarter 2, 2022), consisting of 1,369 buses, 306 trucks, and 268 delivery vans), which is 0.2% of the total California population of these vehicle types[5]. The compound annual growth rate for California commercial electric vehicles for the period 2010 (120 registrations) to 2022 (1,943 registrations) was 26%. The growth rate is projected to increase to 31.5% for the global commercial electric vehicle market through 2026[6]. The current breakdown of California commercial electric vehicle registrations is shown in Figure 11.

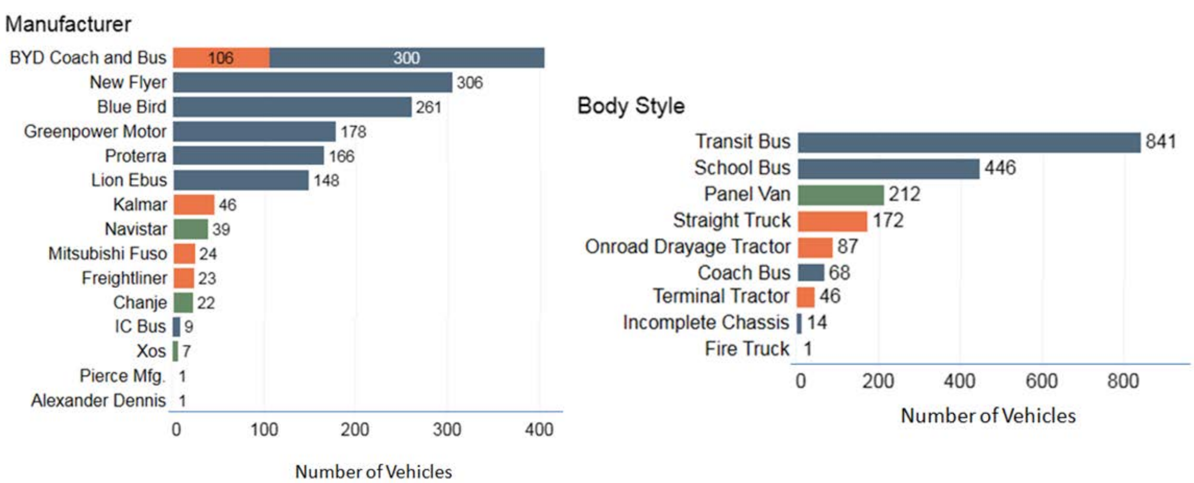

Figure 11. Commercial Electric Vehicle Registrations in California (second quarter 2022)

[4] California Energy Commission, Summary of California Vehicle and Transportation Energy, https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/summary-california-vehicle-and-transportation

[5] California Energy Commission, Medium-Duty and Heavy-Duty Zero-Emission Vehicles in California, https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/medium-and-heavy#:~:text=Medium%2DDuty%3A%20Vehicles%20with%20a,weight%20classes%207%20and%208.

[6] Berkshire Hathaway, BusinessWire, Commercial Electric Vehicles Market Report 2022, 14 November 2022, https://www.businesswire.com/news/home/20221114005564/en/Commercial-Electric-Vehicles-Global-Market-Report-2022-Government-Subsidies-Boosting-Sector-Growth---ResearchAndMarkets.com

As of the end of 2021, the worldwide registrations of commercial electric vehicles were 865,000, consisting of 180,000 commercial electric vehicles (1% of global sales) and 685,000 electric buses (44% of global sales)[7]. NREL's prediction is that elect these populations will grow to 15.5 commercial electric vehicles (54% of global sales) and 1.7 million electric buses (83% of global sales) by 2040.

The number of truck tractors and other medium- and heavy-duty trucks (over 10,000 pounds gross vehicle weight) registrations in the US is 14,369,339 according to the latest US Department of Energy statistics[8]. The most recent sales information for new commercial truck sales in the US[9] (for calendar year 2022) indicate sales of MD trucks totaled 221,834 and Class 8 HD truck sales were 254,000. Using the 1% ratio of electric to conventional propulsion systems, estimated sales of electric MD trucks is 2,218 and using the 0.2% ratio the estimated sales of Class 8 HD electric trucks is 508. As stated by CALSTART, sales of new battery electric buses in the US as of September 2022 was 2,101, bringing the population of full-size battery-electric buses to 5,269, a growth rate of 66% relative to 2021[10]. The growth of the zero-emission bus (ZEB) population in the U.S. is summarized in Table 1[11].

Table 1. Population of U.S. Full-Size Transit Electric Buses 2021 and 2022

2021	2022	Increase 2021 to 2022	Growth (%)
3,168	5,269	2,101	66%

Based upon the referenced market reports, and using growth rates representative of the last five years, sales of new vehicles that would benefit from MW charging can then be estimated as shown in Table 2.

[7] Joshi, P., and Gokhale-Welch, C., National Renewable Energy Laboratory, Fundamentals of Electric Vehicles Report, November 2022, https://www.nrel.gov/docs/fy23osti/84498.pdf.

[8] U.S. Department of Transportation, Bureau of Transportation Statistics, Number of U.S. Truck Registrations by Type, Table 1-22b, https://www.bts.gov/browse-statistical-products-and-data/national-transportation-statistics/number-us-truck

[9] Manzi, P., National Automobile Dealers Association, Commercial Truck Sales Increase 3.8% in 2022 over 2021, ATD Truck Beat, 31 December 2022, https://www.nada.org/atd/atd-insider/atd-truck-beat-commercial-truck-sales-increase-38-2022-over-2021

[10] Sustainable Bus, 66 Percent Growth for US Electric Bus Market in 2022, 3 February 2023, https://www.sustainable-bus.com/news/usa-electric-bus-market-2022-calstart/#:~:text=The%20US%20e%2Dbus%20market,it%20was%203%2C297%20in%202021).

[11] Calstart, Zeroing in on ZEBs, the advanced technology transit bus index: A ZEB inventory Report for the United States and Canada, 2 February 2023, https://calstart.org/zeroing-in-on-zebs-2023/

Table 2. Projected Sales of US Vehicles that Would Benefit from MW Charging Availability

Vehicle Type	2022	2023	2024	2025	2026	CAGR (%)
MD Trucks	2,218	2,795	3,521	4,437	5,590	26
HD Trucks	508	635	794	992	1,240	25
Battery Electric Buses	2,101	2,752	3,606	4,723	6,187	31
Totals:	4,827	6,182	7,921	10,152	13,018	

The calculations shown in Table 2 provide a means of estimating the current upper bound on the production volumes associated with components for MW charging systems.

Tier 1 Industry Outreach Survey Results

To protect potentially sensitive survey participant responses, answers to questions posed during the interviews have been aggregated.

Approach to Market: All but one of the Tier 1 participants in the industry outreach surveys expressed commitment to evaluating the MCS market for both vehicle and charging infrastructure components. The dissenting participant indicated a high level of revenue (20% during 2022) from electric vehicle components but indicated a weak demand for MCS systems. Several of the survey participants have indicated receipt of RFQs for higher voltage vehicle architecture components and charging systems.

Key Take-Aways:

- The electric truck industry today is in early stages of deployment with only a few thousand heavy duty electric trucks and buses deployed.
- This is expected to rapidly change, with Tier 1 Industry expecting component sales for electric trucks will be 20% - 45% of company revenue by 2030.
- With the limited experience with electric trucks so far, there is significant uncertainty on the complete operational needs of fleets once electric trucks are fully deployed. Hence, views on component and vehicle needs vary across the industry. Some of the industry outreach survey participants expressed concern regarding the negative impact of current supply chain issues on the target timeline for sales of commercial electric MD and HD vehicles.
- OEMs and Tier 1s are still evaluating the needs of fleets in order to assess the market for MCS. It was noted that many of the electric powertrain components are applicable to both battery electric and fuel cell commercial vehicles.
- The uncertainty in the demand for MCS will impact the timelines for OEMs, Tier 1s, and EVSE manufacturers to make commitments regarding production of vehicle and charging station components compatible with MCS protocols.

- One cause of delay in development of high-power charging systems is the lack of available MD and HD battery electric vehicles. This is expected to change over the next two years as many of the major OEMs are introducing new electric vehicle platforms.

Commitment to Electrification

Committed EV component production investments by the Tier 1 industry outreach interview participants for 2023 ranged from $400M to over $800M. The portion of these investments related to MCS was not specified. All of the participants indicated they were optimistic about the growth of MD and HD electric vehicle sales and were cautiously investing in facilities and personnel to meet the expected demand. At the request of OEMs, two of the survey participants have branched out to provide electric powertrain design and integration services in addition to components and indicated a lack of electric powertrain engineering expertise at several MD and HD vehicle manufacturers. Nevertheless, the Tier 1 suppliers indicated that product specifications are predominately developed by the vehicle OEMs.

The six Tier 1 suppliers are expanding capabilities and product offerings through acquisitions. Several are currently offering or planning products for non-road vehicles such as those employed in agricultural, mining, and construction industries.

Electric vehicle components now being developed by the Tier 1 suppliers are expected to be introduced to the market between 2027 and 2030. Two of the interviewees noted that developing an integrated vehicle power electronics design that operates at higher voltages while simultaneously addressing safety concerns and costs will provide an early and significant market advantage.

Key Take-Aways:

- All of the OEMs and Tier 1 suppliers included in the industry outreach surveys and interviews are monitoring or developing systems capable of MW charging.
- There are questions on the actual power requirements for extreme high-power charging and the size of the market, especially with CCS having capability up to and perhaps exceed 480kW (500-700A at 1000V). Although there is general consensus that heavy duty trucks will be MCS based.
- Most Tier 1s rely on the OEMs to define electric powertrain component specifications.

Components and Technology Currently in Production

This section addresses the current and anticipated commercial electric vehicle architectures, factors driving the selected voltage and current levels, battery charging specifications, and commercial vehicle industry concerns and challenges.

Vehicle Voltage and Power Levels

Interview participants indicated that current MD and HD electric commercial vehicles have operating voltages that range from 400 to 800 volts. These same participants projected operating voltages of 900 to 1250 volts after 2030. These are summarized in Figure 12. Three of the Tier 1 interviewees indicated that operating voltages are expected to remain below 850 volts for the next three to four years. It was also stated that the efficiency improvements associated with operating at greater than 850 volts are not great enough to justify the additional costs.

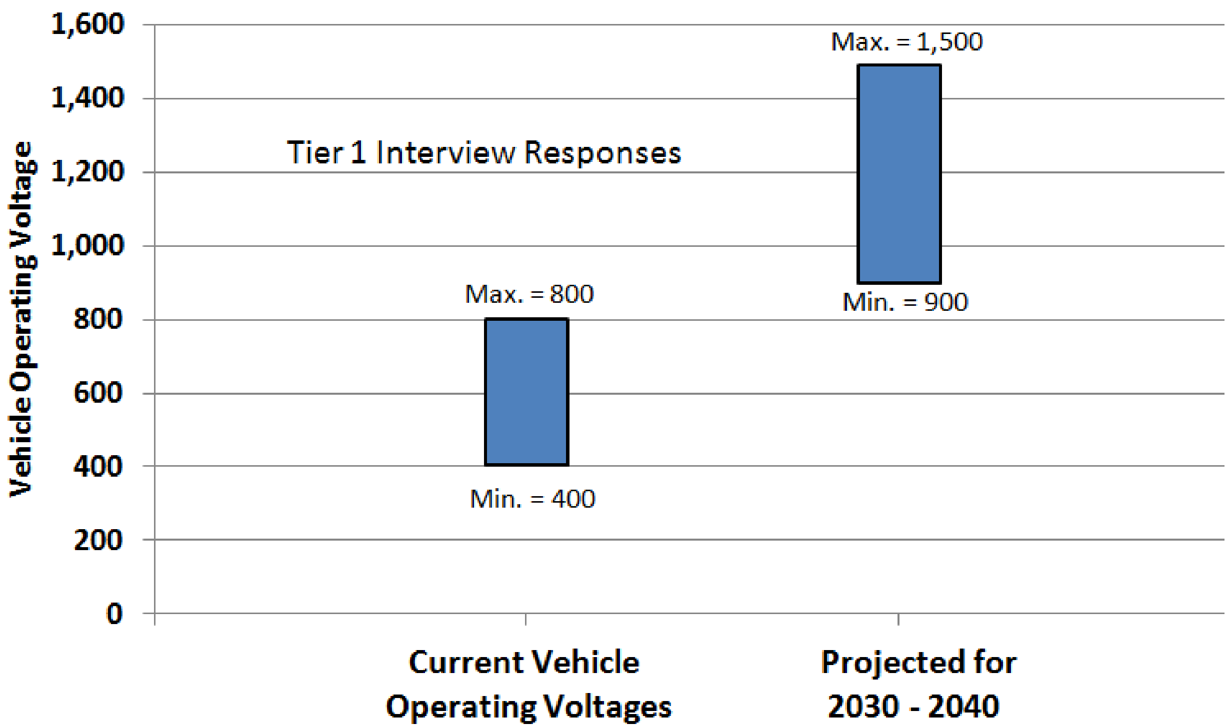

Figure 12. Current and Projected MD and HD Commercial Electric Vehicle Operating Voltages

Tier 1s indicate that some OEMs are requesting quotes for electronic junction boxes rated up to 3,000 amps and 750 volts (2.5 MW capacity) for HD vehicles with large battery packs. The junction box splits the current to multiple, lower-amperage, parallel circuits downstream of the charger. Motor manufacturers reported OEM requests for drives and motors that operate at greater than 1,000 volts.

One charging system manufacturer that participated in the interviews currently offers a 1.5 MW, 480 volt system designed to charge up to 20 vehicles simultaneously using CCS connectors or a pantograph (DC output voltage varies from 150 Vdc to 1,000 Vdc.

Key Take-Aways:

- Truck OEMs and Tier 1s commented that trucks will need charging power above current CCS limits and will require high power charging standardized ports and connectors.
- Tier 1 suppliers were unanimous in predicting that vehicle voltages will not exceed 1000 volts prior to 2030 but may subsequently move to higher levels. The results of an extensive study by one of the major Tier 1 suppliers indicated that long haul Class 8 trucks would adopt 800kWh batteries as a compromise between range, battery weight and cost. This would indicate charging power levels of 800kW currently and 1.2MW in future (1.5C with improved thermal management).
- The leading EVSE companies and Truck OEMs have prototype extreme high power charging systems available today, or planned for the near future. Europe appears to be leading US with MCS and high-power demonstrations. Initial production versions could be available in the next 2-3 years.

Factors Driving Vehicle Operating Voltages

The Tier 1 industry outreach interview participants were asked to define the key drivers for EV commercial vehicle operating voltages. Maximum current is a limiting factor for high power charging or discharging from battery packs, which is resulting in the industry considering higher vehicle voltage levels. There are several advantages to moving to higher operating voltages, including[12]:

- High voltage motors generally have higher efficiency ratings compared to their lower voltage counterparts as well as higher torque levels and higher power-to-weight ratios. Motors operating at higher voltage levels also provide higher torque at higher rotational speeds.
- Increasing voltage levels reduces the current levels in cables and connectors, with a corresponding decrease in thermal loads, but increases the insulation requirements.
- Higher voltages reduce battery charging times and cable thermal issues.

There are limits in moving to higher voltages, however, and these were noted by the Tier 1 interviewees. Currently, the primary limit to higher voltages is the capacity of the power electronics components. Vehicle architectures are capable of accommodating higher voltage, higher power operation, but the electronics, connectors, contactors, capacitors, and junction boxes are limited to 850 volts. This allows peak over-voltage levels of up to 900 volts to be tolerated. Higher power levels also introduce additional cooling requirements, which add weight and complexity to the components. One of the Tier 1 suppliers explained that semiconductors are not currently rated to operate above 850 volts. Recent developments using silicon carbide, have increased the blocking voltage (also known as the drain-to-source

[12] Lovati, S., Electrical Engineering Times Europe, Shifting the EV Bus to 800 V: Benefits and Design Challenges, 28 September 2022, https://www.eetimes.eu/shifting-the-ev-bus-to-800-v-benefits-and-design-challenges/

breakdown voltage; the voltage at which the reverse-biased body-drift diode breaks down) using an edge termination technique to increase the blocking voltage to 3,850 volts, but these are not yet commercially available. Advantages of silicon carbide include a) ability to support a higher electric field (up to 10 times greater than silicon alone), which allows three times greater blockage voltages), b) lower leakage currents, c) switching frequencies up to five times greater than silicon, and d) ability to withstand high temperatures without additional cooling. Higher voltages will require the entire power electronics systems to be redesigned, including the printed circuit boards and controllers.

Key Take-Aways:

- Initial deployments of EVSE and Trucks are likely to be up to 1000A limit and up to 1000V, hence up to 1 MW. This actual power will depend on vehicle architecture voltage. For example, trucks today operating at 800V, would be limited to 1000A x 800V = 800kW, or less if the Truck also limits maximum current.
- Advances in power electronic components are required to increase operation voltages beyond 850 V. This includes transistors, capacitors, substrates, connectors, contactors, and junction boxes. Silicon carbide has been shown to increase blocking voltages, but additional development is required to replace traditional silicon circuits with silicon carbide counterparts.

Battery Charging Levels

Existing DC charging stations have output capacities[13] ranging from 50 kW to 500 kW[14] and efforts are underway[15] to increase power levels beyond 650 kW and to over 1 MW[16]. A summary of the input and output power levels[17], output current ratings, and associated

[13] U.S. Department of Transportation, Electric Vehicle Charging Speeds, 2 February 2022, https://www.transportation.gov/rural/ev/toolkit/ev-basics/charging-speeds#:~:text=Level%202%20equipment%20offers%20charging,empty%20in%201%2D2%20hours.

[14] Meintz, A., National Renewable Energy Laboratory, Charging Infrastructure Technologies: Development of a Multiport, >1 MW Charging System for Medium- and Heavy-Duty Electric Vehicles, 24 June 2021, https://www.energy.gov/sites/default/files/2021-06/elt204_meintz_2021_o_5-14_551pm_KF_TM_LS.pdf

[15] Andersson, M., Energy Storage Solutions for Electric Bus Fast Charging Stations, Uppsala Universitet, 2020, http://www.diva-portal.org/smash/get/diva2:1080948/FULLTEXT01.pdf

[16] Bohn, T., SAE J3271 Megawatt Charging System Standard; Part of MW+ Multiport Electric Vehicle Charging for Everything that 'Rolls, Flies, or Floats', EPRI Bus & Truck, 12 April 2022, https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=78275

[17] Makeen, P.; Ghali, H.A.; Memon, S. A Review of Various Fast Charging Power and Thermal Protocols for Electric Vehicles Represented by Lithium-Ion Battery Systems. *Future Transp*. 2022, 2, 281–299. https://doi.org/10.3390/futuretransp2010015

standards and protocols[18] are provided in Table 3. Several organizations, including SAE, CharIN, and ISO/IEC are working on standards for megawatt charging systems.

Table 3. DC Charging System Designations, Specifications, and Protocols

Charging System	Charger Output		Protocol
	Power Range (kW)	Current (Amps)	
Level-3	50 to 350	200	1) Guobiao standard 20234, 2) CHAdeMO, 3) SAE J3068, SAE J3105, 4) IEC Standard 62196
Level-3, CCS	150 to 500	500	IEC 62196 Type 1 and Type 2 connectors, CharIN, 2014/94/EU, Tesla Supercharger, Vehicle-Grid Integration Program (VGI), IEEE P2030.13,
Level-3, MCS	Up to 3,750	Up to 3,000	CharIN, MCS (Formerly HPCCV) Working Group, UL2251 (Touch Safe), ISO/IEC 15118-20, SAE J3271.

Standards development includes, 1) system level charging description/requirements, 2) electromechanical coupler/inlet requirements (like J1772), 3) physical/software layer communication, 4) charging cables (cooling, cord handling/automated connection), 5) use cases including DER/microgrid interconnections (V2G), and 5) interoperability/testing requirements. Argonne National Laboratory has provided the following updates on applicable standards activities[16]:

- IEEE P2030.13 – out for ballot now, published soon
- IEEE IC22-002 Industry Connections activity – High Power EV Charging, Formed in March 2022, surveys to EV + EVSE manufacturers, utilities-EVSPs on needs https://standards.ieee.org/industry-connections/high-power-electric-vehicle-charging-infrastructure/
- SAE AIR 7357 (MCS for aircraft) – monthly meetings; requirements survey, focus on airframe certification process/requirements; leveraging J3271 MCS TIR
- IEC80005-4 (MCS, DC marine charging) – monthly meetings/input from industry, biggest issues are automated connection systems, parallel PE paths/grounding and parallel inlet-charger operation on current sharing-safety interlock master

[18] Khalid, M.R., Alam, M.S., Sarwar, A., Jamil Asghar, M.S., A Comprehensive Review on Electric Vehicles Charging Infrastructures and their Impacts on Power-Quality of the Utility Grid, *eTransportation*, https://www.sciencedirect.com/science/article/abs/pii/S2590116819300062?via%3Dihub

- SAE J3271 MCS – TIR V0 in public review folder (12/30/2022) Document needs more input/detail; Migrate CharIN MCS white paper requirements into J3271 TIR as ‘information references’ now, with links to the source (J3271 V1 due in June)

The Tier 1 industry outreach interview participants were asked to provide opinions on the developing battery charging levels for MD and HD commercial electric vehicles. The participants indicated charging stations, pantographs, and wireless systems are all being investigated as viable technologies for high-power (greater and 1 MW) charging. All of the Tier 1 participants stated that current components are compatible with CCS, with vehicle operating voltages ranging from 450 to 850 volts. Some Tier 1s are investigation both on-board and charging station systems with MW capability. It was noted that on-board chargers are currently limited to 450 kW due to volume and weight constraints. Two of the Tier 1 interview participants stated that the maximum charging system capacity requests received to date have been less than 750 kW.

It was noted during the interviews that the energy delivery rate for fueling diesel trucks is approximately 4 MW for each fuel dispensing unit, based on the energy content of diesel fuel. The fill rate for diesel is 10 gallons per minute.

Key Takeaways:

- The goal of 100 miles range in 10 minutes, equates to around 1.5MW charging based upon today’s truck efficiency of around 2.5 kWh/mile. Tesla is stating 1.7 kWh/mile for their Semi, which makes the target charging power around 1 MW.
- The next step in charging power is expected to be 1500A at 1000V, which is up to 1.5MW. Europe has plans to migrate up to this power level.
- The high-power charging levels will require several technical advancements:
  - Current battery chemistry limits charging power to around 1.5x the battery energy (1.5 C rate). For a 1 MWH truck, this would be 1.5MW, but many class 8 trucks are currently 500 kWh, and charging power would be limited to 750kW. Increasing battery size to 1 MWh is feasible but doubles and reduces payload due to the greater battery weight. Some manufacturers place a limit of 0.8 C for continuous charging and 1.5 C peak to optimize life of batteries utilizing currently available chemistries.
  - Future battery chemistries may enable higher C rate charging, but these are likely several years away and will require advances in battery thermal management.
  - Thermal management becomes a greater challenge as the battery and vehicle electrical systems will need to be kept cool, and the heat generated becomes hard to dissipate because the vehicle is stationary.
  - The incoming electrical current will need to be distributed to keep current/conductor within limits for conductor and connector ratings as well as heat dissipation requirements. This will add more cost to the junction/distribution box.

- There are currently no known production trucks with capability to charge at 1.5 MW. With the additional costs and technical complications, it is not clear this would happen for several years. It will likely depend on whether fleets will have sufficient business case for the additional benefits of 1.5MW versus the challenges of cost, and reduced payload.
- Higher power CCS equipment may post a challenge to MCS. Some EVSE manufacturers are evaluating systems that have a current rating of 650 amps. Some HD trucks and perhaps all MD trucks may be fitted with CCS (if requested by fleets).

MW Charging Concerns and Challenges

The development of charging systems with delivery ratings exceeding 1 MW offers a number of challenges. The Tier 1 interview participants expressed concerns and needs regarding safety, power electronics, thermal management, battery impacts, costs, and infrastructure readiness.

Safety: The maximum voltage rating for currently available connectors and junction boxes is 1000 volts. Updated standards and associated safety requirements will be required for connectors, cables, and power electronic components if operating voltages are increased above 1500 volts. Basic signaling and controls rely on the charging system communications system and are integral to safety-related functions. Examples include status of the connector, status of the vehicle, capacity of the cable, load balancing (energy flow from EVSE to vehicle), and thermal state of the battery.

Cyber risks associated with the charging stations are also a safety concern as is potential damage to the battery that can result in fires and compromises in the life safety systems. Wear and tear, accidental damage, vandalism, ground fault interrupter failure, and theft of components can also expose personnel to electrical shock.

Power Electronics: As noted earlier, current power electronic components have been developed with maximum voltage ratings less than 1000 volts. Additional development work is required to develop systems with higher power ratings. Moving to higher vehicle system voltages will require redesigning of other components such as HVAC, power steering, actuators, water pumps, and fans.

A key challenge for traditional MD and HD OEMs is the lack of expertise in the area of powertrain development, which for traditional ICE vehicles was addressed by key suppliers such as the established engine and transmission suppliers.

It is expected that MD and HD vehicle electrical architectures will evolve to include multiple charging ports to be compatible with both CCS and MCS, and as noted above, some HD trucks and perhaps all MD trucks may be fitted with CCS (if requested by fleets).

Thermal Management: Thermal management for both the charging station components and vehicle on-board components was noted by the interviewees as a key challenge for MW-level charging. Feasibility studies have been performed, but it was agreed that significant development remains. One of the key areas of thermal loading is related to I^2R losses in bus bars and contactors. Currently available contactors are not rated for the high current loads associated with high power electric drive systems.

Current CCS systems can tolerate overload (high power) conditions for up to 10 minutes before thermal conditions require shut down.

Battery Impacts: Power management protocols are being developed to control current and voltages that allow fast charging with minimum charging loss, high efficiency, and increased battery life. These protocols are typically built into the battery management system. Cell chemistries that reduce the internal resistance of the cells are being investigated. Increasing charging current levels accelerates battery aging disproportionally, leading to capacity and power fade and posing an unacceptable safety hazard during operation[19]. A dynamic charging protocol based on improved modeling of the battery at various ambient conditions, along with artificial intelligence, are expected to ensure a safe charging process with reduced charging current and higher efficiency levels.

Cell balancing may require slower charging rates. Another concern is multiple battery packs feeding a single junction box and the impact of varying voltages, such as arcing.

Costs: It was noted that one of the biggest challenge to MW charging is the cost of the high-power charging infrastructure and high electricity rates associated with demand charges. Battery storage at the charging stations may alleviate some of these costs. Because of the high installation costs, fueling station owners are reluctant to installing electric charging stations without government or electric company financial incentives for doing so. Other disadvantages of high-power charging systems that remain to be addressed include: 1) concerns over ownership and control of the system, including the roles of the customer and the electric utility company, and 2) concerns on operation and maintenance of the equipment.

Infrastructure Readiness: The current technology readiness level for MCS is 6 (prototype demonstrations are underway). Estimates of when MW charging will be ready for deployment range from 2027 to 2030 and are dependent upon the timely installation of the required grid infrastructure and integration with utility company command and control systems. Interview participants also pointed out that lead times for installing MW charging stations can range from 18 months to two years depending upon the size of the associated substation and distance to power lines. One Tier 1 supplier indicated that larger substations, greater than 10 MW, that are proposed for construction in defined green sites (sites having stringent environmental requirements) can require up to five years to obtain the required permits and approvals.

[19] Wassiliadis, N.; Schneider, J.; Frank, A.; Wildfeuer, L.; Lin, X.; Jossen, A.; Lienkamp, M. Review of fast charging strategies for lithium-ion battery systems and their applicability for battery electric vehicles. J. Energy Storage 2021, 44, 103306, https://www.sciencedirect.com/science/article/abs/pii/S2352152X21009981?via%3Dihub

Interoperability is also a concern. CCS and MCS voltages must be compatible with vehicle operating voltages, which may limit the use of dual CCS or CCS plus MCS ports.

Key Takeaways:

Identified Challenges for MCS:

- The Tier 1 industry outreach participants provided the following challenges to implementing MCS:
  - Development of and compliance with safety standards.
  - Development of high voltage, high amperage power electronics components, including SiC components, cables, and connectors.
  - Thermal management systems for cables, junction boxes, bus bars, and connectors.
  - Battery chemistries, battery thermal management, and battery management systems. High thermal loads are a primary concern for battery life.
  - Higher vehicle voltages will require redesign of other components such as HVAC, power steering, actuators, water pumps, and fans.
  - Reducing demand charges for high power charging will have to be addressed. This could involve local energy storage systems.
  - Concerns over ownership and control of the MCS charging system, including the roles of the customer and the electric utility company, and 2) concerns on operation and maintenance of the equipment.
  - Time requirements for utilities to install substations capable of accommodating MW charging stations. Some utilities are quoting two years from initial agreement to completion for these substations.
- Many of the Tier 1s expressed concern regarding the elevated cost of the infrastructure for high-power charging and how these costs will be amortized.

Future Architectures and MCS

The Tier 1 interview participants were asked for their input regarding the timeframe during which MCS is expected to be implemented, vehicle charger port configurations, power and voltage levels, and the impact on vehicle costs associated with implementing MCS.

Expected Date MCS Will Be in Production

The Tier 1 suppliers included in the outreach interviews that are pursuing components to support MW-level charging are targeting introduction dates that range from 2027 to 2030. Some of the suppliers are waiting to determine how the market will develop prior to committing resources to product development. Several of the suppliers are actively developing vehicle components to support MCS and are working with several vehicle OEMs to define component specifications. Availability of vehicles that are MCS compliant is also expected to delay initial deployments. Delays in vehicle availability are related to battery chemistries and power electronics limitations.

Vehicle Charge Port Configurations

There are several options for vehicle charging going forward: single port CCS (up to 350kW), dual port CCS (potentially up to 700kW), single port MCS (potentially up to 3.75MW), and MCS + CCS ports to keep compatibility with CCS.

The Tier 1 interview participants indicated compliance with CCS protocols, including IEC 62196, 2014/94/EU, and ISO 15118. Responses were mixed regarding the types of ports to include for future electric trucks, with some favoring dual CCS ports and other favoring one CCS and one MCS port. It was generally agreed that at least one CCS port will be required to allow the vehicle to recharge at facilities equipped with legacy CCS systems. Some participants expressed the opinion that retail charging facilities may limit each vehicle to access only one charging station connector. Some EVSE manufacturers are evaluating a wider range of interoperability for a wider range of charging protocols, including pin and sleeve systems similar to the ones developed by Tesla.

Several of the Tier 1 suppliers indicated they were investigating automated (robotic) charging connection systems. This would reduce personnel requirements for high power charging (it has been suggested that trained staff would be required for safety reasons). Although this could drive requirements for specialized charging connectors (e.g., pantograph, pin/sleeve), there are also robotic arm systems which can use standard CCS (or MCS) connectors.

It has been noted that Tesla has installed V4 chargers in the Netherlands that include a CCS2 coupler and are rated at 1000 volts and 615 amps[16].

MCS Power and Voltage Levels

To maintain battery life, the charge rate should not exceed 0.8 C continuous and 1.5 C peak. Charge rates of 2 C to 3 C are possible today, but the associated battery chemistry is expensive, and heavy. Promising chemistries capable of supporting higher C-rates are expected to move from passenger cars to MD and HD vehicles. Increased production volumes would lower the cost of these new battery chemistries.

To achieve less than 30-minute recharging times (which for HD trucks means charging power > 1+MW) and long cycle life (2000+ charge/discharge cycles), improved battery and EVSE thermal management systems must be developed. It was suggested that solid state batteries may be candidates for the high-power applications.

If thermal management systems are improved, higher charging C-rates can be achieved with minimal impacts on battery life. Questions that must be addressed are: 1) does diffusion of lithium cause plating and decrease in battery life, 2) what are the relative impacts of thermal management and battery chemistry on battery life, and 3) will solid state batteries allow higher C-rates? One of the major Tier 1s estimated that the upper charge rate limit during the next 5 years will be 1.5 C. Others said they expect cells to be developed specifically for commercial electric vehicle batteries to accommodate MW charging. OEMs have already been requesting these types of batteries from suppliers. These batteries will likely require immersion cooling systems.

Today’s main battery chemistry is developed for high energy density and charging rates are limited to protect battery life. The instantaneous charge rates may be higher, but the average charging rate for an automotive battery cell from 10-80% SOC is typically around 1.5C resulting in a charge time of around 40 minutes. However, HD Truck battery packs have charge rates around 0.5 C.

Impact on Vehicle Costs

The Tier 1 industry outreach participants were asked for their opinions regarding the expected additional cost for an MCS-capable vehicle.

Much uncertainty exists around the cost of enabling MD and HD vehicles to be MCS-compatible, although most OEMs expect the new charging system components to add somewhere between $3,000 and $5,000 to the purchase price. Significant price reductions for vehicle upgrades are expected as MCS component production increases. A few OEMs noted that additional upgrades such as thermal management will need to be made to the vehicle architecture to enable charging at 1 MW and above, particularly once voltages exceed 1000 volts, and that these costs are likely to be significant: These vehicle cost increases were reflected by the Tier 1 interviewees, but the range of estimates was greater, with the low estimate equal to $1,000 per vehicle and the high estimate being $10,000 per vehicle, with the high estimate including upgrades of vehicle ancillary systems to operate at the higher voltages.

Components that OEMs expect will require upgrading include:

- Thermal management/cooling
- Charging port
- Battery management system (BMS)
- Bus bars, conductors, and wiring
- Battery
- Power distribution units (PDUs), junction boxes.
- Electric HVAC systems

- Electric air brake compressor
- Power steering
- On-board charger

Key Takeaways:

- MCS refers to the connector type, and there are alternatives. Although the main benefit of a standard connector is inter-operability, including communications between the charging station and vehicle. It is likely that MCS charging stations will be integrated with utility command and control systems (i.e., demand response control).
- There is increasing interest in automated (robotic) systems for managing charging. There have been demonstrations of robotic arms working with MCS / CCS style connectors. Alternate connectors such as “pin and sleeve” and inductive charging systems which may make automated charging easier and less expensive.
- Questions have been posed regarding the future importance of automated / robotic charging systems. There remains interest in autonomous trucking especially in highway driving applications. There is also interest in implementing automated charging at depots to reduce the staffing cost.
- The increase in charging station costs for MCS compared to CCS are expected to range from $1,000 to $3,000.
- The increase in on-board vehicle costs for MCS compared to CCS are predicted to range from $3,000 to $10,000, with power electronics, junction boxes, high-voltage high-current cables, power electronics, and liquid cooling systems representing significant portions of these costs.

Readiness and Business Case for Truck MCS

Several of the Tier 1 interview participants indicated the business case for MCS is incomplete and is dependent upon technology readiness, customer requirements, and OEM product schedules. Some Tier 1s indicated there have been no orders for specific MCS components, but there has been significant industry interest. Fleet expectations must be understood and quantified, such as required charging times and locations (e.g., is MW charging necessary?). In addition, the Tier 1s have the perception that the electric grid is not ready to support MW charging in the next two to three years.

Business Factors to be Resolved

Business factors to be resolved include both end customer (fleet) requirements, product availability, and costs for the MCS system relative to alternatives (e.g., dual port CCS). Other business considerations identified by the Tier 1 interview participants include:

- Site constraints required for the MCS charging stations: this may include the requirement for an on-site substation and the loss of parking spaces to accommodate charger access and installation of equipment.
- Trade-off of shorter charging times and operational needs: a financial assessment to quantify cost savings associated with rapid charging will be required to justify the added cost of the MCS system.
- Electricity costs: charging the vehicles during peak electricity price periods must be evaluated against lack of vehicle availability during the charging sessions.
- Total cost of ownership: will the improved efficiency associated with higher vehicle operating voltages and greater vehicle availability justify the additional MCS costs? Since electric trucks are expensive assets fleets are expected to use them as much as possible (e.g. as close to 24 hrs/day as possible) and hence want less charging times, even for depot operations.
- Several of the Tier 1 interview participants commented on options for reducing both capital and operating costs associated with MD and HD electric commercial vehicles. One option to improve utilization of assets is Truck-as-a-Service (TasS) which provides battery electric trucks to individual drivers or small fleets as part of a full package service that includes use of the truck, charging and maintenance. The TaaS service provides value for owner-operators by removing the need for an initial investment in a new fleet, one of the highest barriers to entry in the new Zero Emission Transportation market[20]. Companies offering TaaS include Volta Trucks[21], Uber Freight[22], and WattEV, which also markets charging infrastructure[23] and has plans to implement 1.2 MW charging[24]. This approach is another option for introducing MCS to the marketplace.

V2G Considerations

It is possible that the higher on-board energy storage associated with MCS vehicles (up to 1 MWh of storage), might lead to cost effective procedures to reduce vehicle operating costs.

[20] Electrive.com, Volvo Trucks to Supply 50 e-trucks to WattEV, 23 Mar 2022, https://www.electrive.com/2022/03/23/volvo-trucks-to-supply-50-e-trucks-to-wattev/

[21] Volta Trucks, Truck as a Service, Volta Trucks - Truck as a Service

[22] Heavy Duty Trucking, Uber Freight Piloting Electric Trucks as a Service in California, 21 February 2023, https://www.truckinginfo.com/10192987/uber-freight-piloting-electric-trucks-as-a-service-in-california-with-wattev

[23] WattEV, Electrifying Heavy Duty Transport, https://www.wattev.com/

[24] Cision, WattEV Secures Funding to Accelerate Heavy-Duty EV Truck-as-a-Service Fleet Deployment in Southern California, 14 July 2022, https://www.prnewswire.com/news-releases/wattev-secures-funding-to-accelerate-heavy-duty-ev-truck-as-a-service-fleet-deployment-in-southern-california-301586896.html

- Three of the six Tier 1 suppliers indicated they are evaluating vehicle-to-grid operations for MD and HD commercial electric vehicles.
- V2G will increase the number of charge/discharge cycles and thus will reduce battery life. However, if the vehicles are charged during electricity rate off-peak times and delivered to the grid during peak price periods, the cost savings may justify electing to participate in V2G programs. The cost trade-offs will vary by fleet.
- Smart chargers will be required to support the V2G program. Standards for V2G include ISO15118, IEEE 1547, UL 1741, and SAE J3072.
- The Tier 1 interview participants indicated it is too early in the MCS development program to quantify potential V2G benefits for MCS.

Industry Coordination for MCS

The Charging Interface Initiative e.V. (CharIN) was established during 2018 and consists of 173 industry participants, including vehicle OEMs, EVSE manufacturers, academic organizations, utility companies, and suppliers. CharIN developed the CCS system and is now taking the lead on the MCS system.[25] All six Tier 1 interviewees are following CharIN's activities, and three are active members.

Key topics currently being addressed include[26]:

- Consideration for public charging
- Provisions for automation
- Charging communication
- Electromagnetic compatibility
- Isolation and safety
- Maximum socket and pin temperatures
- Short circuit protection
- Bus voltage range
- Minimum and maximum current levels
- Thermal management
- Insulation requirements

[25] CharIN e.V., Megawatt Charging System (MCS), 2023, https://www.charin.global/technology/mcs/

[26] CharIN e.V., CharlIN White Paper, Megawatt Charging System (MCS), Recommendations and Requirements for MCS Related Standard Bodies and Solution Suppliers, Version 1.0, 24 Nov 2022, https://www.charin.global/media/pages/technology/knowledge-base/c708ba3361-1670238823/whitepaper_megawatt_charging_system_1.0.pdf

- Hardware (coupler, EVSE port locations, torque, insertion/extraction force, drop test, adapters, mating durability, thermal boundary conditions, cable)

It is noted that CharIN is also working with identified standards organizations to develop the MCS protocols, including:

- International Organization for Standardization (ISO)
- The International Electrochemical Commission (IEC)
- The Institute of Electrical and Electronics Engineers (IEEE)
- The Society of Automotive Engineers (SAE)
- Underwriters Laboratory (UL)

Currently, the CharIN MCS recommendations are:

- Single conductive plug
- Max 1.250 volt & 3.000 ampere (DC)
- PLC + ISO/IEC 15118-20
- Touch Safe (UL2251)
- On-handle software-interpreted override switch
- Adheres to OSHA & ADA (& local equivalent) standards
- FCC Class A EMI (& local equivalent)
- Located on left side of the vehicle, roughly hip height
- Capable of being automated
- UL (NRTL) certified
- Cyber-Secure
- V2X (bi-directional)

Key Takeaways:

- The business case for MCS will depend upon the requirements of MD and HD fleets. This will include duty cycle, TCO, operations, availability, and grid readiness. Government mandates and market acceptance remain to be determined for high-power charging of MD and HD commercial electric vehicles.
- It is likely that MCS charging stations will be integrated with utility command and control systems (i.e., demand response control).
- It remains to be determined how important automated / robotic charging will be in the future. There remains interest in autonomous trucking especially in highway driving

applications. There is also interest in implementing automated charging at depots to reduce the staffing cost.

- Vehicle-to-Grid functionality is a secondary area of interest as MCS is being developed. Tier 1s are evaluating V2G as an option to reduce operating costs for vehicle owners.
- Several industry organizations are hosting cooperative and informative discussions with industry and government organization interested in high-power charging of commercial electric vehicles, including CharIN, SAE, and ISO, with CharIN currently taking the lead role. All of the Tier 1 interview participants are monitoring MCS activities and three have taken an active role in the MCS standards development.

4 TIER 1 SURVEY CONCLUSIONS

Interviews were conducted with Tier 1 suppliers in conjunction with the eTRUC program goal of understanding the status and potential for high power truck charging to support fleet operations in California. Interview discussion topics and questions were prepared with the goal of obtaining vehicle industry views on the development roadmap for trucks to be ready for high power, megawatt charging, including the current status, developments, and the expected schedule for reducing charging time.

Current Status

All of the Tier 1 suppliers included in the industry outreach surveys are monitoring or developing systems capable of MW-level charging. Although the MCS standard offers the benefit of interoperability, there are alternative high-power charging solutions, including multi-port connectors and automated charging.

Initial deployments of EVSE and MD/HD commercial electric trucks are likely to have current limits of 1,000 amps and up to 1,000 volts, which implies up to 1 MW. The actual power will depend upon vehicle architecture operating voltage. For example, trucks operating at 800 volts, which is typical for current electric trucks, would be limited to 1,000 amps and 800 volts, which is equal to 800 kW or less if there are also limits on maximum current.

The next step in charging power is expected to be 1,500 amps at 1,000 volts (i.e., up to 1.5 MW). Europe has plans in place to migrate to this level. Due to the additional costs and technical complications, it is expected that moving to 1.5 MW charging will not occur in the US until after 2030. It will depend upon whether fleets will have a sufficient business case to justify the additional benefits of 1.5 MW charging, including the impact of reduced payload.

Moving to the full MCS target of 3,000 amps and 1,250 volts (= 3.75 MW) is appropriate for specialty applications (mining, industrial, off-highway, agricultural, marine) where the costs and technical challenges can be resolved. For on-highway, a move to the higher power level presents additional issues to address. It remains to define power requirements related to MD and HD commercial electric vehicle duty cycles. Additional issues to be resolve include backward compatibility of charging systems (for example, if initial MCS stations are installed with 900 to 1,000 Vdc rather than 1,250 Vdc), will OEMs accommodate vehicle operating voltages above 1,250 volts, and will automate charging be required for future compatibility with autonomous trucks for safety and ergonomics issues.

Key Takeaways

The following key takeaways resulted from the Tier 1 industry outreach interviews.

Market

- The electric truck industry today is in early stages of deployment with only a few thousand heavy duty electric trucks and buses deployed. This is expected to rapidly change, with Tier 1 Industry expecting component sales for electric trucks will be 20% - 45% of company revenue by 2030.
- With the limited experience with electric trucks so far, there is significant uncertainty on the complete operational needs of fleets once electric trucks are fully deployed. Hence, views on component and vehicle needs vary across the industry.
- OEMs and Tier 1s are still evaluating the needs of fleets in order to assess the market for MCS. The uncertainty in the demand for MCS will impact the timelines for OEMs, Tier 1s, and EVSE manufacturers to make commitments regarding production of vehicle and charging station components compatible with MCS protocols.
- One cause of delay in development of high-power charging systems is the lack of available MD and HD battery electric vehicles. This is expected to change over the next two years as many of the major OEMs are introducing new electric vehicle platforms.

Technology

- Most Tier 1s rely on the OEMs to define electric powertrain component specifications.
- Tier 1 suppliers were unanimous in predicting that vehicle voltages will not exceed 1000 volts prior to 2030.
- The leading EVSE companies and Truck OEMs have prototype extreme high power charging systems available today or planned for the near future. Initial pilot versions could be available in the next 2-3 years.
- Advances in power electronic components are required to increase operation voltages beyond 850 V. This includes transistors, capacitors, substrates, connectors, contactors, and junction boxes. All of the Tier 1 representatives indicate that future operating voltages will likely be greater than 1000 volts.
- The high-power charging levels will require several technical advancements:
  - Current battery chemistry limits charging power to around 1.5x the battery energy (1.5 C rate). Some manufacturers place a limit of 0.8 C for continuous charging and 1.5 C peak to optimize life of batteries utilizing currently available chemistries.
  - Future battery chemistries may enable higher C rate charging, but these are likely several years away and will require advances in battery thermal management.

  - Long haul Class 8 trucks will likely adopt 800kWh batteries as a compromise between range, battery weight and cost. This would indicate charging power levels of 800kW currently and 1.2MW in future (1.5C with improved thermal management).
  - Thermal management becomes a greater challenge as the battery and vehicle electrical systems will need to be kept cool, and the heat generated becomes hard to dissipate because the vehicle is stationary.
  - The incoming electrical current will need to be distributed to keep current/conductor within limits for conductor and connector ratings as well as heat dissipation requirements. This will add more cost to the junction/distribution box.
- The Tier 1 industry outreach participants provided the following challenges to implementing MCS:
  - Development of and compliance with safety standards.
  - Higher vehicle voltages will require redesign of other components such as HVAC, power steering, actuators, water pumps, and fans.
  - Reducing demand charges for high power charging will have to be addressed. This could involve local energy storage systems.
  - Concerns over ownership and control of the MCS charging system, including the roles of the customer and the electric utility company, and 2) concerns on operation and maintenance of the equipment.
  - Time requirements for utilities to install substations capable of accommodating MW charging stations. Some utilities are quoting two years from initial agreement to completion for these substations.
  - Some HD trucks and perhaps all MD trucks may be fitted with CCS (if requested by fleets).

Costs

- Many of the Tier 1s expressed concern regarding the elevated cost of the infrastructure for high-power charging and how these costs will be amortized.
- The increase in charging station costs for MCS compared to CCS are expected to range from $1,000 to $3,000.
- The increase in on-board vehicle costs for MCS compared to CCS are predicted to range from $3,000 to $10,000, with power electronics, junction boxes, high-voltage high-current cables, power electronics, and liquid cooling systems representing significant portions of these costs.

5 JOINT CONCLUSIONS

Interviews were conducted with OEMS and Tier 1 suppliers in conjunction with the eTRUC program goal of understanding the status and potential for high power truck charging to support fleet operations in California.

OEMs and Tier 1 component suppliers were generally in agreement that MCS will be the standard of the future, with 2/3rds of OEMs interviewed planning to integrate MCS into their trucks by 2030. Additionally, all Tier 1 suppliers included in the industry outreach surveys are monitoring or developing systems capable of MW-level charging.

MCS technology is still in the early stages of deployment however, and critical questions remain about what components will need to be upgraded to enable standardized 1 MW charging and how much cost this will add to the overall vehicle price. Another cause of delay in development of high-power charging systems is the lack of available MD and HD battery electric vehicles. This is expected to change over the next two years as many of the major OEMs are introducing new electric vehicle platforms.

Planning for future MCS deployment needs is essential when assessing the scale of transformation needed to meet potential heavy duty vehicle electric charging needs. MCS will need to be rolled out at scale and require significant amounts of power and investment to meet this anticipated demand.

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