2024 TECHNICAL UPDATE

# Alternative Charging Technology Evaluation and R&D Plan

Electric Truck Research and Utilization Center (eTRUC) Project (Task 4.1)

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Electric Truck Research and Utilization Center (eTRUC) Project (Task 4.1)

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# ABSTRACT

The Electric Truck Research and Utilization Center (eTRUC) seeks to accelerate the commercial adoption of high power, megawatt-level charging technologies for heavy-duty battery electric trucks.

One of the goals of eTRUC is to evaluate the current and future state of megawatt-level technology and understand the potential impact of these developments on the adoption of electric heavy-duty trucks. This report identifies alternative electric vehicle supply equipment (EVSE) configurations and the perceived gaps in the development of megawatt-level charging technologies. This report also evaluates the impacts of megawatt-level charging from the utility grid perspective and identifies challenges for integrating and managing charging demands.

## Keywords

Heavy-duty
Electrification
Truck
Freight
Charging infrastructure
Battery electric vehicles
Drayage
Megawatt charging

# ACRONYM/TERM LIST

| Acronym/Term | Meaning |
|---|---|
| A | Amp(s) |
| AC | Alternating Current |
| AI | Artificial Intelligence |
| BESS | Battery Energy Storage Systems |
| BEV | Battery Electric Vehicle |
| CAPEX | Capital Expenses |
| CCS | Combined Charging System |
| CharIN | Charging Interface Initiative |
| DC | Direct Current |
| DCaaS | DC-as-a-Service |
| DCFC | Direct Current Fast Charging |
| DCLC | DC Load Center |
| DER | Distributed Energy Resources |
| DOE | Department of Energy |
| eTRUC | Electric Truck Research and Utilization Center |
| EPRI | Electric Power Research Institute |
| ESR | Electric Service Requirements |
| EVSE | Electric Vehicle Supply Equipment |
| EV | Electric Vehicle |
| kV | kilovolt(s) |
| kW | kilowatt(s) |
| LV | Low Voltage (typically 480 VAC) |
| L4/L5 | Autonomous driving modes – High Driving Automation, Full Driving Automation |
| NACS | North American Charging System |
| MCS | Megawatt Charging System |
| MW | megawatt(s) |
| OPEX | Operating Expenses |
| PCC | Point of Common Coupling |
| PV | Photovoltaic |
| R&D | Research and Development |

| Acronym/Term | Meaning |
| --- | --- |
| SAE | Society of Automotive Engineers |
| SCE | Southern California Edison |
| SiC | Silicon Carbide based power electronics |
| SST | Solid State Transformer |
| TIR | Technical Information Report |
| TRL | Technology Readiness Level |
| V | Volt(s) |
| VAC | Alternating current voltage |
| Var | Volt-Ampere Reactive |
| VDC | Direct current voltage |
| V1G | Unidirectional grid-to-vehicle only |
| V2G | Vehicle-to-Grid (electrical power specifically from vehicle to the grid) |
| VGI | Vehicle-Grid-Integration (bidirectional electrical power flow) |

# EXECUTIVE SUMMARY

An objective of the eTRUC program is to develop new high-efficiency, high power charging components and systems that address the gaps and limitations known to the industry today. To support this goal, we lay out an R&D plan for identifying and prioritizing emerging technologies, alternative delivery systems, and operational enhancements. This plan is anticipated to inform suggested activity areas for the high power testing infrastructure, capabilities, and resources being established at the Southern California Edison (SCE) R&D Testing Center under Task 4.2 of the project.

A list of suggested R&D topics addressed in this report are listed below. The topics are based on engagement with stakeholders – namely, electric vehicle supply equipment (EVSE) manufacturers, truck original equipment manufacturers (OEMs), U.S Department of Energy national laboratories, utility advisors on electric vehicle (EV) projects, and input from the Industry Technology Advisory Committee (ITAC).

- Low voltage AC supply (480 V) EVSE designs based on a centralized DC Hub
- Easily upgradable systems – containerization and/or modularization
- Medium voltage connected EVSE solutions (typically 1,000–35,000 V)
- Integration of energy storage and distributed energy resources (DER)
- 1,500A dispenser designs
- Buck-boost DC-DC converters to allow future DC voltage increases to 1,250+ V
- Silicon carbide (SiC) AC-DC and DC-DC stages and other high-efficiency designs
- Universal connector solutions that are footprint- and cost-efficient
- Connections able to support autonomous trucks
- Utility integrated charge management systems (site charging profile meets real-time power availability)
- Charging system volt-var capabilities to support grid needs
- Charging system phase balancing to support grid needs
- Vehicle-to-grid (V2G) capability (including stationary energy storage and DER to grid)
- Enabling predictable load profiles via reservation systems and artificial intelligence (AI) forecasting of expected charging
- Charging slot reservation systems with links to main fleet management systems
- Megawatt-scale energy management systems integrated with utility command and control/dispatch systems
- Remote monitoring with predictive maintenance capability
- Self-healing EVSE designs

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# 1 INTRODUCTION, PURPOSE, AND BACKGROUND

## Introduction

This document summarizes work performed under Task 4.1 of the Electric Truck Research and Utilization Center (eTRUC) project, with a focus on megawatt-scale charging primarily for heavy-duty trucks. This effort aims to create a research and development (R&D) plan that lays the groundwork for identifying and prioritizing emerging technologies, alternative delivery systems, and operational enhancements that address some performance and operational gaps in high power charging technologies today. This plan will be used to provide suggested activity areas for the high power testing infrastructure, capabilities, and resources being established at the Southern California Edison (SCE) R&D Testing Center for Task 4.2 of the project. The R&D plan and the R&D testing center are complementary to accomplishing the objectives of driving innovation and collaboration among electric vehicle supply equipment (EVSE) manufacturers, truck original equipment manufacturers (OEMs), utilities, and other stakeholders. Enabling access to high-quality testing, instrumentation, and validation capabilities for battery electric vehicles (BEVs) and their charging systems is key for accelerating the pace of innovation in high power charging technology development and deployment in the state of California.

The report outlines evolving high power charging architectures, advanced components, alternative delivery technologies, grid integration capabilities, utility service enhancements, and other improvements necessary to address gaps and limitations of current high power charging technologies and systems.

## Overall Project and Background

The eTRUC project seeks to accelerate commercial adoption of the high power Combined Charging System (CCS) and megawatt-level technologies in primarily heavy-duty vocations such as drayage and line haul. The overall eTRUC project will engage broad stakeholders including but not limited to pollution-burdened and impacted communities, truck fleets, charging equipment and service providers, electric utilities, and planning agencies. The eTRUC project seeks to investigate higher efficiency and higher power density charging components and systems as well as assess the opportunities for standardization for high power public charging systems. The eTRUC project will help to plan, design, and deploy innovative public corridor charging strategies that extend the delivery range and increase the operational flexibility of large weight class battery electric trucks beginning with drayage operations.

The battery electric commercial vehicle industry recognizes the need for charging at power levels beyond the CCS capabilities. For heavy-duty BEVs this is expected to be in megawatts, and the development of these systems is relatively immature, with a variety of vehicle connecting systems being considered. These approaches include conductive automated charging connector systems defined by the Society of Automotive Engineers (SAE) J3105 series and inductive automated high power charging as defined by SAE J2954-2. Conductive automated high power charging is currently used by transit bus fleets, mining operations, and ports. Inductive automated high power charging is also currently used by transit buses. The Megawatt Charging System (MCS), a new charging connector specification developed by the Charging Interface Initiative (CharIN), is another candidate and offers charging at up to 3.75 MW (3,000A maximum at 1,250 VDC). The latest specification of MCS is Version 3.2, which is expected to be finalized and published in 2024, with plans for adoption by the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) as an international standard. SAE is developing the draft MCS standard (J3271) based on the MCS specification. Multiple MCS prototypes in certain pre-standardized configurations have been developed and lab tested by vendors. A few field charging tests with pilot MCS connectors have been completed this year. Commercial versions of MCS connectors on EVSE are expected to enter the market in 2024 with continued opportunities for technology advancements.

# 2 IDENTIFICATION AND PRIORITIZATION FOR FUTURE RESEARCH EFFORT

## Megawatt-Scale Charging Roadmap

The scope of this R&D plan originated from topics discussed during interactions with the EVSE industry as well as through technical discussions within ongoing research activities led by EPRI in collaboration with the electric utility industry, the U.S. Department of Energy (DOE), and EVSE manufacturers. We compiled insights about the currently anticipated evolution of initial megawatt charging offerings along with broader needs for advancements in the areas of technology/design, performance (reliability, efficiency), grid integration, standardization, interoperability, and infrastructure scalability. Some of these broader needs are crucial to support larger deployments of heavy-duty vehicles. We have categorized the current state of development and an expected future state (10+ years), as shown in Table 1.

Table 1. Current and Expected Future State for Megawatt-Scale Charging Infrastructure

| Key Features | Current State | Future State (10+ Years) |
|---|---|---|
| Utility service | • Low voltage service typically up to 3 MW, with a maximum current rating of 3,000–4,000A and occasionally fed by more than one transformer for power levels above 3 MW<br>• Large uncertainty in utility load driven by unpredictable truck charging and low utilization of charging equipment | • Multiple connections to medium voltage utility grid (initially through multiple low-frequency transformers, eventually through transformer-less medium voltage connected charging equipment).<br>• Initial 9–12 MW, expanding to 20+ MW in the future<br>• Reasonably predictable load profiles and support by energy storage as appropriate |
| EVSE features | • 1,000A @ maximum 1,000 VDC dispensing (1 MW)<br>• AC Hub (mostly)<br>• Unidirectional grid-to-vehicle only (V1G)<br>• Any energy storage or distributed energy resources (DER) integrated on AC supply | • 1,500A at 1,000 VDC (medium term), 3,000A at 1,250 VDC (long term)<br>• DC Hub for sites with a mix of 1 MW and below chargers<br>• Optional: Vehicle-to-grid (V2G) capable<br>• Optional: Integrated battery and DER on DC Hub |
| Efficiency | • Typically, CCS EVSE efficiency 75–95% | • Efficiency 95+% higher with silicon carbide (SiC) AC-DC and DC-DC |

Table 1 (continued). Current and Expected Future State for Megawatt-Scale Charging Infrastructure

| Key Features | Current State | Future State (10+ Years) |
|---|---|---|
| Reliability | • Some remote monitoring of faults<br>• High downtime at certain sites | • Remote monitoring of core systems<br>• Multistage designs enabling self-healing<br>• Uptime exceeds 97%, ensuring equipment is not down for more than 1 week/year for maintenance |
| Connectors | • Various connector options<br>• Some automated charge capability | • "Universal connection system" supporting legacy trucks<br>• Application-specific: Automated charging supporting trucks capable of fully autonomous driving (L4/L5) |

From this view of the expected future state, we developed a series of research topics that would support the development of high power EVSE technology and optimize grid integration of megawatt-scale charging sites as well as auxiliary systems/activities to improve operation of charging sites. These topics are presented in Table 2.

Table 2. Research Topics to Support Development of Megawatt Charging Stations

| Development Areas | Research Topics |
|---|---|
| High power charging technology | • Centralized low voltage supply EVSE designs based on DC Hub<br>• Easily upgradable systems – containerization and/or modularization<br>• Medium voltage connected EVSE solutions<br>• Integration of energy storage and DER<br>• 1,500A dispenser designs<br>• Buck-boost DC-DC converters to allow future DC voltage increases to 1,250+ V<br>• SiC AC-DC and DC-DC stages and other high-efficiency designs<br>• Universal connector solutions that are footprint and cost efficient<br>• Connections able to support autonomous trucks |
| Grid integration | • Utility integrated charge management systems (site charging profile meets real-time power availability)<br>• Charging system volt-var capabilities to support grid needs<br>• Charging system phase balancing to support grid needs<br>• V2G capability (includes stationary energy storage and DER to grid) |
| Operational improvements | • Enabling predictable load profiles via reservation systems, artificial intelligence (AI) forecasting of expected charging<br>• Charging slot reservation systems with links to main fleet management systems<br>• Megawatt-scale energy management systems integrated with utility command and control/dispatch systems.<br>• Remote monitoring with predictive maintenance capability<br>• Self-healing EVSE designs |

These research topics should close performance gaps, improve the reliability and efficiency of EVSE, and support integration with the utility grid. In addition to focusing on the technology elements, research should ensure alignment with fleet requirements and consider implications to the economics of establishing and operating megawatt-scale charging stations. The following chapters provide additional details on the suggested R&D activities.

# 3 HIGH POWER CHARGING TECHNOLOGY DEVELOPMENTS

The current state of high power charging technology feeds low voltage AC (480 V) power from the utility into a rectification stage converting the AC power to DC. The DC power then feeds a charging dispenser that provides demanded current and voltage to the vehicle. The dispenser will also process payments from the vehicle operator. The process typically involves the following steps:

- Utility transformer: Steps down medium voltage from the utility distribution grid to 480 VAC secondary service for the charging site and provides electrical isolation
- 480 V switchgear: Equipment used for protection and metering
- EVSE power cabinet: Includes rectifiers or power inverters to convert AC power to DC at 700–1,000 VDC
- Charging dispenser: Includes DC/DC converters to convert DC to the appropriate level as required by the electric vehicle (EV) for charging. These units have a maximum current around 500A and are theoretically capable of charging at up to 500 kW. However, the actual power will depend on voltage and current demanded by the EV. The charging dispenser and power cabinet can be combined into a single “all-in-one" unit.

Utility low voltage connected types of EVSE are limited to around 3 MW maximum power consumption for a single, three-phase secondary service to the site. Switchgear and utility metering equipment rated for 3,000–4,000A are typically used. Switchgear and utility metering equipment rated above 3,000–4,000A have traditionally been considered low volume or special order equipment and are priced accordingly. This has resulted in limited application of switchgear rated above 3,000–4,000A in industry practices and in utility transformer sizing. Outside the EV industry, applications above this power level would normally consider utilizing higher voltage equipment to reduce the amperage flows if feeding a single device or multiple transformers if feeding multiple devices.

## Alternative High Power EVSE Configurations

As the industry moves to megawatt charging, the charging dispenser power will need to increase towards 1+ MW, and the total site power demand is likely to exceed 3 MW. Based on industry discussions, charging technologies are rapidly evolving to accommodate these higher powers. This section summarizes targeted alternative megawatt charging technology options, some of which, as described by EVSE manufacturers, are likely in the pre-commercial stages of product development.

- Technologies integrated with DER such as photovoltaic (PV) systems and battery energy storage systems (BESS) are shown in specific options, although DER can be integrated on the AC side in most designs.
- Load management (demand response) capabilities are not shown exclusively but are expected to be offered with most options.
- Vehicle-grid integration (VGI) is emerging, and a few bidirectional converter-based designs are shown. Implementations of VGI-enabled technologies can vary significantly based on performance requirements, site location/grid characteristics on-site, and cost.
- A 12.4 kV utility distribution (medium voltage) is shown for illustrative purposes. U.S. distribution voltages may vary from 4.1–34.5 kV.
- Megawatt-capable charging dispensers are currently prototypes and are expected to become commercially available in the next 3–5 years.

The targeted alternative megawatt charging technology options are expected to complement the infrastructure needed for rapid deployment of multi-port megawatt-scale charging stations for meeting/exceeding heavy-duty BEV charging requirements, operating economically within the constraints imposed by the electric grid, and scaling up infrastructure with minimal costs.

In the following section, each targeted technology option is described with a single-line schematic, a high-level description of functionality, and our assessment of the Technology Readiness Level (TRL).

We have grouped the targeted technology options into four generic schemes for the purposes of illustration and distinction.

1. Individual dispensers on an AC Hub
2. Central DC-supplied dispensers on a DC Hub
3. All-in-one systems combining rectification, conversion, and dispensing
4. Multi-megawatt dispensers

It is important to note that in practice, there are different embodiments of these four generic schemes.

1. **Individual Dispensers on an AC Hub**
   a. Power Cabinet Feeding a Dispenser for Charging

      A typical prototype megawatt charging system consisting of six existing 150–175 kW AC/DC power modules integrated together to operate as a 1 MW AC/DC power source is shown in Figure 1. These types of systems can be supplied by a single low voltage (480 V) utility connection and can deliver 1 MW of power to a megawatt charger for charging one single heavy-duty BEV at a time.

      The TRL is 6–8 since these exist as prototypes and should be entering first commercial deployments soon.

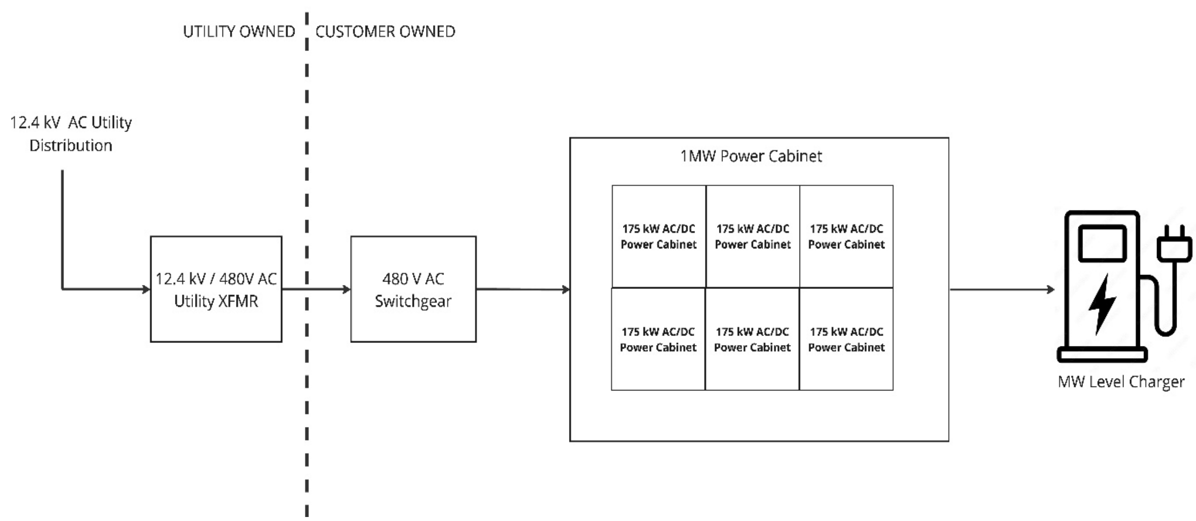


Figure 1. Modular Power Cabinet Solution Using Existing Power Modules

b. Megawatt-Level Power Cabinets per Charger

If more megawatt charging dispensers are needed, power cabinets can be connected in parallel. Figure 2 shows an example, with three 1 MW power cabinets that each house AC/DC power modules supplying one charger each. Each power cabinet can deliver up to 1 MW to each charger and up to 3 MW total for simultaneous charging of three heavy-duty BEVs. The low voltage (480 V) utility connection offers limited expandability. Adding chargers beyond the 3 MW power limit requires an additional low voltage utility supply feed to the site, which is expensive and requires a lengthy coordination process with the utility to upgrade service.

The TRL is 6–8 as these systems are becoming available and will be commercially deployed soon.

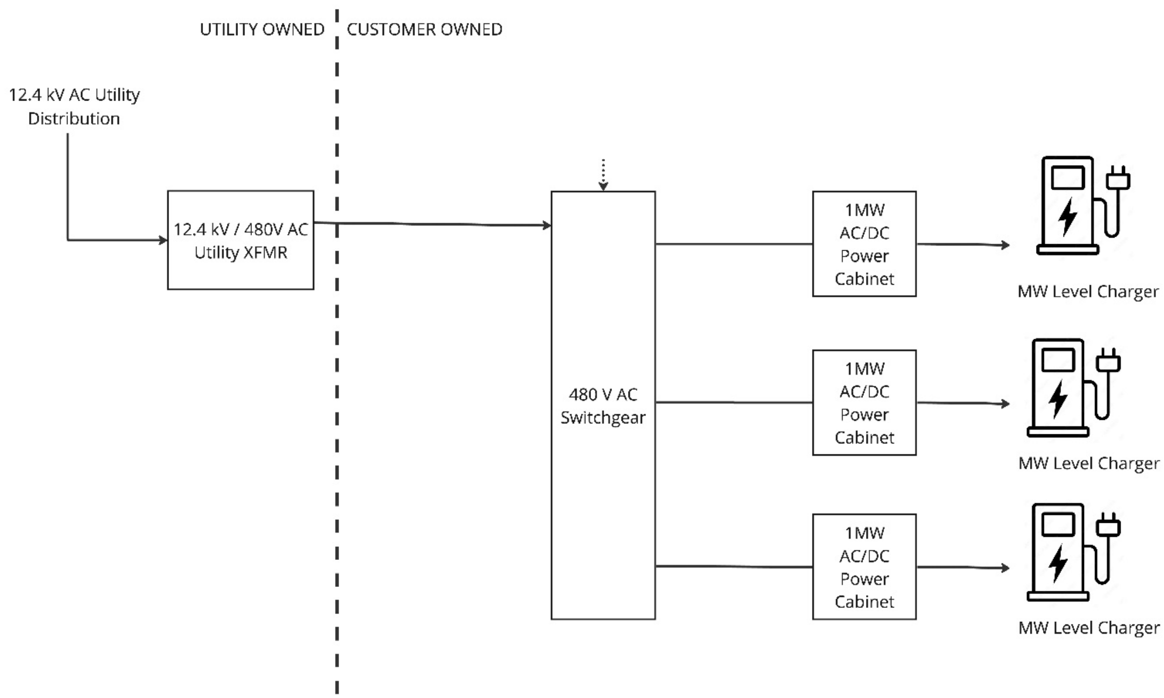


Figure 2. Megawatt-Level Power Cabinets per Charger

c. Containerized Plug and Play Solution

An alternative approach to option 1(b) described above is to have the components assembled and prepackaged within a standard shipping container, as shown in Figure 3. This can be a "plug and play" system, with benefits such as portability and ease of installation and commissioning. The containerized system can be direct medium voltage supplied with the utility transformer housed inside the container.

The TRL is 7–8 since these products are being offered for commercial deployment.

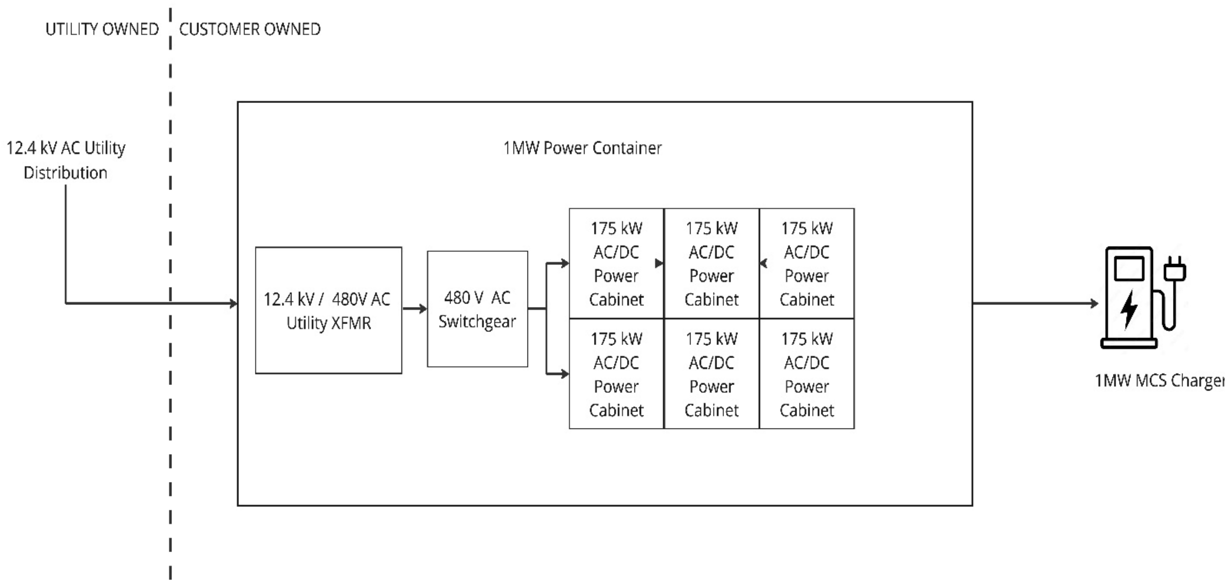


Figure 3. Containerized, Plug and Play Solution

d. Integration of Battery Energy Storage (BES) with AC Hub

Each of the options above can be integrated with DER such as BESS and/or solar on the AC side, as shown in Figure 4.

The TRL for AC-integrated BESS and solar is 8–9, with several commercial systems deployed into the marketplace.

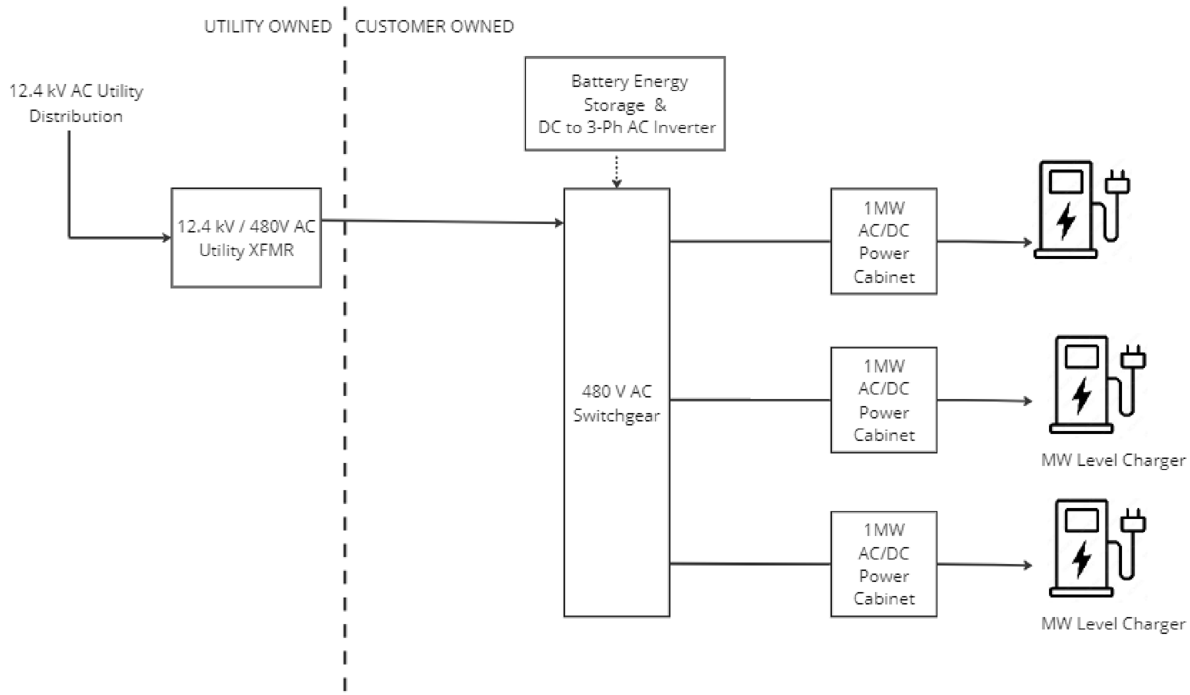


Figure 4. BESS Integrated Megawatt-Level Power Cabinets per Charger

**2. Central DC Supplied Dispensers on a DC Hub**

a. Centralized Rectifier with Internal DC Bus

The charging system uses a centralized bulk rectifier powered by a single low voltage utility connection. As shown in Figure 5, the bulk rectifier converts 480 VAC to 1,000 VDC and supplies an internal (or closed) DC bus regulated at 1,000 VDC. The DC bus is dedicated to managed sharing of DC power across the three 1 MW MCS chargers. The MCS chargers have DC/DC converters to lower the voltage below 1,000 VDC as requested by the vehicle during charging. The main advantage of this system is its flexibility to mix and match chargers for slow overnight charging or fast opportunity charging, and/or even Level 2 charging as long as the total charge power requirement is less than 3 MW.

The TRL is 6–8 as this configuration is becoming more widely available for DC fast charging at lower charging powers (<400 kW) and is expected to be used at higher powers in megawatt-level charging. For upgrading from the current lower charging powers (<400 kW) to megawatt-level charging, only DC side upgrades are needed. These include upgrading the DC conductors on the downstream side of the DC bus and replacing chargers with those capable of delivering up to 3 MW of power.

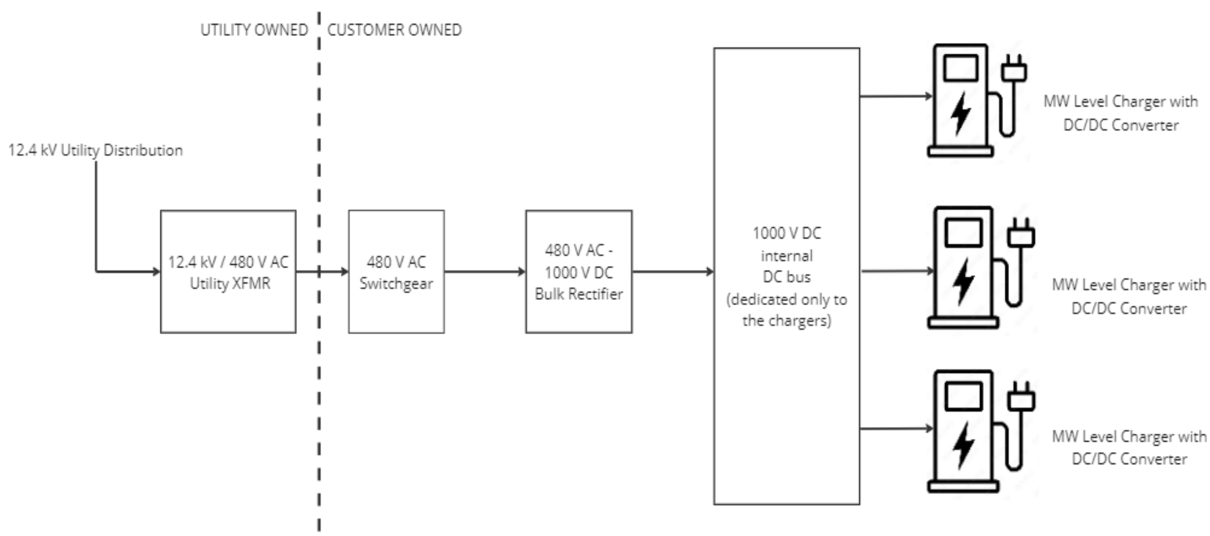


Figure 5. Centralized Rectifier with Internal DC Bus

b. Medium Voltage Converter (or Solid State Transformer [SST]) with Centralized Open DC Bus

   For larger charging sites, the required utility power is expected to reach 9–12 MW in the next 2–3 years. Using multiple low voltage utility feeds, as described in option 1(b), to achieve a higher range of 9–12 MW is very expensive. Charger technologies are expected to move to medium voltage supply in the next 5–8 years, depending on market demand and opportunities for medium voltage charger technology advancements. In such a case, the charging system could employ a medium voltage converter that connects to the utility distribution, for example, at 12.4 kV AC, as shown in Figure 6. An option for the medium voltage converter design is an SST, which is built with solid-state SiC-based components. SiC-based designs are expected to be much smaller in footprint, can offer higher power throughputs, and will operate more efficiently.

c. The medium voltage converter, or the SST, converts higher voltage AC to 1,000 VDC and feeds an "open" DC bus. The "open" DC bus is managed by the DC Load Center (DCLC) specified to handle the protection, control, and coordination of DC power. The DCLC and "open" DC bus serve as an integration platform for connecting external DC sources such as DER (including PV systems and BESS) with low interconnection costs. The reason for this is because unlike AC-interconnection, the external DC sources can connect to the DC platform without the need for an inverter at each interconnect point. The DC sources can supply the charging load while reducing the dependence on utility power and connection capacity requirements. Additionally, DC sources such as BESS can lower demand costs for the site operator by discharging during higher cost utility peak hours and charging during off-peak hours. The DC platform can supply DC loads other than chargers such as DC buildings, building loads, and data centers.

   The charging system creates pathways for scalable megawatt charging architectures. This occurs because upgrades are needed downstream of the DC bus only, and charging capacities of more than 3 MW are possible (unlike the centralized rectifier with internal DC bus configuration discussed above). Given this configuration, utility upgrades and AC equipment upgrades are not needed, with expansions such as adding more chargers or replacing chargers with higher power ones. This configuration also enables options to connect any type of charger such as the Level 2 AC or DC Fast Charger (DCFC) or the megawatt charger. The DCLC design is significant because it enables the interoperable and compatible operation of power cabinets (or converters) and chargers irrespective of size or the type of charger. With a standardized DCLC and open DC bus design, we expect the evolution of a new paradigm where any charger can operate with any converter or power source regardless of manufacturer or brand.

   SSTs use power electronics stages with high-frequency switching to convert the incoming AC power to DC. SSTs are being considered for various applications including replacement of conventional AC transformers as well as AC-DC rectification. The TRL is 6–8 since SST technology in EV charging applications is being evaluated, and initial production units are appearing in certain global markets. According to one market report,[1] the global market for SSTs is valued at $185M in 2022 and is estimated to reach $563M in 2031. SST market valuations and projections are drastically different, and it is challenging to provide a reliable estimate. From a deployment standpoint, it is difficult to know where commercial SSTs are being deployed and for what applications due to lack of publicly reported data and information.

EPRI has worked on SST development, design analysis, and demonstration since 2004 primarily for utility distribution applications.[2,3,4,5,6] For over a decade, SSTs were mostly researched, and small prototypes were built in labs. There have been a few deployments of SSTs for the U.S. Navy for shipboard supply systems, which are custom-designed and custom-built. No design or performance data about these deployments are available in the public domain. In EPRI's experience, industry interest in SSTs as a potential power solution for EV fleet charging has steadily increased in the past 3–4 years, with the DOE-funded efforts on SST-related cohorts and various SST vendors showing interest in prototype development. In EPRI's EVSE surveys, a few manufacturers confirmed SST research and development efforts to develop medium voltage connected converters for their future product offerings.

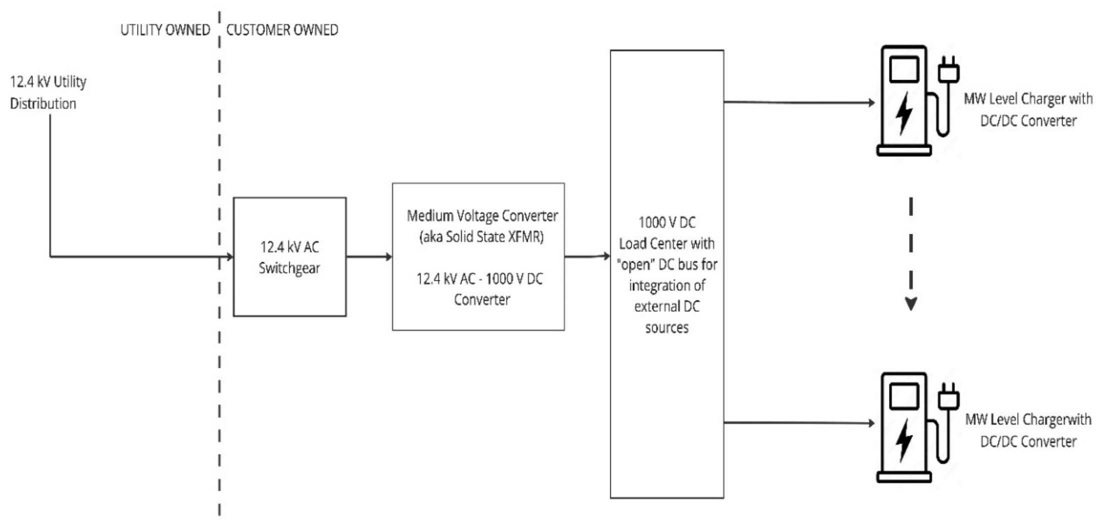


Figure 6. Medium Voltage Converter with Centralized Open DC Bus

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[1] Global Solid State Transformer Market Outlook 2031. https://www.transparencymarketresearch.com/solid-State-transformer.html.

[2] *Development of a New Multilevel Converter-Based Intelligent Universal Transformer: Design Analysis*. EPRI, Palo Alto, CA: 2004. 1002159.

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[6] *Field Prototype Development of Intelligent Universal Transformer*. EPRI, Palo Alto, CA: 2011. 1022009.

d. Bidirectional Medium Voltage Converter (or Bidirectional SST) with Centralized Open DC Bus

An evolution of the previous option 2(b) is for the charging system to be a bidirectional converter, as shown in Figure 7. A three-phase inverter module is integrated with the medium voltage converter to facilitate power export to the utility grid. DER such as BESS and other DC microgrid devices can be integrated on the DC side of the medium voltage converter (either at the converter or at the open DC bus) without the need for distributed inverters and multiple interconnection points to the utility grid. The bidirectional function is optional for megawatt charging unless a specific use case warrants bidirectional power flow or export to the grid for economic or grid reliability reasons.

The TRL is 6–7 with SSTs being developed with bidirectional capabilities.

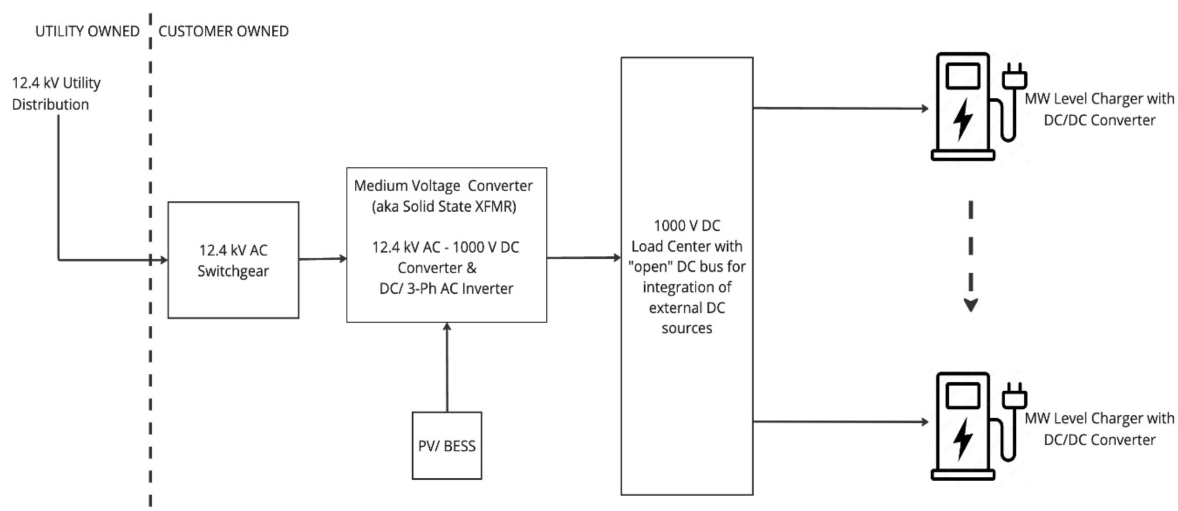


Figure 7. Bidirectional Medium Voltage Converter with Centralized Open DC Bus

e. DER/BESS Integrated with Centralized Open DC Bus:

As explained in options 2(b) and 2(c) above, the open DC bus enables DER such as BESS to be integrated on the DC side to serve charging needs without the need for upgrading the utility connection. Figure 8 shows the single-line schematic with DC-side integration, which reduces capital expenses (CAPEX) and operating expenses (OPEX) through avoided (or deferred) utility infrastructure upgrades, decreased cost of utility interconnection and site hardware (DC-side interconnection), lower energy and demand costs, and lower conversion losses overall.

The TRL is 3–6 since demonstrated testing of fully integrated DER/BESS for megawatt charging has been limited.

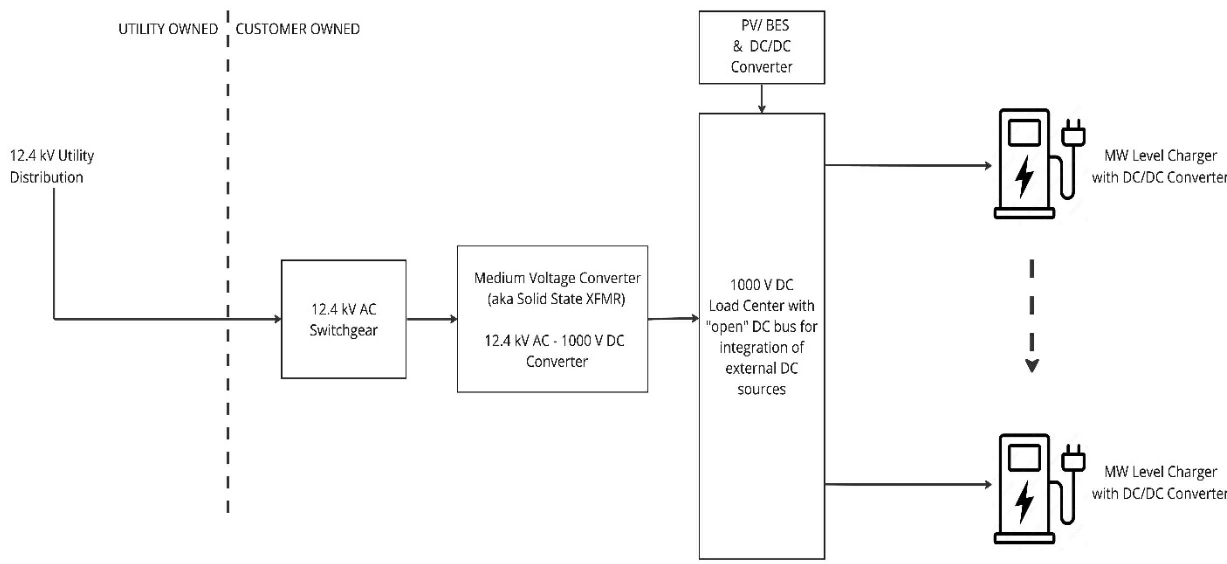


Figure 8. DER-Integrated Medium Voltage Converter with Centralized DC Bus

**3. All-in-One Designs Combining Rectification, Conversion, and Dispensing**

a. Low Voltage AC-Fed All-in-One Charger

The all-in-one design is intended to reduce the installation burden by having all the EVSE hardware in a single unit. This works well for sites that only plan to have a few chargers. Figure 9 shows a three-charger site, with each EVSE rated at least 1 MW due to the low voltage (480 V) connection. The all-in-one design includes an AC-DC converter stage, which converts 480 VAC power to 1,000 VDC. The converter is followed by a DC/DC converter stage, which enables the delivery of DC power to the heavy-duty BEV at less than 1,000 VDC.

The TRL is 3–6 since this design exists today for up to 350 kW, but prototyping for megawatt-scale charging is limited.

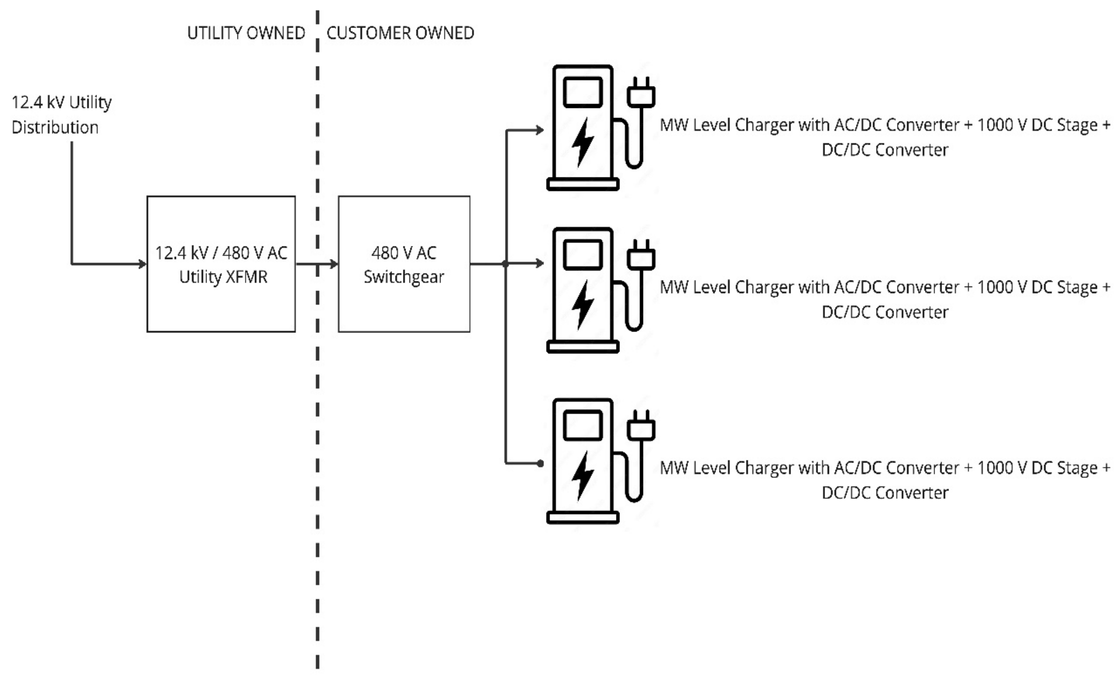


Figure 9. Low Voltage AC-Fed All-in-One Charger for a Three-Charger Site

b. BESS-Integrated Medium Voltage AC-Fed All-in-One Charger

The all-in-one charger system shown in Figure 10 is like option 3(a) described above, except for the addition of integrated BESS to support higher charging powers and reduce grid peak demand.

The TRL is 3–6 as these systems are available for 350 kW, but there is limited demonstration at megawatt scale.

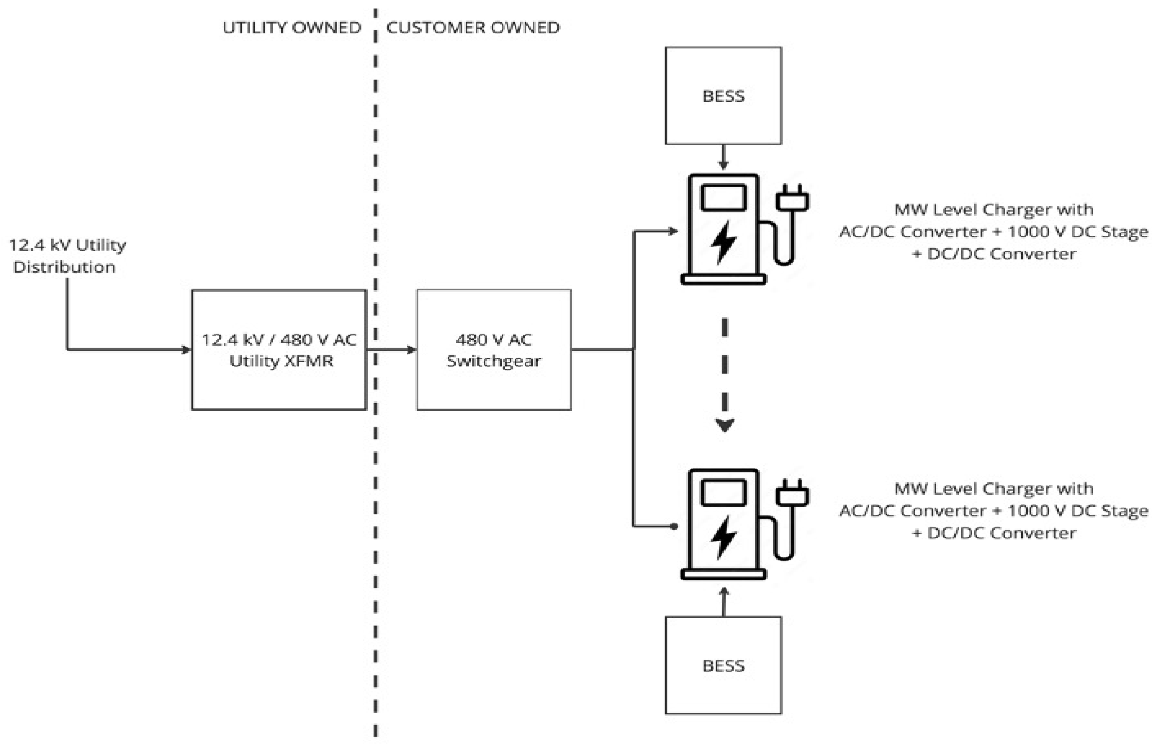


Figure 10. BESS-Integrated Low Voltage AC-Fed All-in-One Charger

### 4. Multi-Megawatt Dispensers

a. 3 MW Charger Power Configuration

A new topology that will likely be adopted in the short-term is multiple low voltage (480 V) feeds for the megawatt-scale charging site, supplied from the medium voltage utility grid. This option requires a substation and a switchyard type design as adoption of heavy-duty trucks and utilization increase. Each charger can supply up to 3 MW, as shown in Figure 11. The key distinction to note here is for the power level requirement, there would be a one-to-one relationship between the utility transformer and the charger. For each additional charger, an additional transformer would be required.

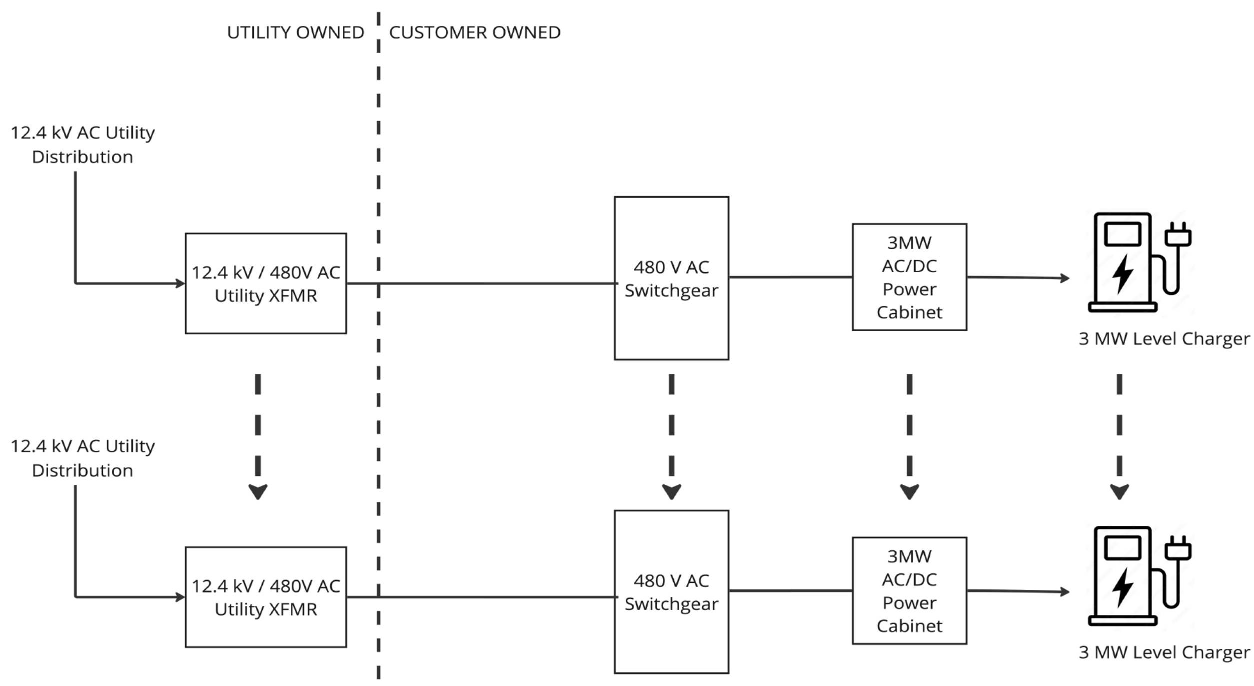


Figure 11. 3 MW Charger Power Configuration

## Expected Developments for High Power Charging

As can be seen above, there are multiple configuration alternatives for megawatt-scale charging systems. A number of key development areas could yield benefits and acceptability of these high power chargers such as:

- Open DC Bus
- Upgradeable, future proofed designs
- Medium voltage connectivity
- Integration of DER and BESS
- Buck/boost DC-DC converters
- Overall site efficiency improvements
- Vehicle connectors

### *Open DC Bus*

High power charging with a centralized DC bus architecture offers advantages in terms of efficiency, cost-effectiveness, scalability, and management of EV charging infrastructure. It can contribute to a more sustainable and practical charging network as EV adoption continues to grow. The open bus approach offers several benefits:

- Flexibility: DC design enables modular expansion of charging equipment by connecting to the central DC bus after deployment. This provides a more scalable upgrade path than would be possible with AC hub systems or closed DC bus systems, which prescribe the devices that can be added post-deployment.
- Efficiency: Compared to AC hubs, DC designs make use of a two-wire system, have no reactive components that reduce losses, and AC-to DC conversion happens only once. This all results in reduced energy losses and increased charging system efficiency.
- DER integration: Integrating DER on the DC side can reduce costs while maintaining a single point of grid interconnection on the AC side.

### *Upgradable, Future-Proofed Site Designs*

As high power charging systems continue to evolve, upgradable, future-proofed site designs will be needed to adapt to growing electric medium- and heavy-duty truck deployments and any associated changes to truck technology. Containerized charging solutions and modular systems are beneficial, especially initially, since these enable faster deployments without incurring significant civil engineering at prospect sites. Modular systems can also be expanded or upgraded as demand increases.

### *Medium Voltage Solutions*

Based on discussions with industry, megawatt charging site power demand is expected to grow to 20+ MW. Instead of such demand being provided by utilities as multiple 480 VAC feeds, there is a benefit in moving to medium voltage supply, which can reduce costs, enable upgrades, and simplify the interconnection. SST designs that convert AC power to DC could provide cost advantages for the medium voltage connection.

Utilities could benefit from owning the transformer and converter unit and providing DC-as-a-service (DCaaS) to charge station operators. This would be a new utility service and would require regulatory approval.

## *Integration of DER and BESS*

The grid supply power to the charging site may be lower than the charging demand, at least at certain times of day. Shortfalls could be overcome using energy storage. Energy storage could allow less usage of the utility grid during peak electricity times. DER, including solar PV and backup generators, might also be beneficial in supporting site power needs.

For these reasons, energy storage and DER integration are expected for megawatt charging sites. Today it is common practice to integrate these on the AC side of the EVSE. In the future, a more cost- and space-effective approach could be to integrate on the DC side, especially since BESS and solar PV are DC devices.

## *Buck/Boost DC-DC Converters*

Today, the DC-DC converters are buck devices reducing the supplied DC voltage at around 1,000 VDC to the 300–900 VDC required by the vehicles. Our discussions with the industry indicated that truck voltages may increase to over 1,000 V in the future. This would lead to the buck DC-DC converters not being able to charge these higher voltage vehicles. A solution to future proof charging would be for the DC-DC converters to be buck-boost designs that would allow the DC-DC converters to supply at voltages above or below 1,000 V.

## *Overall Site Efficiency Improvements*

With total site charging power potentially reaching 9–12 MW, overall efficiency becomes important to minimize losses, which would lead to higher operational costs and more cooling requirements. Efficiency can be improved at the transformer and rectifier stages as well as the DC-DC conversion stages. SST designs can be beneficial, and the associated operating cost savings could justify the use of higher efficiency power electronics such as SiC.

## *Vehicle Connectors*

Although new connector and cable system designs are not a research gap in and of themselves, there are a plethora of connector options, and the industry is far from having a single ubiquitous connector for all trucks. The various connectors can be broadly grouped into three categories:

- **Cabled Connectors**

  Several connector and cable combinations exist. These systems typically require liquid cooling above 300A, which can lead to large, bulky, heavy connectors and cables that can require some effort to plug into the vehicle. A list of connector types includes the following:

  - CCS – typically up to ~500 kW (500A at around 1,000 VDC) (SAE J1772 standard)
  - North American Charging Standard (NACS) – possibly up to 900 kW (900A at around 1,000 VDC[7]) (SAE J3400 Technical Information Report [TIR])
  - Tesla Semi Megacharger – believed to be capable of 1 MW.[8] Prototype versions of the Tesla Megacharger seem to be implementations of Version 2 of the CharIN MCS standard. No specification and or performance data for the Tesla Megacharger are available.
  - MCS connector – up to 3.75 MW (3,000A at 1,250 VDC) (SAE J3271 TIR)

- **Conductive Automated Connectors**

  Conductive automated connectors are designed to facilitate automated engagement with the vehicle charging ports. These connectors are covered by SAE J3105 recommended practice and include the following:

  - Infrastructure, cross rail pantograph – the current standard is for 450 kW and is expected to develop to over 1 MW.
  - Vehicle-mounted pantograph – the current standard is also for 450 kW.
  - Pin and socket – the current standard is 1.2 MW, but has capability to over 10 MW.

- **Inductive Automated Connectors**

  Inductive automated connectors use magnetic resonance to transfer energy wirelessly between a pad-mounted magnet and a magnet onboard the vehicle. Current power levels are 250–500 kW using an 8–10 in. (20–25 cm) air gap. These systems are covered by SAE J2954 recommended practice.

  These connection systems are still in development to be fully capable of 1+ MW charging. The fact that there are multiple connector options in development demonstrates that the

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[7] F. Lambert, Tesla Confirms Its Supercharger is Way More Powerful than Previously Thought. Electrek, November 2022.

[8] F. Lambert, Close Look at Tesla's Massive Megacharger for Its Tesla Semi Electric Truck. Electrek, August 2023.

best connector choice is dependent not only on power capability but also on factors such as overall cost and operational convenience.

Ideally, a single connector type would be adopted for electric trucks, especially for those that will publicly charge, even if only occasionally, since this would simplify EVSE site designs (by not requiring multi-connector types) and rollout of truck charging corridors that could charge all trucks, not just those with a specific connector. Unfortunately, the idea of a single connector may not be practical as CCS connectors will be needed for legacy trucks, which means EVSE dispensers in turn will require available multiple connectors either cabled to the dispenser or as an adapter between different connectors. The industry is already seeing deployments of competing connector standards based on MCS and the Tesla Semi connector.

Connector development today is short-term and focused on prototyping and productionizing the connector designs. However, it would be beneficial to look at other key vehicle technology trends that intersect with electrification such as autonomous trucking. While this is still a few years from routine deployment, there is the question of how autonomous electric trucks will be charged. One option is for charging station operators to have staff available to connect and disconnect trucks to chargers. The other option is to have the EVSE charging connection automated, which would drive the need for either automated conductive or inductive connectors. One benefit of automated charging is reduced labor costs associated with connecting and disconnecting electric trucks. For these reasons, it is possible that a type of automated connector could become the dominant design for electric trucks in the long term.

A key question is how to best future-proof dispensers and their vehicle connection systems, such that these systems support and enable truck electrification and automated charging needs without requiring a complete upgrade of the dispensers after only a few years of deployment. The challenge is that the industry has already started to deploy initial megawatt charging stations, and these are setting certain technology deployment paths (for example, high power CCS stations, new MCS-based stations, and stations using Tesla Semi connectors). This means it is likely the industry will undergo required changes in EVSE connector configurations over the next few years and will need to accept the associated upgrade costs.

A beneficial research area would be to identify technology migration paths – from the connectors being deployed today to the expected future connector type in 2040–2050. These pathways could be analyzed to understand the best options and required investment needed to support any required transition in technology.

# 4 POTENTIAL GRID IMPACTS AND INFRASTRUCTURE DEPLOYMENT REQUIREMENTS

Effects on the utility power system will intensify as the penetration of megawatt-level charging increases. For potential grid impacts, we have been able to develop a series of research topics based on discussions with Southern California Edison (SCE) and other utilities with first-hand experience on this subject. Input has been included from the DOE national laboratories involved in various efforts focused on high power charging station design and grid interconnection testing and evaluation. A new working group at SAE is also seeking to develop grid integration standards for megawatt charging (J3271).

## Grid-Related Challenges

A list of impact areas related to the grid and grid integration – with key research topics to address the challenges – are shown in Table 3.

Table 3. Grid Integration Related Challenges

| Impact Areas | Research Topics |
|---|---|
| Hosting capacity, loading | • Hosting capacity, power flow, and loading guidelines for megawatt-scale charging<br>• Interconnection impacts at low voltage (480 V) vs. distribution medium voltage (4.1 kV and above) |
| Coincident peak demand | • Predictive systems for forecasting peak (location, feeder)<br>• Megawatt-scale energy management systems integrated with utility command and control/dispatch systems<br>• Optimal sizing of DER and associated operational strategies |
| Software, communication, and cyber-physical security | • Testbed for evaluating charger software initiated bidirectional information exchange, communication, control, and demand response<br>• Cyber-physical security |
| AC power quality at point of common coupling (PCC) | • Active and passing filtering for harmonic compliance<br>• Power factor control/management<br>• Load or phase imbalance<br>• Frequency regulation |
| Voltage rating of medium voltage converters | • Versatile converter designs to interconnect over a wide range of medium voltages served by the utility grid |
| Site or facility-level power quality | • Ride-through performance during voltage sags/swells and frequency variation<br>• Operational impacts on other loads at startup (including inrush and voltage stability) during and after transient events such as momentary outages and voltage sags/swells |

Table 3 (continued). Grid Integration Related Challenges

| Impact Areas | Research Topics |
| --- | --- |
| Grid dynamics, controls, system stability | • Voltage recovery (fault-induced delayed voltage recovery)<br>• Post-fault response to transmission and distribution system events and faults<br>• Impacts due to constant current control vs. constant power control during normal charging operations<br>• Testing and performance data for load modeling<br>• Auto-islanding, DC operation (during utility outage)<br>• Autonomous recovery post-fault |
| Electric Service Requirements (ESR) and procedures | • Megawatt-scale charging infrastructure is key for grid reliability and operation. Targeted revisions to ESR define procedures for self-disconnect (protection) and self-recovery. |
| Grid services | • Grid restart after outage (black start)<br>• Voltage support<br>• Fast frequency response – underfrequency load response<br>• Volt-var optimization and control |
| Standards compatibility | • Power export/delivery standards for V2G, local DER, utility distributed resources, grid services, and communication/control<br>• Different practices/procedures across utility regions |
| Interconnection procedure and safety practices | • Interconnection process and requirements for megawatt-scale charging sites and bidirectional converters<br>• Grounding and surge protection |

## Regulatory, Policy Challenges

A list of regulatory and policy challenges – summarized into impact areas and potential research to address each topic – are shown in Table 4.

Table 4. Regulatory and Policy Challenges

| Impact Areas | Research Topics |
|---|---|
| Regulatory policy | • Additional demonstrations and real-world deployments of medium voltage connected charging designs to collect technical performance and operational data for helping utilities educate regulators and state energy commissions<br>• Information/data to support economic studies and others to compile the business case for new paradigms such as utility DCaaS for fleets<br>• Cost of service studies for megawatt-scale charging<br>• Cost attribution/allocation procedures for rate recovery<br>• New tariff/rate designs, value to ratepayers<br>• Answering the question of whether utilities should plan ahead and upgrade infrastructure in key locations expected to support vehicle electrification |
| Line of demarcation for utility ownership, maintenance | • Megawatt-scale charging facilities that need to be treated and maintained like utility assets to ensure grid stability operation and reliability<br>• New definitions of “line of demarcation” that define procedures for co-sharing roles/responsibilities between site owner and utility |

# 5 OPERATIONAL IMPROVEMENTS

## Objectives

The operational characteristics of megawatt-scale charging stations differ from today's passenger DCFC in two specific areas worthy of R&D:

- Uncertainty in charging demand is more significant.
- In the future, we would expect megawatt charging stations to have site powers exceeding 20 MW, and when a truck begins charging, the additional power draw may ramp to 1+MW in a few seconds. Without any notice, this can be a challenge for the utility. Additionally, charging station operators and fleets can also benefit from a managed approach to megawatt-scale charging.
- The megawatt charging network must have high uptime.

The trucking industry will be dependent on being able to charge their vehicles and will be sensitive to any delays or inability to charge their vehicles.

## Managing Charging Demand Uncertainty

The goal of a managed charging demand at a station can provide benefits to all stakeholders:

- Utilities

  The goal would be to provide a robust forecast of charging power demand for day-ahead, hour-ahead, and 15-minute ahead to allow utilities to appropriately schedule power within their system.
- Charging Station Operators

  Charging station operators will want to maximize utilization of their EVSE to improve profitability. A clear forecast of expected charging through the coming days could allow station operators to incentivize their fleet customers to schedule charging at low utilization times.

Charging station operators can also manage peak demands on their stations by scheduling truck charging and/or reducing charge power available to meet an agreed truck charging time. Maximum power management can enable the charging site to manage its charging services to be within the power capacity of its utility service and the EVSE rating.

- Fleets

  Fleets will require certainty that charging points are available for their trucks to use. Hence, a reservation system would be greatly beneficial. Additionally, fleets may want to adjust their operations to use charging stations at low utilization times of day when the cost of charging may be lower.

## R&D Opportunities for Managed Charging Demand Tools

Software solutions could be developed to provide managed charging demand. These solutions could focus on three key aspects:

- EVSE Reservation Systems

  Online reservation systems allow truck drivers to reserve charging slots in advance. This system could allow private depots to make their chargers available for other fleets to use, when not used by depot trucks. Reservation systems could be extended to register when trucks arrive and depart as well as effectively manage payments.

  The reservation systems would need to manage late or early arrivals. If the action is left with the truck driver making the booking, then the driver will need to book a longer window for charging than that required to charge the vehicle. This will lead to under-utilized EVSE, although the charging station operator might recover costs through a reservation charge.

  An improved solution would be to have dynamic reservations optimized by the reservation software based on the bookings and number of charging points available. This could be modeled after restaurant booking systems that can cater to early/late arrivals of guests. The reservation system could also interface with utility command and control to provide the updated power demand forecast and receive any requests to restrict power.

- Integration of Charging Reservations into Fleet Management Systems

  A sophisticated fleet will track its vehicles and expected arrival times at depots. Fleets can send messages to their drivers to slow their journeys to meet optimum arrival times and improve fuel efficiency. In addition, fleets can track delays in journeys and manage their depot docks accordingly.

  This approach of fleet-managed arrivals could be extended to the reservation system. The fleet management software could exchange data with the reservation system to provide improved management of dynamic reservation slots.

- Future Load Forecasting

  In principle, reserved charging slots can provide a strong basis for forecasting charging demand. This could be supplemented by gathering data on seasonal variations in expected load demand, which can be extracted from historical EVSE usage data.

Charging demand forecasting based on reservation systems is outside the current eTRUC program focus, although the demonstration sites will be able to provide initial data on variations in load demand from trucks visiting the locations.

## TRL for Managed Charging Software

The key elements of the software for managed charging exist today. Software solutions exist for fleet management systems and for interactions with utility command and control. Similarly, hotel and restaurant reservation systems are well established. Certain passenger car charge-point operators provide real-time availability of their charging stations and manage payments. However, the reservation and load demand forecasting software has not yet been developed specifically for trucking applications using megawatt chargers. This would imply that the managed charging solution for megawatt charging of trucks is TRL 4–5 in that it exists but has not yet been proven as a system in the relevant environment.

## Targeting High EVSE Uptime

High uptime is critical for megawatt-scale charging since the chargers become essential to trucking operations. In our surveys, the industry stated that uptime would need to be 97+%. Additionally, high uptime should improve the return on investment for charging station operators easing financing for initial systems and upgrades. Two R&D approaches could improve uptimes: 1) remote monitoring of systems and prognostics, and 2) development of redundancy and self-healing designs.

### *Remote Monitoring and Prognostics*

Remote monitoring systems can collect real-time data on key operating systems and enable immediate recognition of fault conditions. If a fault is detected, the remote operator can try to remotely reset the system and/or dispatch maintenance staff to service the faulty equipment. This can reduce the duration of any downtime and improve operational reliability.

Prognostic systems seek to predict when maintenance conditions will occur in the future. The analysis is based on operational data including parameters such as voltage, current, ambient temperatures, and device operating temperatures. The goal is to forecast when the operating behavior of key components will go outside design limits. The prognostic tools could be a combination of physics-based models and big data analysis.

Remote monitoring technology – typically referred to as supervisory control and data acquisition (SCADA) systems – exists today for industrial applications and will just need to be applied to megawatt-scale charging. This would suggest a TRL level of 7+.

Prognostic analysis tools have been developed for several applications, but the models will need to be developed for megawatt charging EVSE and any neural networks trained on specific data sets. This would suggest that megawatt charging prognostics are currently around TRL 4–5.

### *Redundancy and Self-Healing EVSE*

An effective means of improving uptime is for the EVSE to be resilient to internal faults. This would require a design having redundancy built in. If an equipment fault occurs, the EVSE could self-heal by shutting down (if necessary), switching out the faulty component, restarting (potentially in a limited power mode), and sending a service request to the remote monitoring station.

The self-healing approach may be more applicable to the power conversion system. These designs typically have AC-DC stages in series with voltage capacity beyond the utility supply to provide overvoltage protection. If an AC-DC stage has a fault, in principle, it could be switched out and the power conversion continues, albeit with lower overvoltage protection until the faulty component is replaced.

The inverter, DC-DC stage could feature DC-DC in parallel to meet the required power level for dispensing. Should one inverter stage go faulty, then it could be switched out and dispensing continues, but at limited power. The other approach would be to have excess charging dispensers at a site. For example, charging dispenser capacity could exceed utility service power. This is typical in public DCFC stations today. Having 10% additional charging dispensers may be sufficient to meet a 97+% uptime requirement with respect to the utility service power.

Redundant and self-healing designs for power conversion stages are being discussed today, especially with the R&D on medium voltage SSTs. A number of publicly funded programs for next-generation SST aim to prove the technology in a relevant environment, suggesting these designs are at TRL 4–5. However, it should be noted that the current goals are to prove SST operation in regular operation, not necessarily self-healing situations.

The redundant design of the DC-DC inverter stage does not need technology development as it is duplicative of existing systems. However, this will add EVSE cost, and redesign work may be required. This would suggest the designs are at TRL 7–8. However, there may be an opportunity for a more optimum redundant design, which minimizes cost impacts. Redundant design approaches are expected to exist but may not have been applied to megawatt charging stations. These designs would likely be TRL 4.

# 6 ENABLING ZERO-EMISSION VEHICLE ADOPTION AND PROJECT OBJECTIVES

## Background on Adoption

Medium- and heavy-duty fleets tend to have inflexible operations. Hence, EVs either have sufficient battery pack sizes such that they can meet the next day's driving needs after charging overnight, or the vehicles will need one or more high power fast charges during the day that do not overly impact the vehicle operating time.

Fleet operations are also cost-sensitive, and fleet owners will need to consider the overall total cost of the EVSE and the vehicles together. Owners will need to be cautious of any cost premiums for megawatt charging if, for example, it significantly increases the costs for buying and operating the EVs and EVSE.

Megawatt charging deployments will need to provide tangible cost benefits for fleets, perhaps enabling longer-range fleet operations or minimizing the charging footprint at a depot.

## Megawatt EVSE and Zero-Emission Vehicle Fleet Adoption

To understand the opportunity for megawatt charging, we identified three general fleet operating situations that characterize expected use cases for megawatt charging:

- Return to base, with vehicles parked overnight – trucks may benefit from opportunity charging at megawatt power levels during the day.
- Public or private charging stations support long haul/multi-day trip operations.
- Public charging stations or agreed access to private depot megawatt charges are available for small fleets that do not have the ability to park overnight for suitable charging.

It is also beneficial to consider the factors that would influence the adoption of megawatt-scale chargers over standard DCFC chargers today (for example up to 350 kW on CCS). Table 5 shows a list of the factors and their influence on the adoption of charger type.

Table 5. EVSE-Related Factors Influencing Electric Truck Adoption

| Factor | Standard DCFC Charger | Megawatt Charger |
|---|---|---|
| Charge time | 4–5 hours overnight<br>1–3 hours shortest depending on battery size | 30–60 minutes |
| Charger capacity | 1 vehicle per charger (overnight) | 1–2 vehicles/hour<br>24+ vehicles/day (in theory) |
| EVSE CAPEX | Scales with site power and number of chargers | Scales with site power and number of chargers<br>Megawatt chargers are expected to be higher cost than standard chargers when production volumes are low, achieving close to parity on $/kW basis in high volume. |
| Operating cost | Lower if demand charges apply | Much higher if peak time charging occurs<br>May require additional labor costs to move vehicles to/from chargers |
| Footprint | Greater, as one charger serves one vehicle | Lower, as one charger serves multiple vehicles |

The CAPEX cost difference between standard and megawatt charging will depend on the fleet situation. Since megawatt chargers can support multiple vehicles, fewer chargers will be required than with standard chargers. Determining which approach is lower cost will depend on the distribution of charging during the day, since the more hours the chargers are used, the lower their effective costs become. Another consideration is that there is more labor effort with megawatt charging in moving vehicles to and from chargers. This will increase operating costs, although in the future these might be offset by automated charging systems.

As a starting point in considering adoption benefits, we identified the merits of megawatt charging for the three fleet situations, as shown in Table 6.

Table 6. Benefits of Megawatt Charging on Electric Truck Adoption

| Fleet | Megawatt Charging Need | Comments |
|---|---|---|
| Return to base | Optional | Primary charging can be overnight. Opportunity megawatt charging might provide some operation benefits. A larger footprint for standard chargers is not necessarily an issue unless the depot has limited parking space. |
| Long haul | Important | Primary charging could be within the 10 hours mandated as the rest period. Since the trucks park at the rest area anyway, there is likely to be less footprint impact of slow charging while parked compared to megawatt fast charging. However, once a day top up megawatt fast charge may be required for expected daily range. |
| (Certain) small fleets | Essential (if overnight charging is not available) | Although some small fleets may have access to overnight locations to charge, drivers for certain small fleets will have to charge their vehicles before going home. These drivers would need to charge their vehicles in minimal time at public stations or with agreed access to depots. |

Our initial takeaways on the benefits of the adoption of megawatt charging can be summarized as follows:

- Return to base and long haul can benefit from the availability of megawatt chargers, although overnight charging may be a main mode of operation. The added convenience of megawatt charging could promote adoption of electric trucks but is not essential.
- For long haul, the need for some trucks to opportunity charge during work hours increases the importance of megawatt charging.
- If opportunity charging with megawatt chargers can be distributed across the whole day, then, in principle, megawatt charger CAPEX will be lower than standard charging and have less footprint.
- Small fleets are likely to see benefits in the availability of megawatt charging as this may be the only pathway for them to use electric trucks.
- How well these benefits will influence adoption will depend on the acceptance of the charging options by the fleets and the cost differences for megawatt charging depending on the fleet situation.

## Project Objectives

The eTRUC project objectives aim to provide insights on the advantages and opportunities for megawatt charging that would drive adoption of electric trucks in different fleet vocations. From our initial adoption review above, the following aspects need to be addressed:

- The CAPEX and operating cost of megawatt vs. standard charging for different fleet situations must be examined. An interesting question is whether opportunity charging at megawatt powers during the day can be lower cost than overnight standard charging. This will only benefit fleets where trucks frequently return to base during the day.
- Assessment of the complete benefits of megawatt charging includes capturing the impacts of operational range increases, convenience and flexibility to support dynamic routes, footprint benefits, and utility integration benefits.
- The challenges for megawatt charging involve utility concerns, economic impacts to vehicle cost and/or battery life, and lack of grid capacity at certain charging sites.
- The most likely mix of standard and megawatt charging at sites for the different fleet situations can involve, for example, the best mix for a public truck stop supporting long haul trucks that visit during the day and park overnight.
- Fleet experience with fast charging at demo sites is necessary.

The intention is to investigate these considerations during the project and leverage this knowledge to develop an improved view on the influences of megawatt charging on zero-emission vehicle truck adoption. Such efforts will lead to more developed recommendations on the path forward for megawatt charging to support electric truck adoption.

**About EPRI**

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**Program**

Electric Transportation

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