Charging Infrastructure Technologies: Development of a Multiport, >1 MW Charging System for Medium- and Heavy-Duty Electric Vehicles

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DOE Vehicle Technologies Program
2020 Annual Merit Review and Peer Evaluation Meeting

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Overview

Timeline

- Project start date: October 2018
- Project end date: September 2021
- Percent complete: 50%

Barriers Addressed

- Integration of Medium Duty (MD) and Heavy Duty (HD) vehicle charging loads consistent with smart grid operation
- Power conversion topologies, electronics, and connectors for megawatt charging.
- A need to develop and enable reduced costs for electric charging infrastructure.
- Developing new control analytics for MD/HD vehicle charge control

Budget

- Total project funding: $7.0 M
- DOE Share: $7.0 M
- Contractor Share: $0
- Fiscal Year 2019 Funding: $3.0 M
- Fiscal Year 2020 Funding: $2.0 M

Partners

- Oak Ridge National Laboratory (ORNL)
- Argonne National Laboratory (ANL)
- National Renewable Energy Lab (NREL)
This project will: develop research tools for a framework to design, optimize, and demonstrate key components of a multi-port 1+ MW medium-voltage connected charging system.

Objective(s): Develop strategies and technologies for multi-port 1+ MW grid-connected stations to recharge MD/HD electric vehicles at fast-charging travel plazas or at fleet depots; through:

- Industry Engagement
- Charging station utilization and load analysis
- Grid impacts and interconnection analysis
- Detailed power electronics component design and controller demonstration
- Site and battery charge control design and controller demonstration
- Charging connector design
Three Lab Approach

NREL Team:
Andrew Meintz
Kevin Bennion
Eric Miller
Shivam Gupta
Shriram Santhanagopalan
Partha Mishra
Ahmed Mohamed
Kevin Walkowicz
Barry Mather
Xiangqi Zhu
Rasel Mahmud

ANL Team:
Ted Bohn
Keith Hardy
Mike Coop
Roland Varriale

ORNL Team:
Brian Rowden
Madhu Chinthavali
Rafal Wojda
Shilpa Marti
Aswad Adib
Rachit Agarwal
David Smith

Total Funding:
$7M over 3 years
NREL: $3M ($1M/yr)
ORNL: $3M ($1M/yr)
ANL: $1M ($0.5M/yr)

HIL: hardware-in-the-loop
## Milestones: All Labs

<table>
<thead>
<tr>
<th>Milestone Name/Description</th>
<th>Deadline</th>
<th>Milestone Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarterly reports on progress of year 1 activities (include tasks 1, 2, 6, 7, 8, 12)</td>
<td>End of Q1, Q2, Q3 FY 19</td>
<td>Quarterly Progress Measures</td>
</tr>
<tr>
<td>Complete the simulation and performance analysis of at least one power conversion topology</td>
<td>9/30/2019</td>
<td>Go/No-Go Milestone</td>
</tr>
<tr>
<td>Quarterly reports on progress of year 2 activities (include tasks 3, 4, 5, 8, 9, 10, 12)</td>
<td>End of Q1, Q2, Q3 FY20</td>
<td>Quarterly Progress Measures</td>
</tr>
<tr>
<td>Battery modeling grid interface control architecture prototype design for power stage; prototype design for power mechanism</td>
<td>9/29/2020</td>
<td>Go/No-Go Milestone</td>
</tr>
<tr>
<td>Quarterly reports on progress of year 3 activities (include tasks 10, 11, 12)</td>
<td>End of Q1, Q2, Q3 FY21</td>
<td>Quarterly Progress Measures</td>
</tr>
<tr>
<td>Complete integration of the overall control architecture and virtual 1 MW evaluation platform; verify through control HIL simulation; evaluate power transfer mechanism using prototype hardware</td>
<td>9/29/2021</td>
<td>Annual Milestone</td>
</tr>
</tbody>
</table>

**Year 2 Milestones will show:**

1. Evaluation of vehicle charge connectors
2. Development of optimized battery charging algorithms for multi-port charge control
3. Site controller development for grid interface and distributed energy resources
4. Module and converter controller simulation and hardware development
5. CAD model development of PE Design with thermal management, grid connection, DC interconnects and charging interface

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**Abbreviations:**

- EV: electric vehicle
- DC: direct current
- DCaas: DC as a Service
- PE: power electronics
- FMEA: Failure Modes and Effects Analysis
Approach: Multi-Task, Multi-Year

- Industry Engagement
- Charger Power / Utilization
- Grid Impacts and Interconnect Analysis
- Detailed Power Electronics Component Design
- Battery Charge Control Optimization
- Connector Design
- Hardware in the Loop Local Controller
- Site Controller
- Prototype Connector Analysis
- Validate Controller Hardware in the Loop
- Validate Connector Design with high current evaluation

Year 1
Year 2
Year 3
Approach: Multi-Task, Multi-Year

PE Interface Controller
Input:
- Grid Supply
- Reactive Power Injection
- Load Active Power Demand
- Quantity of PV/ES Dispatch

Task 8
Task 9
Task 5

Task 10
DMS

Distribution Feeder Model
13.2 kV AC

Task 3

Energy Storage Model

Task 9

Photovoltaics Model

Task 12

~2kV DC

Task 8

Vehicle Battery Management System

PE Models (Switches, Passives, etc.)

Site Controller
Grid Interface Control
DER Control
Charging Dispenser Power Control

Controller in Hardware
CAD Models of Hardware

Input:
- Grid Supply
- Reactive Power Injection
- Load Active Power Demand
- Quantity of PV/ES Dispatch

EVSE Controller
PV Controller
ES Controller
Grid Interface Controller

CAD: Computer aided design
EVSE: electric vehicle supply equipment
ES: energy storage
PV: photovoltaics
PE: Power Electronics

RT- Platform (Opal-RT, RTDS, etc.)

Argonne National Laboratory
Oak Ridge National Laboratory
NREL
### Technical Accomplishments and Progress:
#### Task 1 / 2 / 3 – PE Topology Review, Simulation, and Selection

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Metric</th>
<th>DC Coupled Arch.</th>
<th>AC Coupled Arch.</th>
<th>MV-CHB Arch.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficiency</strong></td>
<td>Semiconductor Losses</td>
<td>Lowest in pure-DER mode</td>
<td>Lowest during pure-grid mode</td>
<td>Balanced</td>
</tr>
<tr>
<td></td>
<td>Overall System Efficiency</td>
<td>94-98%</td>
<td>92-95%</td>
<td>95-98%</td>
</tr>
<tr>
<td></td>
<td>Standby Efficiency</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>Transient DC Voltage Stability</td>
<td>Better</td>
<td>Good</td>
<td>Best</td>
</tr>
<tr>
<td></td>
<td>Grid-side voltage stability</td>
<td>Best</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Advanced Grid Support</td>
<td>Comparable</td>
<td>Comparable</td>
<td>Comparable</td>
</tr>
<tr>
<td></td>
<td>Output current ripple control</td>
<td>Good</td>
<td>Good</td>
<td>Best</td>
</tr>
<tr>
<td><strong>System Ratings</strong></td>
<td>Active device ratings</td>
<td>Good</td>
<td>Good</td>
<td>Best, Low due to Modular converter structure</td>
</tr>
<tr>
<td></td>
<td>Low Frequency Stepdown Transformer</td>
<td>Required</td>
<td>Required</td>
<td>Not Required</td>
</tr>
<tr>
<td></td>
<td>AC-side breaker and switchgear requirements</td>
<td>High-current AC interface</td>
<td>High-current AC interface</td>
<td>Low-current AC interface</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>Modularity</td>
<td>Good</td>
<td>Good</td>
<td>Best</td>
</tr>
<tr>
<td></td>
<td>System Scalability</td>
<td>Good – Parallel systems required in BOS</td>
<td>Poor – Parallel systems required in BOS, stages for DER inclusion</td>
<td>Best – minimum BOS for multi-MW installation</td>
</tr>
</tbody>
</table>

**Best Overall Performance and Balance of System Utilization**

1. Efficiency: initial evaluation based on semiconductor losses and refined with passive element losses
2. AC and DC Coupled based on 480V class which limits switch utilization
   - Optimization for wide-bandgap (WBG) introduction for increased switching frequency and higher voltage consideration
3. Complexity of adding DER to system

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CHB: Cascaded H-Bridge  
DER: Distributed Energy Resource  
MV: medium voltage  
BOS: Balance of System
Technical Accomplishments and Progress:
Task 1 / 2 / 3 – PE Topology Review, Simulation, and Selection

- Detailed MV Architecture investigation
  - Detailed loss values including passives, protection, and interconnects
  - Translation to thermal management requirements
  - Final device selection
- MV Gate Drive Test Hardware
  - MV Si/SiC Device level testing providing detailed PE model input
- Thermal Management
  - Strategy, sizing, and ancillary impact
- Cabinet level AC Grid Connection and Protection
- Cabinet level DC interconnects (DER/Load)
- DC interface to Charge connector
Technical Accomplishments and Progress:
Task 1 / 2 / 3 – PE Topology Review, Simulation, and Selection

Each Module Pack is 300 kW
- 4 Module Packs Per Phase (1.2 MW)
- 12 Module Packs Total (3.6 MW)

- CHB-DAB 300kW Module Pack (AC-DC, DC/DC isolated)
- Air Cooled
- Max Output Power: 300 kW
- Output Voltage: 2000V DC

- Load Converter Module Pack (Isolated DC/DC)
- Air Cooled
- Max Output Power: 400 kW
- Output Voltage: 1500V DC
Technical Accomplishments and Progress:
Task 4 / 5 – MW+ Charging Equipment and Module Control

- Estimate 2X improvement in Power Density in MV architecture
- Expect BOS comparison to improve the Power Density further
- Potential for increased efficiency both at PE and BOS

![CAD Models of Hardware](image_url)

**Technical Specifications**

- **Balance of System – Transformer, Switchgear, etc.**
  - 480 V
  - 400 kW
  - 25-40 ft²
  - > 95% Efficiency

- **Power Converter Grid to DC bus**
  - 13.8 kV
  - 3.6 MW
  - 80-110 ft²
  - > 95% Efficiency

- **Load Converter 1.5 kV**
  - Coupled DC bus
  - 2 kV
  - Efficiency η > 98%

- **Charge Station**
  - Efficiency η > 97%
  - Estimate 2X improvement in Power Density in MV architecture
  - Expect BOS comparison to improve the Power Density further
  - Potential for increased efficiency both at PE and BOS
Controller hardware-in-the-loop (CHIL) demonstration for year 3

- **Switch-level model** for a single port using a digital real-time simulator system with field programmable gate array (FPGA) for switch timing interface

- Digital Signal Processors (DSPs) will be used to implement a **switch-level controller** for each inverter/converter.
  - Grid Interface
  - Energy Storage System
  - Photovoltaics
  - EV Supply Equipment

- Each DSP will interface with the site controller through the power electronic interface controller

- Additional ports of the system will be modelled as average-value models
Technical Accomplishments and Progress:
Task 6 – Site Utilization and Load Profile

Linear Programming Used to Define Usage vs Charge Needs in Western Region

- Prospective zones for fast-charging (1+MW) were chosen by looking for overlap in travel with the road network.
- **6,284 possible locations** were considered in the analysis.
- A vehicle can only be electrified if each **300-mile block of driving** includes at least one opportunity to charge.
- The sum of the location is limited, representing limited capital for charging infrastructure (i.e. limitation on how many charge locations are feasible)
Technical Accomplishments and Progress:
Task 6 – Site Utilization and Load Profile

- Building stations continues to increase electrification with diminishing returns
- The average energy dispensed by each station peaks and recedes as new stations electrify roadways with increasingly sparse traffic
- 65% of the vehicle travel considered in this study could be electrified with 300-mile range vehicles and 50 charging locations.
- Further analysis will include slow charging in depots and rest areas to understand the influence on the load profile and number of fast charging stations.
Technical Accomplishments and Progress:
Task 7 – Grid Impacts Analysis

- Voltage sensitivity analysis \(^1\) to determine best- and worst-case areas for HD charging stations (i.e. retrofitted travel center locations)

- Both time series analysis and extreme snapshot case analysis have been performed on 4 representative distribution system

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### Distribution Systems: Best Location

#### Feeder Requirements

<table>
<thead>
<tr>
<th>Distribution Systems: Best Location</th>
<th>Ramp Rate</th>
<th>Peak Charging Load</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without mitigation (MW/min)</td>
<td>With mitigation (MW/min)</td>
<td>Without mitigation (MW)</td>
</tr>
</tbody>
</table>
|                                    | **Smart Charger Capacity (Reactive Power support) Requirement** **
|                                    | Without mitigation | With mitigation | Without | With mitigation |
| IEEE standardized test case: IEEE 34-bus system | Nominal | 2.00 | 5.00 | 3.50 | 6.50 | Total Capacity: 8.23 MVA Q Capacity: 5.05 MVAR |
|                                           | Maximum | 2.50 | 5.50 | 4.00 | 7.00 |
| Single feeder case: California feeder | Nominal | 1.80 | 2.50 | 1.80 | 30.00 * | Total Capacity: 33.71 MVA Q Capacity: 15.37 MVAR |
|                                           | Maximum | 2.00 | 3.00 | 2.00 | 31.50 * |
| Two feeder case: Hawaii feeder M1&M2   | Nominal | 2.16 | 6.50 | 5.50 | 70.00 * | Total Capacity: 78.65 MVA Q Capacity: 35.86 MVAR |
|                                           | Maximum | 2.20 | 7.00 | 6.50 | 75.00 * |
| Dedicated feeder case: derived from California feeder | Nominal | 2.17 | 5.22 | 19.50 | 47.00 * | Total Capacity: 52809kVA Q Capacity: 24079kvar |
|                                           | Maximum | 2.22 | 5.33 | 20.00 | 48.00 * |

- Analysis for four representative distribution systems.
- This **shows best location**, the max load feeders can hold will be lower at other locations.
- Considering substation cap (e.g. 10MVA), with smart charger support, max **charge load can reach 5 times of that without any mitigation strategies** (e.g., 10MW V.S. 1.8 MW for single feeder case)
- If equipped with PV and energy storage, the feeders can handle higher charging load

* Total capacity will be limited by substation transformer and sub-transmission limitations

** Smart charger capacity calculated from nominal charging load with mitigation
Objective: (a) Implement battery charging algorithm using real-time hardware, (b) Demonstrate adaptivity of BMS charging algorithm in response to change of reference setpoint from site controller

- Algorithm: Constant current, constant voltage (CC-CV) charging of a battery cell based on voltage feedback
- Real-time hardware: CC-CV algorithm resides on a pcDuino, acting as the BMS
Technical Accomplishments and Progress:
Task 8 – Battery Load Profile and Optimal Charge Control

Objective: Explore model-based optimal charging algorithms

Scenario:
Based on the number of vehicles plugged-in, the site controller can constrain the maximum charging power (current) at some ports.

Model-based optimal charging algorithms can modify the charging profile based on changing (current/power) constraints, while aiming to show comparable performance to “business as usual” (i.e. no site controller limited current/power) situations.
Technical Accomplishments and Progress:
Task 12 – Design and Thermal Management of 1+MW Connector

• Supporting the CharIN High Power Charging for Commercial Vehicles (HPCCV) Task Force to evaluate performance of prototype connector hardware from industry partners
  • Developed approach to support four levels of evaluations
    • Level 0: Unpowered Fit and ergonomics
    • Level 1: Powered without cooling up to 350 A
    • Level 2: Powered with connector cooling up to 1000 A
    • Level 3: Powered with connector and inlet cooling up to 3000A
  • Developed draft hardware specification setup and shared with HPCCV task force members and industry partners
  • Developing experiment hardware designs for each evaluation level
• Evaluation event planned for **Fall 2020 (September / October)**
• A second event planned for early 2021 will support further ergonomics and thermal evaluation as well vehicle-to-charging equipment communication and operational conditions
Technical Accomplishments and Progress:
Task 13 / 14 / 15 – Industry Engagement and Recommendations

- MD/HD truck, Bus, DCaaS Charging Topics:
  - Year 1: collect requirements from industry input; generate summary
  - Year 2: discuss case studies, develop use cases/test cases, test bed capabilities

- Work-in-progress draft summary report reviewed during ANL hosted workshop, Sept. 2019. Industry engagement group has expanded each month, (~275 members) adding subject matter experts covering sub-transmission utility inter-connection to battery terminal charging path systems.

- FY19 summary report appendix content added each month with case studies of relevant examples present multiport DC charging installations with MW+ utility interfaces (bus, port electrification, etc), automated connection systems, fleets, etc.

- Safety and communication related aspects of MW+ level DC charging are being addressed in weekly CharIN HPCCV subcommittee meetings with industry subject matter experts. WYE capacitance, fault protecting devices, Lorentz force issues.
Two main concerns raised at the last AMR:

- ... the industry collaborations are not very clear despite having a very long list of potential partners. The reviewer asked who is supporting and doing what.
  - Response: The charging connector effort at NREL is directly supporting the HPCCV taskforce for evaluation of prototype connectors for major OEMs and Tier-1 suppliers. In addition, the work from Task 1-3 on the power electronics design and Task 6 on the charger utilization have been shared through the industry engagement group (~275 members).

- ... a single 1MW+ charger at 480 volts (V) gives about 2000 A current. Ten such charging ports require 20 kA current. The reviewer asked whether it would make sense to look at higher voltage power electronic topologies
  - Response: The team evaluated 480 V approaches as a point of comparison but has chosen a 13.2 kV approach for the year 3 evaluation.
Collaboration and Coordination
Multi-Lab Approach with Multiple Industry Partners

NREL Team:
Andrew Meintz
Kevin Bennion
Eric Miller
Shivam Gupta
Shriram Santhanagopalan
Partha Mishra
Ahmed Mohamed
Kevin Walkowicz
Barry Mather
Xiangqi Zhu
Rasel Mahmud

ANL Team:
Ted Bohn
Keith Hardy

ORNL Team:
Brian Rowden
Madhu Chinthavali
Rafal Woida
Shilpa Marti
Aswaad Adib
Rachit Agarwal
David Smith

• Utilities, planning services, site operators
  Black & Veatch, Burns & McDonnel, CTE, AEP-Ohio, Duke Energy, EPRI, MG&E, PG&E,
  Seattle City Light, Southern Company, CTA-Chicago, Electrify America, EVgo,
  Loves/Trillium, TA Petro

• EVSE, power electronics, couplers/cable systems
  ABB, BTC Power, Chargepoint, Delta Products, Eaton, Efacec, Heliox, Siemens, Tritium,
  Marquette Univ., JMM Consulting, Huber+Suhner, ITT, Phoenix Contact, Power Hydrant,
  Rema, Schunk, Staubli, TE Connectivity,

• Vehicle OEM, end users/customers
  Autocar Truck, BYD, Cummins, DTNA/Daimler, FCA, Ford, Gillig, MAN/VW Group,
  Navistar, New Flyer, Nova Bus, PACCAR/Peterbuilt, Proterra, Tesla, Thor, Transpower,
  Penske Leasing, Ruan Transportation

• DOE Funded/Lab coordination
  ANL, NREL, ORNL, U-Del, ThinkSmartGrid, EPRI
• Definition and refinement of 1+MW charging site scenario (distribution feeder and charger utilization) that will drive understanding and R&D

• 1+MW Charging System Emulation Platform
  – Availability and additional characterization of wide-bandgap medium-voltage industrial modules
  – Scaling the high frequency and high bandwidth control in CHIL platform to simulate multi-port site.
  – Integrating the embedded DSP controller hardware with the real-time platform
  – Development of site controller optimization algorithm that balances grid interface requirements, onsite energy resources, and battery charging while maintaining real-time performance.
Proposed Future Research

- Project, as a proposed and funded is a 3-year project.
- Remainder of FY20:
  - Develop switch-level and average value models to represent charging hardware
  - Demonstrate charging control optimization for integration with site controller
  - Support charging connector evaluation

<table>
<thead>
<tr>
<th>Milestone Name/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 3 Power stage parameter design and hardware component selection.</td>
</tr>
<tr>
<td>Task 4 Technical assessment of supply equipment for MD/HD applications and ultra-fast chargers</td>
</tr>
<tr>
<td>Task 5 Develop module controller for each power stage of single multiport MW charging system</td>
</tr>
<tr>
<td>Task 8 Evaluate control with battery cells in PHIL environment to assess coordination with multiple chargers and charger support of grid services</td>
</tr>
<tr>
<td>Task 10 Develop smart control for overall site management that incorporates grid objectives, minimizes charging time, and supports multiport charging stations with onsite DER</td>
</tr>
<tr>
<td>Task 12 Support evaluation of prototype design for technology validation</td>
</tr>
</tbody>
</table>

Any proposed future work is subject to change based on funding levels.
Proposed Future Research

- FY21:
  - Integration of the overall control and virtual 1+ MW multi-port charging system evaluation platform;
  - Verify through control HIL simulation the charging system response to grid disturbances, effectiveness of site control, and grid interface control capability to mitigating grid impact
  - Evaluation of power transfer mechanism using prototype hardware

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 10</td>
<td>Evaluate smart control for overall site management in controller HIL environment using plant models for system components to include appropriate response and control</td>
</tr>
<tr>
<td>Task 11</td>
<td>Function validation of single multiport MW charging system through controller HIL simulation</td>
</tr>
<tr>
<td>Task 12</td>
<td>Perform analysis and modeling to evaluate power transfer mechanisms and develop prototype design for technology validation</td>
</tr>
<tr>
<td>Task 13 - 15</td>
<td>Identify standards gaps, perform interoperability testing; collect data for standards</td>
</tr>
</tbody>
</table>

Any proposed future work is subject to change based on funding levels
Summary

This project will:

1) Address challenges and develop solutions for **1+ MW systems through a national laboratory and industry collaboration**

2) Overcome barriers to deployment of a 1+ MW-scale integrated charging station and provide answers to fundamental questions associated with the feasibility of the system
   - Identify hardware component needs
   - **Develop and test hardware and system** designs
   - Develop design guidelines and performance metrics
   - Assess potential **grid impacts and grid services**

3) Develop safe systems and smart energy management techniques, including on-site resource sizing and control.

4) Demonstrate through controller hardware-in-the-loop the **real-time operation of a 1+MW charging system** to analyze grid integration, power electronics control, site-level energy control, and system communication requirements.
Thank You!
The 1+MW Team

www.nrel.gov

NREL/PR-5400-76707
Technical Back-Up Slides
• ORNL Medium voltage device (discrete/module) characterization test bench for Si vs. SiC device comparison
## Technical Back-Up Slides

### Task 7 – Grid Impacts Analysis

#### Distribution Systems: Mediocre Location

<table>
<thead>
<tr>
<th></th>
<th>Feeder Requirements</th>
<th>Note</th>
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<tbody>
<tr>
<td></td>
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<td>With mitigation (MW/min)</td>
</tr>
<tr>
<td>IEEE standardized test case: IEEE 34-bus system</td>
<td>Nominal</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>0.08</td>
</tr>
<tr>
<td>Single feeder case: California feeder</td>
<td>Nominal</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>0.35</td>
</tr>
<tr>
<td>Two feeder case: Hawaii feeder M1&amp;M2</td>
<td>Nominal</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>0.50</td>
</tr>
<tr>
<td>Dedicated feeder case: derived from California feeder</td>
<td>Nominal</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>n/a</td>
</tr>
</tbody>
</table>

** Smart charger capacity calculated from nominal charging load with mitigation