Project ID # ELT204

Development of a Multi-Port, 1+MW Charging System for Medium- and Heavy-Duty Electric Vehicles

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National Renewable Energy Laboratory (Lead Lab)

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June 13, 2019

DOE Vehicle Technologies Program
2019 Annual Merit Review and Peer Evaluation Meeting

Overview

Timeline

- Project start date: 10/01/2018
- Project end date: 9/30/2021 (3 years)
- Percent complete: 15%

Budget

- Total project funding: $6.0M + $1M (ANL) over 3 years
- DOE share: $6.0
- Contractor share: $0
- Funding for FY 2018: $0
- Funding for FY 2019: $2.0M

HD: heavy duty
MD: medium duty
PEV: plug-in electric vehicle

Barriers

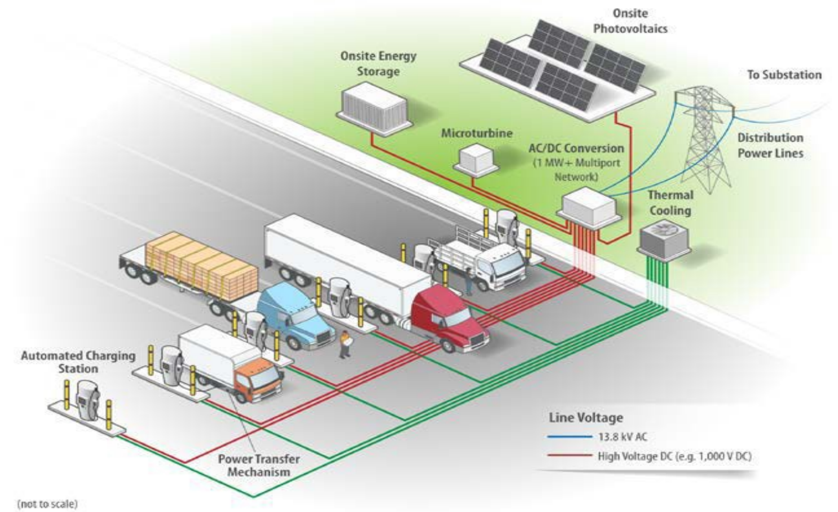
- Barriers addressed:
  - A need for managed Medium Duty and Heavy Duty (MDHD) vehicle charging loads consistent with smart grid operations
  - A need to develop and enable reduced costs for electric charging infrastructure
  - A need to develop new control analytics for MD/HD PEV charge control

Partners

- National Renewable Energy Laboratory (NREL)
- Oak Ridge National Laboratory (ORNL)
- Argonne National Laboratory (ANL) Electric Power Research Institute (EPRI)

Relevance

This project will develop research tools and a framework to design and optimize key components and operation of a flexible, multi-port 1+ MW fast-charging grid-connected system that minimizes grid infrastructure cost/impact and allows for integration with distributed energy resources (DER), such as photovoltaics and energy storage.



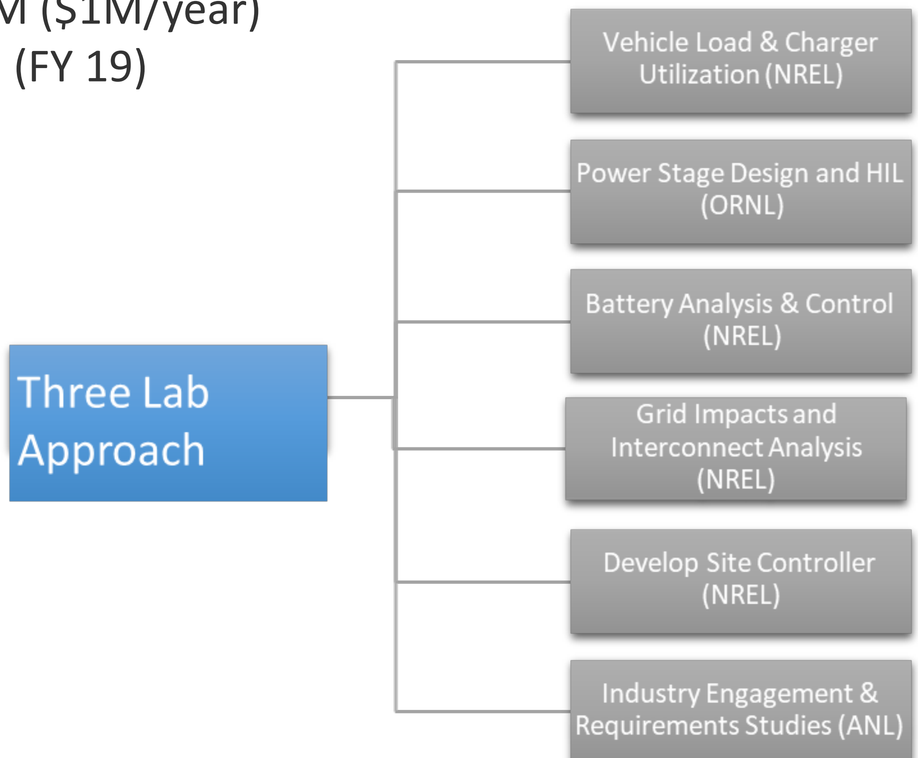
This project will:

1) Address challenges and develop solutions for beyond extreme fast charging (XFC) (1+ MW) systems through a national laboratory 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
3) Identify hardware component needs
4) Develop and test hardware and system designs
5) Develop design guidelines and performance metrics
6) Assess potential grid impacts and grid services
7) Develop safe systems and smart energy management techniques including on-site resource sizing and management.

Resources

Total funding: $7M over 3 years

NREL: $3M ($1M/year)
ORNL: $3M ($1M/year)
ANL: $1M (FY 19)



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HIL: hardware-in-the-loop

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Milestones: All Labs

Milestone Name/Description	Deadline	Milestone Type
Quarterly reports on progress of year 1 activities (include tasks 1, 2, 6, 7, 8, 12)	End of Q1, Q2, Q3 FY 19	Quarterly Progress Measures
Complete the simulation and performance analysis of at least one power conversion topology	9/30/2019	Go/No-Go Milestone
Provide Draft Summary Report on Industry Engagement and Charging Requirements for MDHD, EV Transit Bus and DC-as-a-Service	9/30/2019	Annual Milestone
Quarterly reports on progress of year 2 activities (include tasks 3, 4, 5, 8, 9, 10, 12)	End of Q1, Q2, Q3 FY20	Quarterly Progress Measures
Battery modeling grid interface control architecture prototype design for power stage; prototype design for power mechanism	9/29/2020	Go/No-Go Milestone
Quarterly reports on progress of year 3 activities (include tasks 10, 11, 12)	End of Q1, Q2, Q3 FY21	Quarterly Progress Measures
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	9/29/2021	Annual Milestone

Year 1 Milestones will Provide:

1) **PE Topology Studies**
2) **Use Case Charge Profiles for Travel Center**
3) **Grid Impacts Analysis**
4) **Progress Update to Develop Optimal Battery Charging Algorithms**
5) **Analysis of Charge Connector Hardware**
6) **Draft of Charging Requirements (Gaps, FMEA, Safety) from Industry Engagement**

EV: electric vehicle
DC: direct current
DCaaS: DC as a Service
PE: power electronics
FMEA: Failure Modes and Effects Analysis

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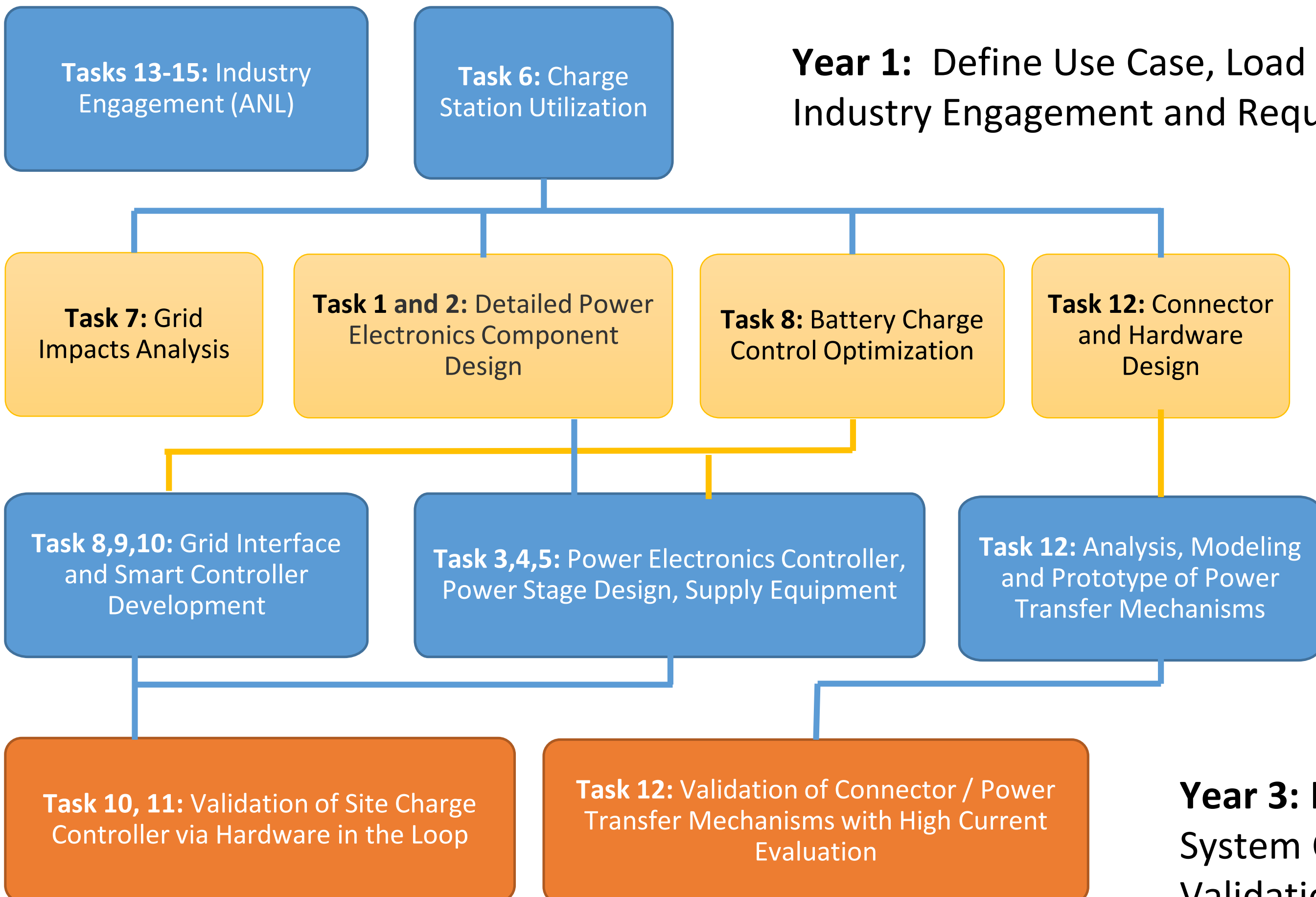
Approach



Year 1: Define Use Case, Load Profiles and Industry Engagement and Requirements

Year 1 and 2: Initial Design of Hardware based on Load Profiles

Year 2: Architecture and Hardware design and modeling

Year 3: Hardware and System Control Validation

Approach: Multi-Task, Multi-Year

Task	Year 1	Year 2	Year 3
1: Literature Review of PE Topologies	■		
2: Perform Simulation Studies of PE Topologies	■		
3: PE Power Stage Parameter Design and Selection		■	
4: Technical Assessment of EV MW+ Charging Equipment		■	
5: Develop Host Controller for Power Stage of MW System		■	
6: Use Case Charge Profile Development for Travel Center	■		
7: Grid Impacts Analysis	■		
8: Battery Load Profile and Optimal Charge Control	■	■	
9: Design Overall Site Controller Architecture		■	
10: Grid Interface Development for Grid Insights		■	■
11. Functional Validation of MW+ through HIL			■
12. Design and Thermal Management of Connector	■	■	■
13. Industry Engagement and Recommendations: MD/HD Truck	■		
14. Industry Engagement and Recommendations: EV Transit Bus	■		
15. Industry Engagement and Recommendations: DC-as-a-Service	■		

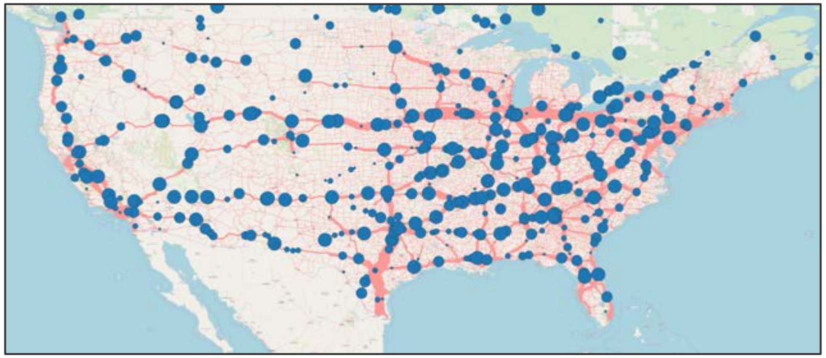
Technical Accomplishments and Progress
Task 6: MW+ Charging Use Cases

Objective

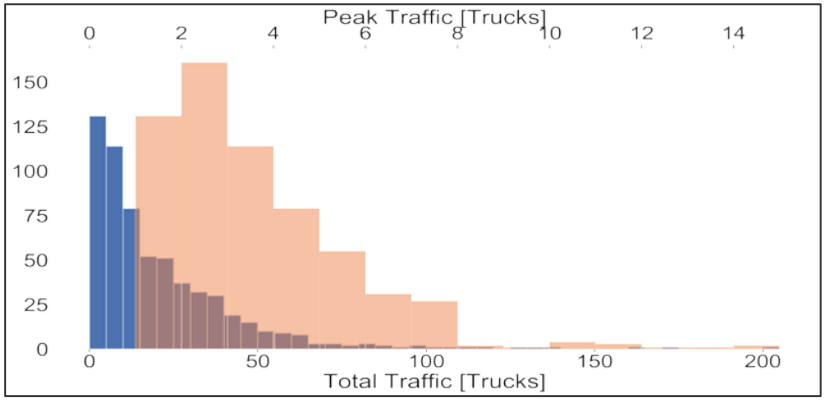
- Develop charging profile(s) consisting of high resolution (1 min) power and energy requirements for MW+ charging station from real-world use data

Approach

1. Use real-world class 8 line haul data (991 trucks over ten days) to obtain location, state of charge and anticipated energy needed until next charge
2. Estimate station charging requirements for anticipated charge locations and assumed vehicle configurations (i.e., 480-mile EV range)
3. Determine station profiles for a range of locations to show variation in stations
4. Provide charge profile outputs to other tasks to analyze hardware and other needs



Estimated station loads based on real-world travel Class 8 trucks

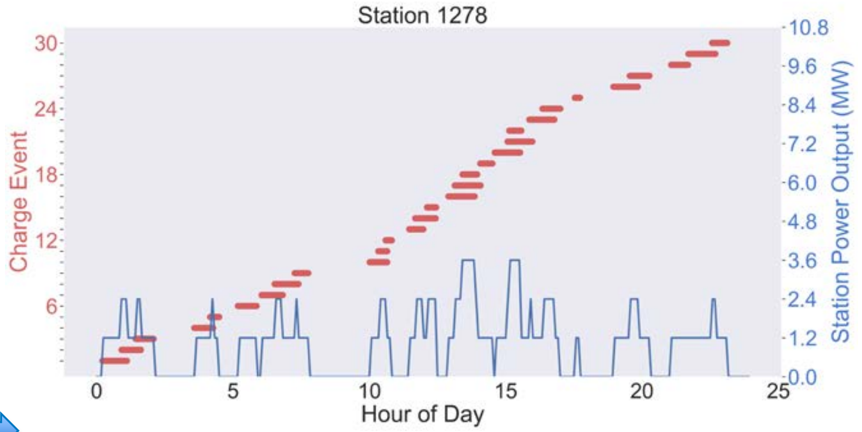


Generating power and energy requirements for distribution of stations to understand estimated station requirements

Technical Accomplishments and Progress Task 6: MW+ Charging Use Cases

Technical Accomplishments:

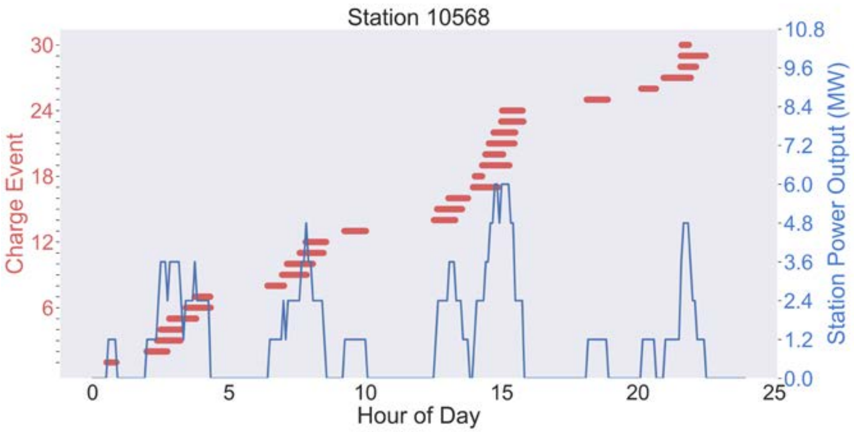
- Developed analysis tools to assess and estimate long-haul trucking energy demands
- Developed preliminary optimization approach to maximize station utilization and reduce total number of stations (minimize $) necessary for vehicle route electrification
- Documenting station load profiles now



Low-Case Charging Station Profile – 30 Trucks

Future Work:

- Refine and expand to a larger number of vehicle samples representing real-world long-haul trucking
- Include additional optimization weighting factors for charge station selection, such as grid infrastructure location preferences



High-Case Charging Station Profile – 30 Trucks

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

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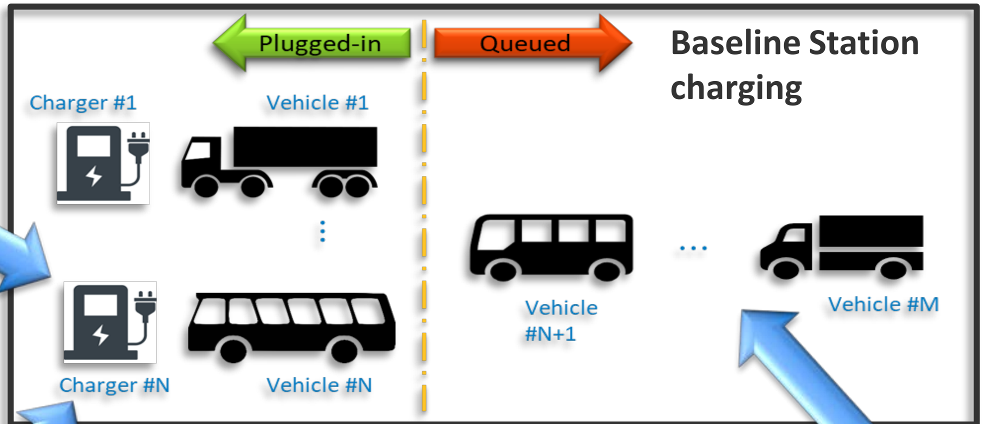
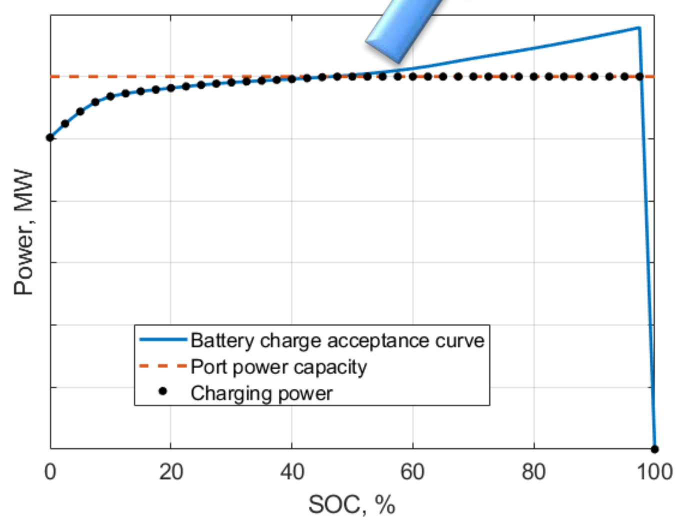
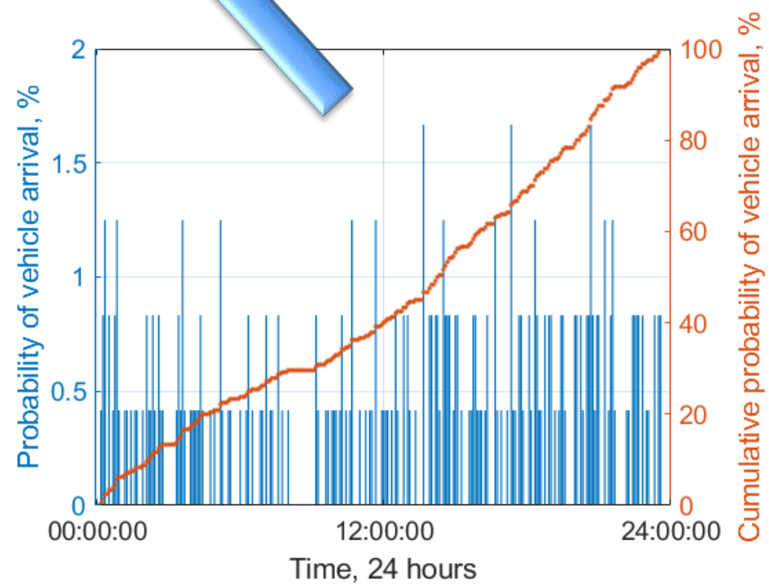
Technical Accomplishments and Progress Task 8: Charge Profiles for Station Design - Charge Port Power & Energy

Optimized grid power to electric vehicle support equipment (EVSEs)





Estimate how batteries will charge: vehicles charge at the EVSE according to port and battery charge acceptance requirements (not linear)



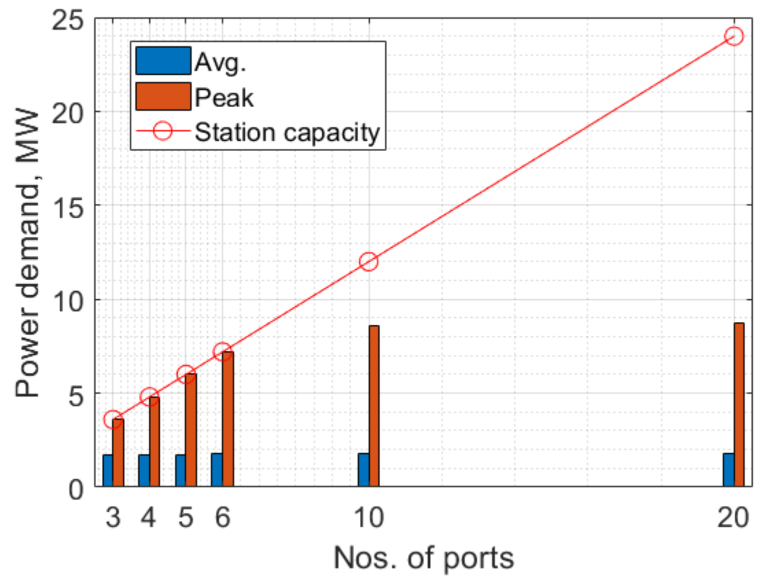
Vehicle arrival distribution: average eight stations at 30 vehicles/day

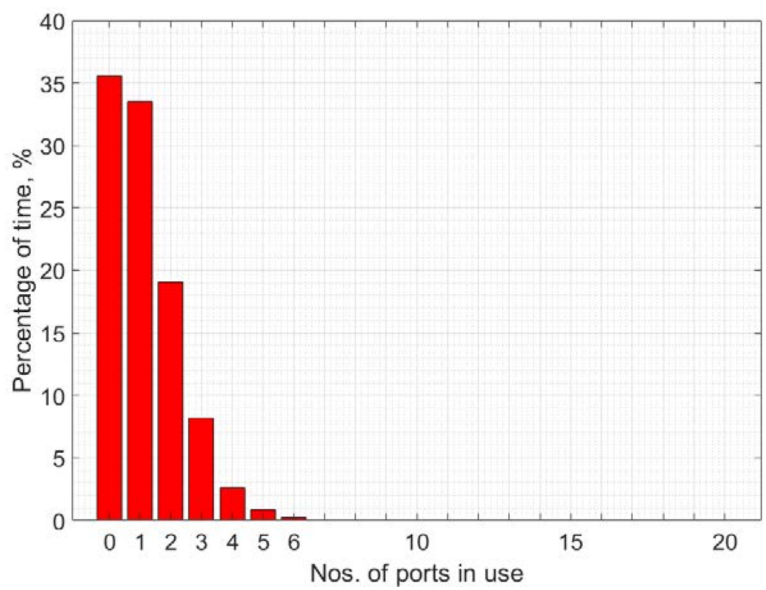
Technical Accomplishments and Progress Task 8: Estimating the Effect of Number of Ports on Station Power Load Profile

Finding Optimum Number of Charge Ports: **i**ncreasing the number of ports beyond vehicle demand will seldom result in higher peak power for the station

Design of Station (# of ports): balance between wait time and limiting station peak power based on estimated number of vehicles to be charging

In this specific simulation: seven charging ports result in negligible wait time and avoid the peak power to reach station capacity





Technical Accomplishments and Progress Task 12: MW+ Charge Connector

Objective

- Identify hardware component needs and quantify technology impacts to support 1+ MW high-power charging

Approach (FY 19)

1. Perform literature survey of materials, fluids, and heat transfer materials that aid in the design of charging mechanisms

2. Evaluate through modeling the performance impacts on the connector current rating of heat transfer approaches compatible with ongoing high-power connector standard proposals

3. Quantify battery thermal requirements and waste heat challenges and opportunities during high-power charging

Materials

Heat-spreading materials

Insulation

Electrical contacts

Cooling

Fluids (type, flow, temperature)

Passive cooling systems

Example pin and socket to be included for heat transfer analysis along with other potential connection mechanisms proposed for high-power charging

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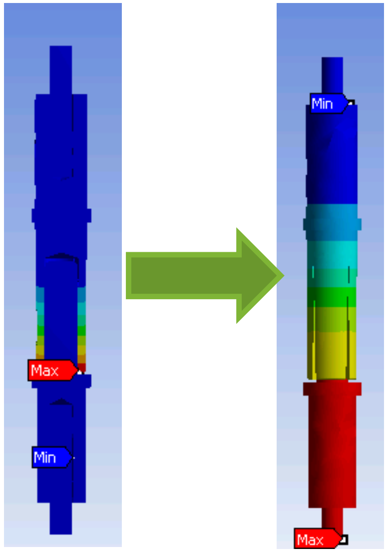
Technical Accomplishments and Progress Task 12: MW+ Charge Connector Thermal Analysis

Technical Accomplishments:

- Developed two-step approach for electro-thermal modeling and simulation
  1. Structural finite element analysis (FEA) of connector to obtain deformed structure after insertion
  2. Electro-thermal FEA of deformed structure under specified current and voltage conditions
- Developing thermal lump capacitance model of large battery packs for quantifying available heat during fast-charge event
- Evaluating potential for waste heat recovery for charge site heat utilization



Structural analysis for thermal and electrical analysis

Future Work:

- Validate model by experimentally characterizing matching baseline hardware
- Apply validated model to study impacts of cooling technologies applied to charging mechanism (connector and cable)
- Quantify excess heat available from charge station components and battery and potential recovery technologies

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

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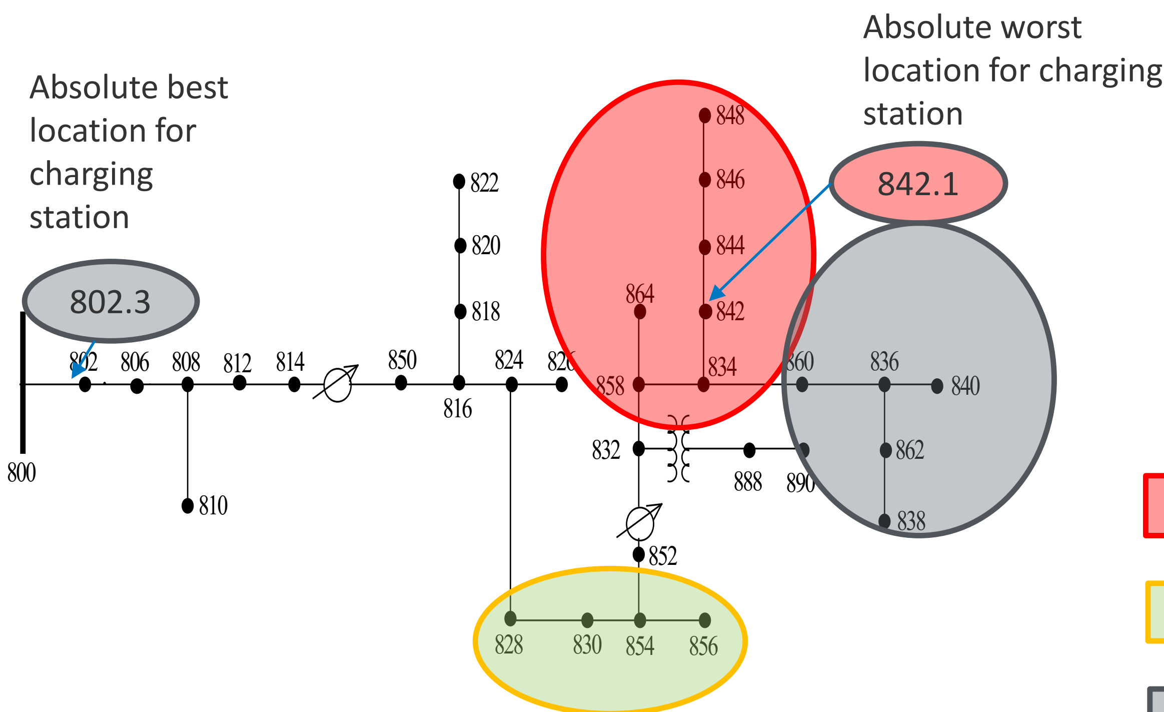
Technical Accomplishments and Progress Task 7: Grid Impacts Analysis – Assessing Hosting Capacity



Worst locations for charging station

Mediocre locations for charging station

Good locations for charging station

Determining best and worst case areas for HD charging stations:

Voltage sensitivity analysis completed

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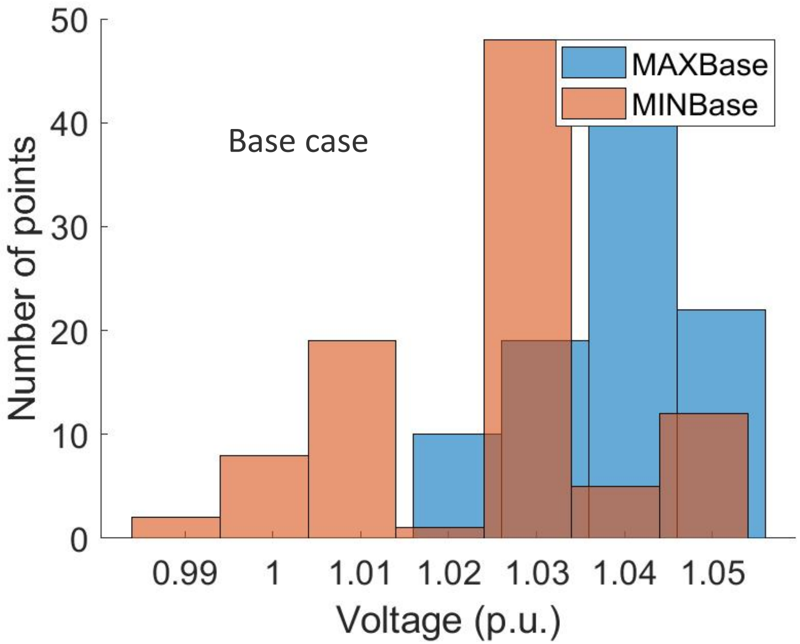
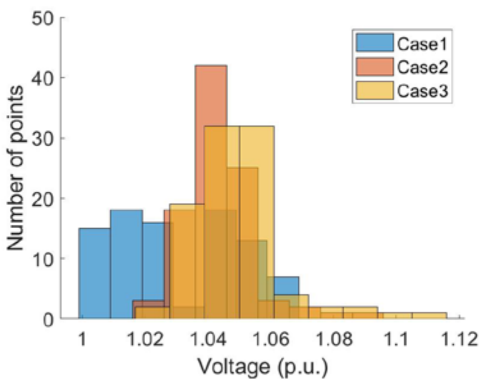
Technical Accomplishments and Progress Task 7: Grid Impacts Analysis – Assessing Hosting Capacity



Distribution of Maximum Daily Voltage of all the nodes



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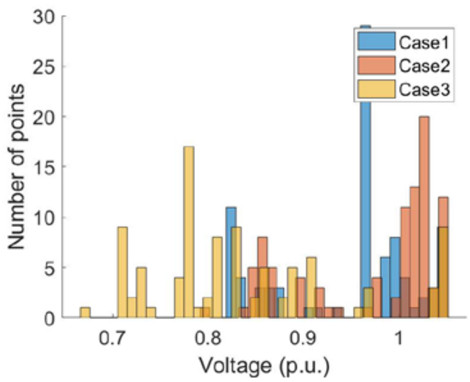
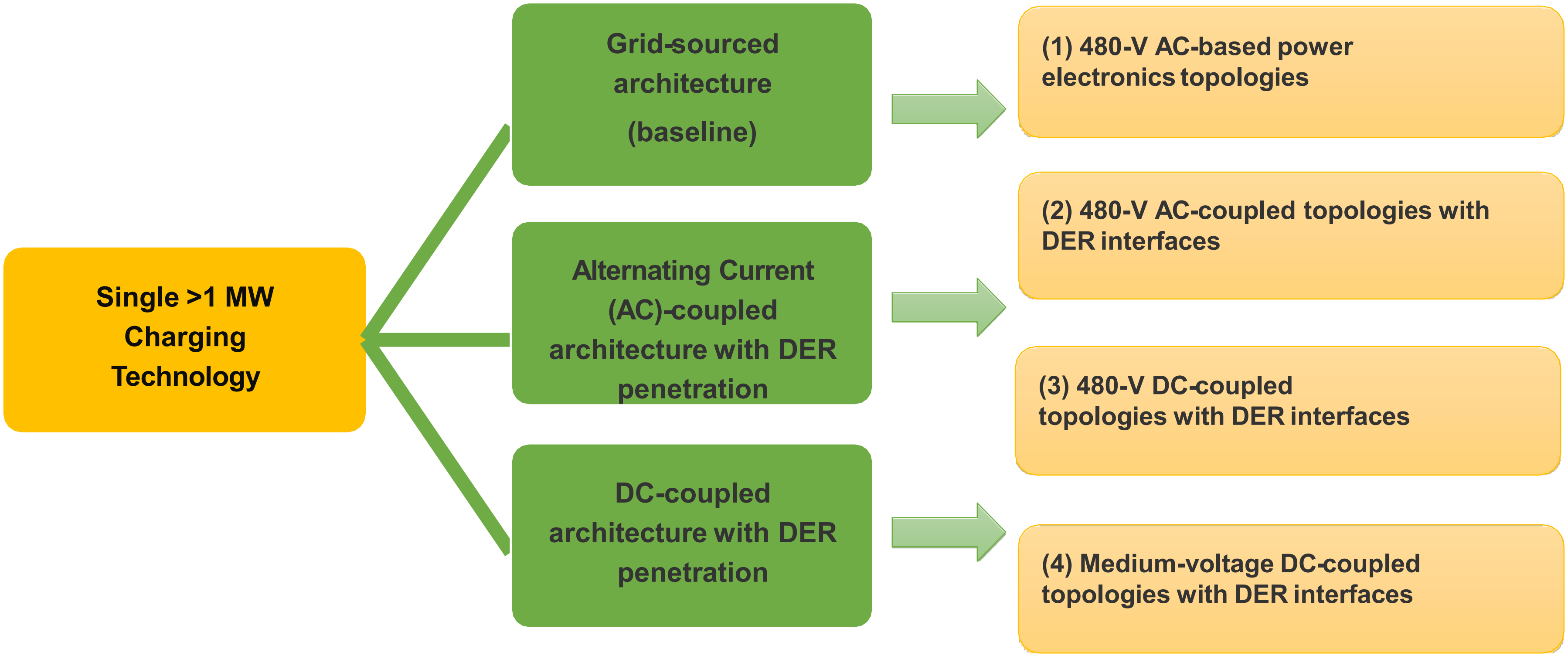


Technical Accomplishments and Progress Tasks 1 & 2: Investigation of Power Electronics Topologies



Investigating four architecture candidates with flexible power converter topologies

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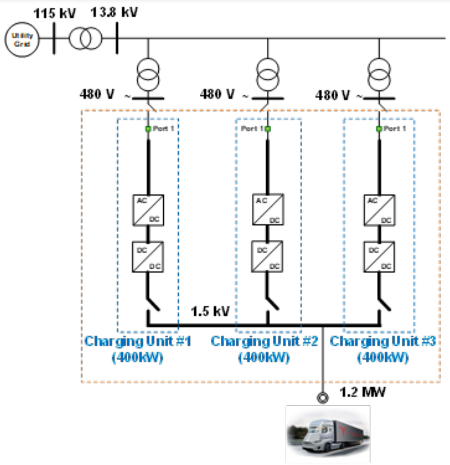
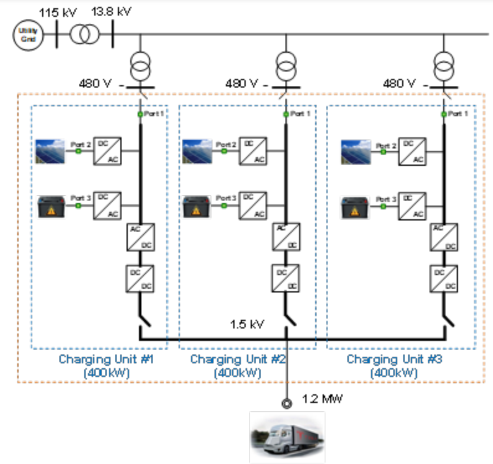
Technical Accomplishments and Progress Tasks 1 & 2: Investigation of Power Electronics Topologies

(1) 480 V AC based power electronics topologies



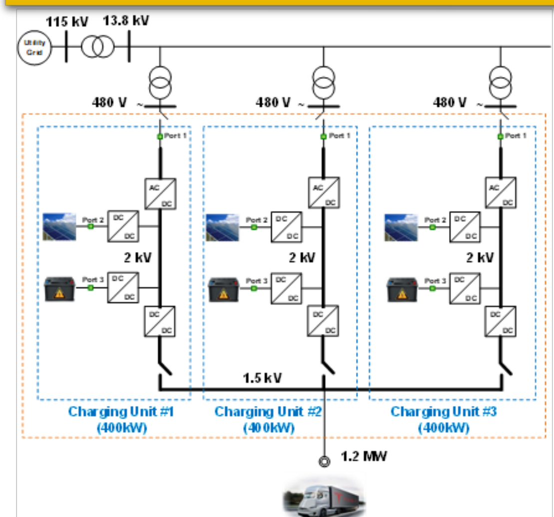
- Grid power only
- Least power stages
- Low control complexity

(2) 480 V AC coupled topologies with DER interfaces



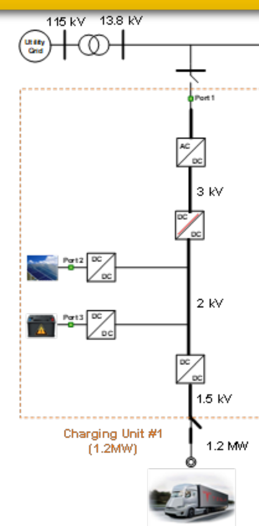
- DER backup power
- Less power stages
- Grid support capable
- AC microgrid control

(3) 480 V DC coupled topologies with DER interfaces



- DER backup power
- DC bus decoupling
- Grid support capable
- DC microgrid control

(4) Medium voltage DC coupled topologies



- Low input current
- Low harmonics
- No bulky transformer
- DER backup power
- Grid support capable

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Technical Accomplishments and Progress Tasks 13-15: MW+ Multi-Port MD/HD Vehicle Charging Requirements Study

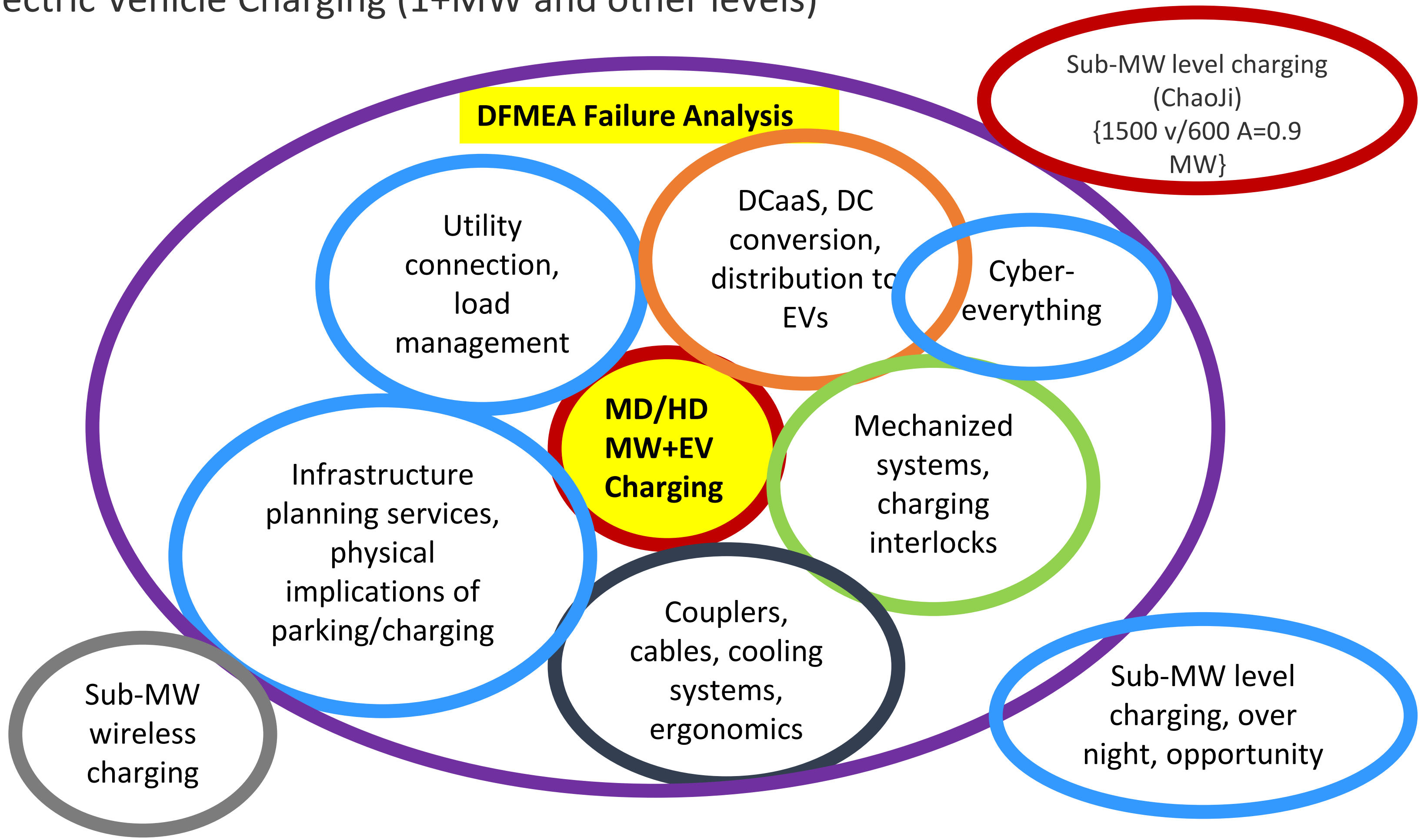
- **Methodology:** Leverage input from industry stakeholders; capture present state of the industry, best practices, and current state of standards; create recommended practices; investigate future interconnection standards that address safety/control issues.

- **Project Plan:** Proceed with monthly meetings on specific topics, investigating industry priorities on source-to-end-point issues with MW-level charging path:

  - Utility/facility inter-tie costs, complexity, obstacles, limitations
  - DC-as-a-Service–related topics, state of industry, costs, tradeoffs
  - Bulk DC distribution from MV-DC converter to DC/DC dispensers
  - Active cooled cables vs. non-cooled, coupler options, risks
  - FMEA comprehensive review of failure modes, risks, mitigation

Technical Accomplishments and Progress Task 13-15: MW+ Multi-Port MD/HD Vehicle Charging Requirements Study

Overlapping Areas Of Common Benefit to MDHD Electric Vehicle Charging (1+MW and other levels)



Technical Accomplishments and Progress Tasks 13-15: MW+ Multi-Port MD/HD Vehicle Charging Requirements Study

Industry Stakeholder Subgroups/Workgroups

- **Utilities, planning services, site operators**
  Black & Veatch, Burns & McDonnel, Center for Transportation and Environment, American Electric Power-Ohio, Duke Energy, EPRI, Madison Gas & Electric, Pacific Gas & Electric, Seattle City Light, Southern Company, Chicago Transit Authority, Electrify America, EVgo, Loves/Trillium, TA-Petro

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

- **Vehicle original equipment manufacturer (OEM), end users/customers**
  Autocar Truck, BYD, Cummins, Daimler Trucks North America/Daimler, Fiat Chrysler Automobiles, Ford, Gillig, MAN/Volkswagon Group, Navistar, New Flyer, Nova Bus, PACCAR/Peterbilt, Proterra, Tesla, Thor, Transpower, Penske Leasing, Ruan Transportation

- **DOE-funded/Lab coordination**
  ANL, NREL, ORNL, University of Delaware, ThinkSmartGrid, EPRI

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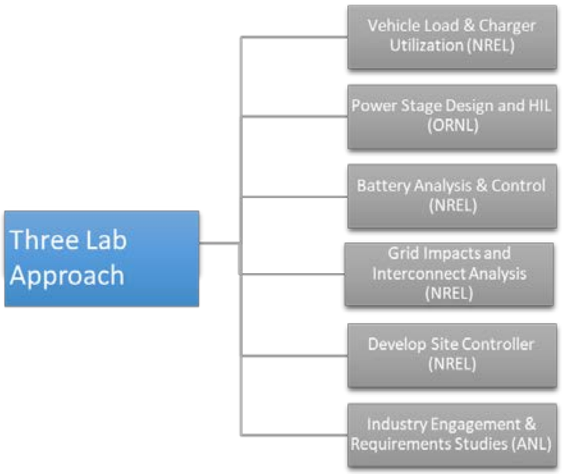
Responses to Previous Year Reviewers' Comments

- This project is a new project for FY 19.

Collaboration and Coordination: Multi-Lab Approach with Multiple Industry Partners



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Coordination across three labs

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ANL Team:
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Key industry partner engagement

- **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**
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- **DOE Funded/Lab coordination**
  ANL, NREL, ORNL, U-Del, ThinkSmartGrid, EPRI

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Remaining Challenges and Barriers

- Definition and refinement of use case (or cases) - Understanding and defining expected high-resolution charge profiles will drive much of the R&D needed
- Developing cost-effective hardware and control solutions to enable 1+ MW systems and improve return on investment for operators and encourage MD/HD adoption
- Site-specific grid integration issues need to be addressed to understand location + power + energy requirements and their impact and integration with grid distribution issues

Proposed Future Research: Remainder of FY 19

Tasks 1-2: Complete the simulation of medium-voltage architecture

- Improve converter performance through power-stage and control-parameter optimization
- Evaluate converter efficiency as a parametric function of various operating conditions
- Evaluate the transient bus voltage variations through different architectures

Task 6: Finalize station load profiles

- Compare charge station locations to existing truck fueling centers
- Include additional weighting factors for charge station selection
- Incorporate mixed-charge types and charge-rate locations

Task 7: Complete the grid impact analysis with refined distribution feeder information

- Statistical analysis of voltage impacts at different nodes on distribution grid

Task 8: Complete model-based charge control

- Fully develop real-time charging algorithm with validation and battery chemistry models

Task 12: Continued connector research

- Validate thermal modeling
- Assess waste heat utilization opportunities

Tasks 13-15: Continued industry interaction and draft report by end of FY 19

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

Proposed Future Research: FY 20 and FY 21

Task	Description	Lead	Q1	Q2	Q3	Q4
Year 2						
Task 3	Power stage parameter design and hardware component selection	ORNL	■	■		
Task 5	Develop host controller for each power stage of single multiport MW charging system	ORNL		■	■	■
Task 4	Technical assessment of supply equipment for MD/HD applications and ultra-fast chargers	ORNL	■	■	■	
Task 8	Evaluate control with battery cells in PHIL environment to assess coordination with multiple chargers and charger support of grid services	NREL		■	■	■
Task 9	Develop smart control for overall site management that incorporates grid objectives, minimizes charging time, and supports multiport charging stations with onsite DER	NREL			■	■
Task 10	Grid interface development for interoperability of the charging system (Q1-Q4)	NREL	■	■	■	■
Task 12	Perform analysis and modeling to down-select power transfer mechanisms and develop prototype design for technology validation	NREL	■	■	■	■
		ORNL	■	■	■	■

Task	Description	Lead	Q1	Q2	Q3	Q4
Year 3						
Task 10	Evaluate smart control for overall site management in controller HIL environment using plant models for system components to include appropriate response and control (Q1-Q3)	NREL	■	■	■	
Task 11	Function validation of single multiport MW charging system through controller HIL simulation (Q1-Q4)	ORNL	■	■	■	■
		NREL	■	■	■	■
Task 12	Revise prototype and develop scaled technology prototype for technology validation and reliability evaluation	NREL		■	■	■

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Summary

This project will:

1) Address challenges and develop solutions for beyond-XFC (1+ MW) systems through a national laboratory 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
3) Identify hardware component needs
4) Develop and test hardware and system designs
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7) Develop safe systems and smart energy management techniques, including on-site resource sizing and management.

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Thank You
The 1+MW Team

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Technical Back-Up Slides

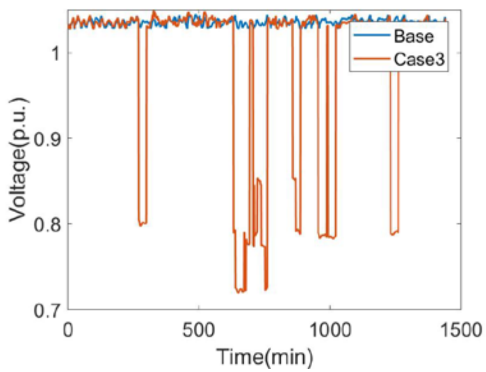
Technical Back-Up Slides

Tasks 1 and 2: Power Electronics Interface Architecture Specifications

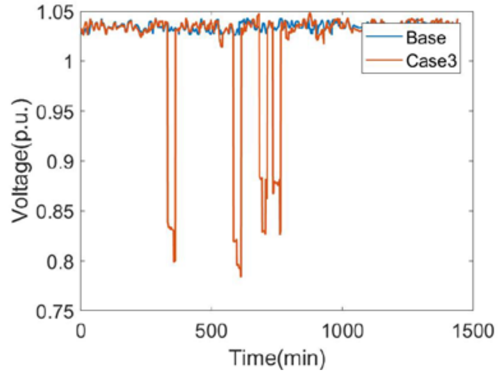
	Parameters	Value
Grid	Grid voltage (low-voltage) RMS, $V_{ll(rms)}$	480 V
	Grid voltage (medium-voltage) RMS, $V_{ll(rms)}$	3.3 kV ~ 13.8 kV
	Line frequency, f	60 Hz
Battery	Rated charging power, P_{load}	1.2 MW
	Battery voltage, V_{batt}	1 kV ~ 1.5 kV
Charging Unit	Number of charging units, N	3~4
	Power rating of each charging unit, P_c	400 kW
	DC bus voltage, V_{bus}	2 kV

Task 7: Example of One-Day Voltage Analysis – Worst Case (842.1)

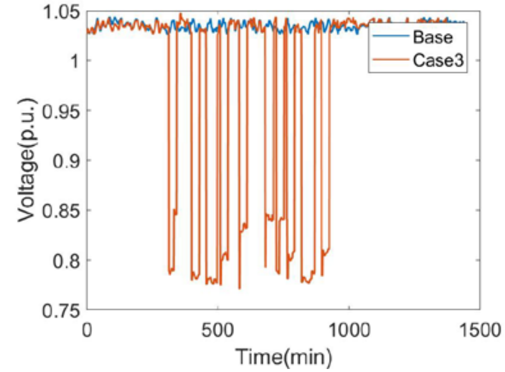
842.1



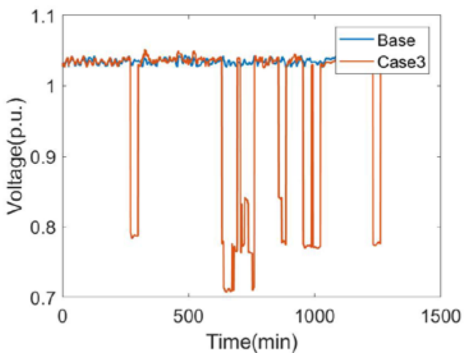
858.1



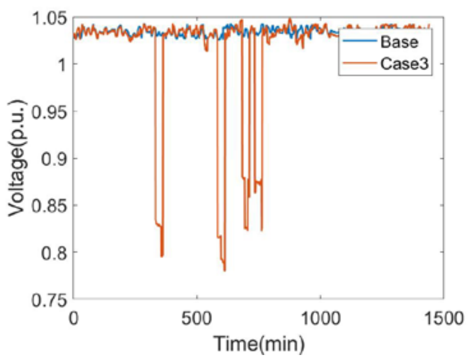
844.2



834.2



846.3



When there is heavy EV charging in voltage-sensitive areas, the weak grid connection is evident at all locations – very poor power quality from a voltage regulation perspective

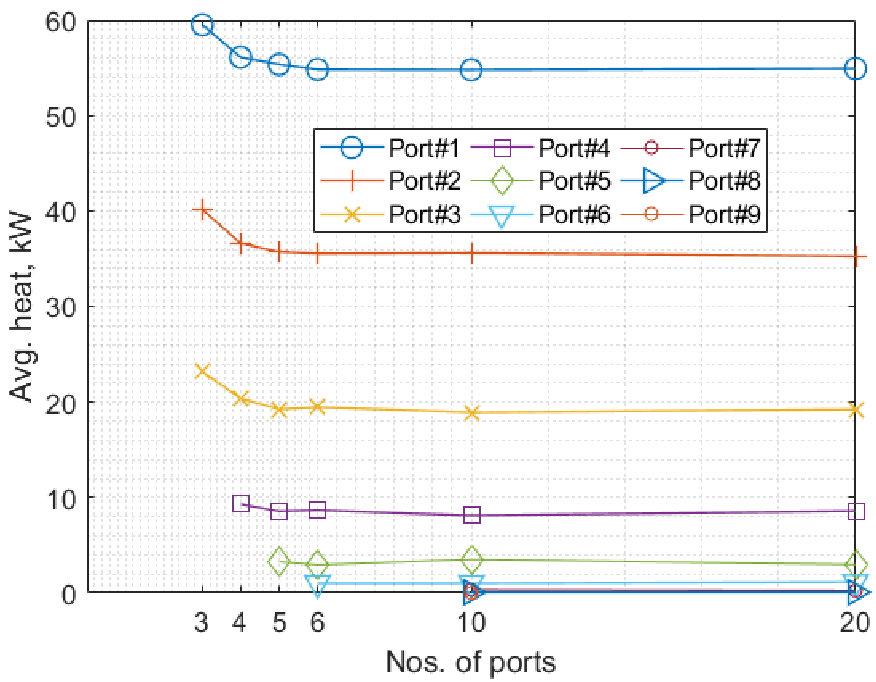
Oak Ridge National Laboratory
NREL National Renewable Energy Laboratory
Argonne National Laboratory

Technical Back-Up Slides

Task 8: Estimating the Effect of Number of Ports on Heat Generation at Port

- This is the heat generated at the EVSE side due to their associated inefficiencies
- Most heat is generated in Port #1 since the queuing algorithm preferentially assigns vehicles to Port #1 to charge, if available, or Port #2 next, and so on and so forth
- Heat generated at a given port (e.g., Port #1, 2, 3) decreases with increase in the number of ports since the port utilization decreases

Avg. heat generated at each port when total nos. of ports vary at the station



Technical Back-Up Slides

Task 12: Electrical Design and Thermal Management of the Connector Mechanism

- Continue external interactions
  - CharIN and ANL Industry Workgroup interaction for industry guidance and relevance

- Connector thermal modeling
  - Apply two-step simulation approach to baseline model (no active cooling)
  - Validate model by experimentally characterizing matching baseline hardware
  - Apply validated model to study impacts of cooling technologies applied to charging mechanism (connector and cable)

- System thermal analysis
  - Waste heat utilization
    - Quantify excess heat available for removal from charge station components and battery
    - Review of waste heat recovery technologies and their applicability for site heat utilization
  - Battery thermal management
    - Quantify battery thermal requirements, including thermal losses during charging and heating needs during cold soak conditions and battery transient temperature response