Award No: DE-EE0009871

Ultra-low Cost, All-SiC Modular Power Converters for DC Fast Charging Equipment Connected Directly to Medium Voltage Distribution System

Srdjan Lukic, Principal Investigator (NCSU)

Team Members: Iqbal Husain (NCSU); Wensong Yu (NCSU); Kenneth Dulaney (NCSU); Richard Sapienza (NCSU); Lisa Poger (NCSU); Heather Brutz (NCSU); Dan Isaksson (Danfoss); Stefan Schröder(Danfoss); Marko Laitinen (Danfoss); Joseph Rowny Jr.(NCSU); Alan Ettlinger (NYPA) ; John Markowitz (NYPA); Gregory Pedrick (NYPA); Patrick G. Stephens (GoTriangle); Aleksandar Vukojevic (ComEd)

Agenda

- Project Overview
- Team Members, Relevant Experience and Key Responsibilities
- Review of Statement of Project Objectives
- Technology Description
- Project Management
- Technology Transfer Plan
- Risk Mitigation

Overview

Timeline

- Project Start Date: April 2022
- Project End Date: April 2026
- Percent Complete: 2%

Barriers

- Development of a low cost oil-free EVSE connecting to utility at medium voltage
- System siting, integration and deployment

Budget

- Total Project Funding
  - DOE Share: $ 3,858,646
  - Contractor Share: $ 1,468,674
- Spending to Date (Q1 2022)
  - DOE Share: $ 0
  - Contractor Share: $ 0

Partners

- NCSU/FREEDM – Lead
- NCSU/NCCTEC
- Danfoss
- New York Power Authority (NYPA)
- Commonwealth Edison
- GoTriangle

Objectives and Relevance

Objectives

- Reduce the cost of SST-based EVSE by at least 50% compared to the baseline system through topology, electrical, and mechanical cost-cutting innovations that reduce BOM costs and improve reliability
- Identify best insertion points for the technology by analyzing the total cost of ownership of SST-based EVSE

Project Impact:

- Demonstrate all-SiC ultra-low cost, light, and compact SST-based EVSE
- Total cost of ownership analysis will guide future roadmapping and development of SST-based EVSEs

Key Deliverables:

- All-SiC SST-based EVSEs operational in the field
- Total cost of ownership analysis

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Key Deliverables:

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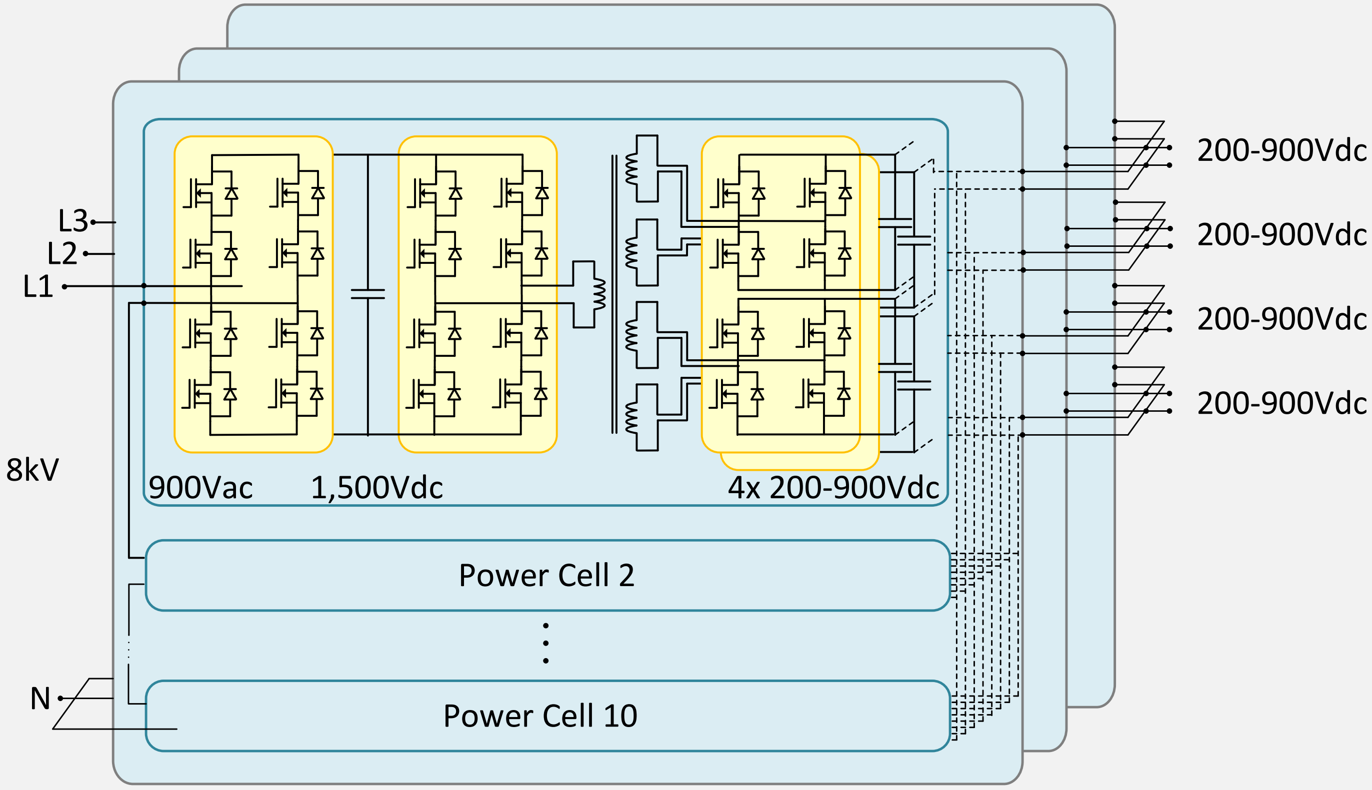
Approach

Technology Goals:

- Integration of galvanic isolation between EVSE charging ports within the SST for cost reduction
- Reduce BOM cost by half
- 3x reduction in system volume
- Maintain SST peak efficiency above 98%

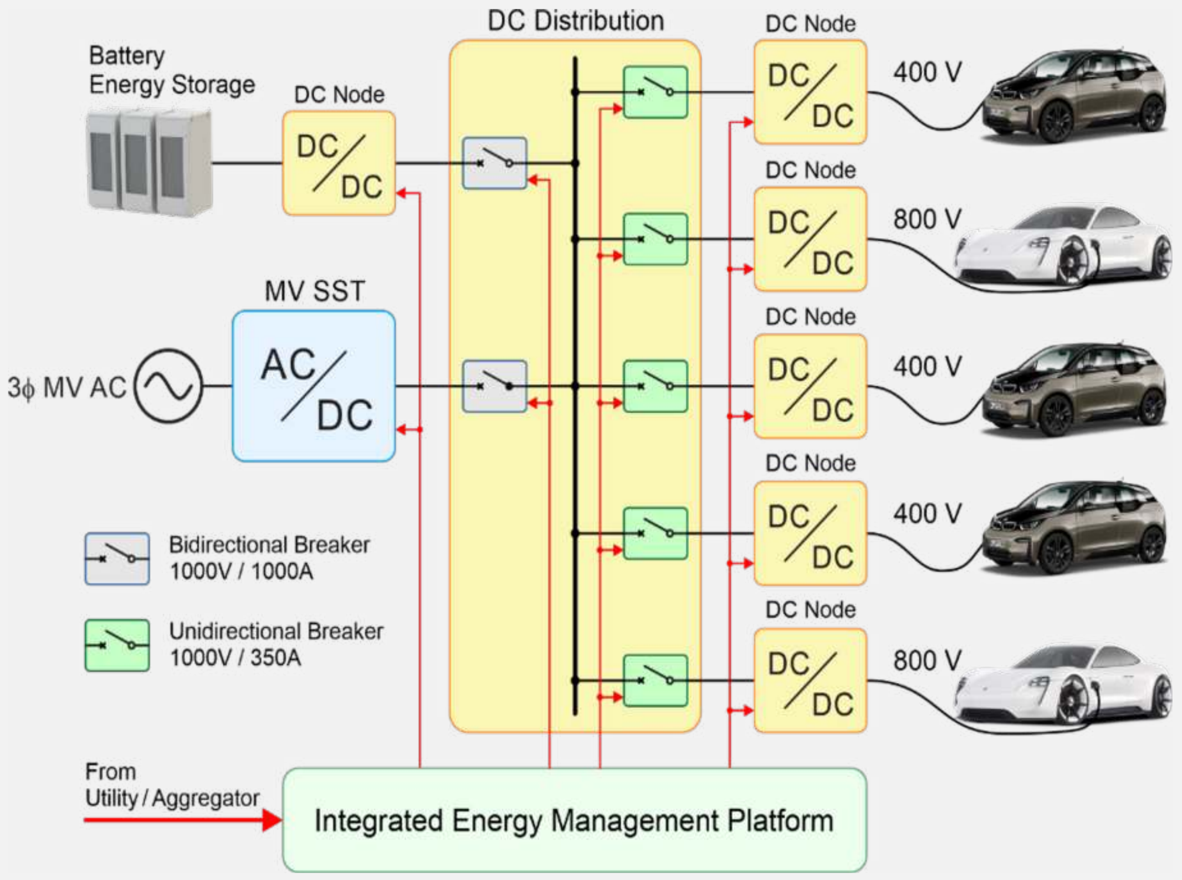


SST is built up of identical **Power Cells** with 900Vac input and 4x independent 200-900V outputs system stacks 10 power cells in series to connect to 15kV class distribution system

Team Introductions

Team Introductions

- Project role: Lead Institution
- Prior Experience in SST Development: Leads on DE-EE0008450*
  - Shared bi-directional Solid State Transformer (SST) connecting directly to the medium voltage (MV) distribution system
  - DC distribution network with solid-state DC protection



*Intelligent, Grid-Friendly, Modular Extreme Fast Charging System with Solid-State Direct-Current Protection

Team Introductions

- Project role: Leading Total cost of Ownership (TCO) Analysis
- Prior Experience
  - Analysis of fleet compositions to create TCO models including recommendations for EVSE infrastructure installations
  - Created the 50 States of Electric Vehicles publications which track policy developments across utilities and state governments as well as rate design changes that pertain to electric vehicles.
  - Staff maintains the DSIRE* database which includes information on incentives provided by utilities that may affect the cost of installing EVSE infrastructure which includes data about EV charging rates offered by investor-owned utilities.

* Database of State Incentives for Renewables & Efficiency

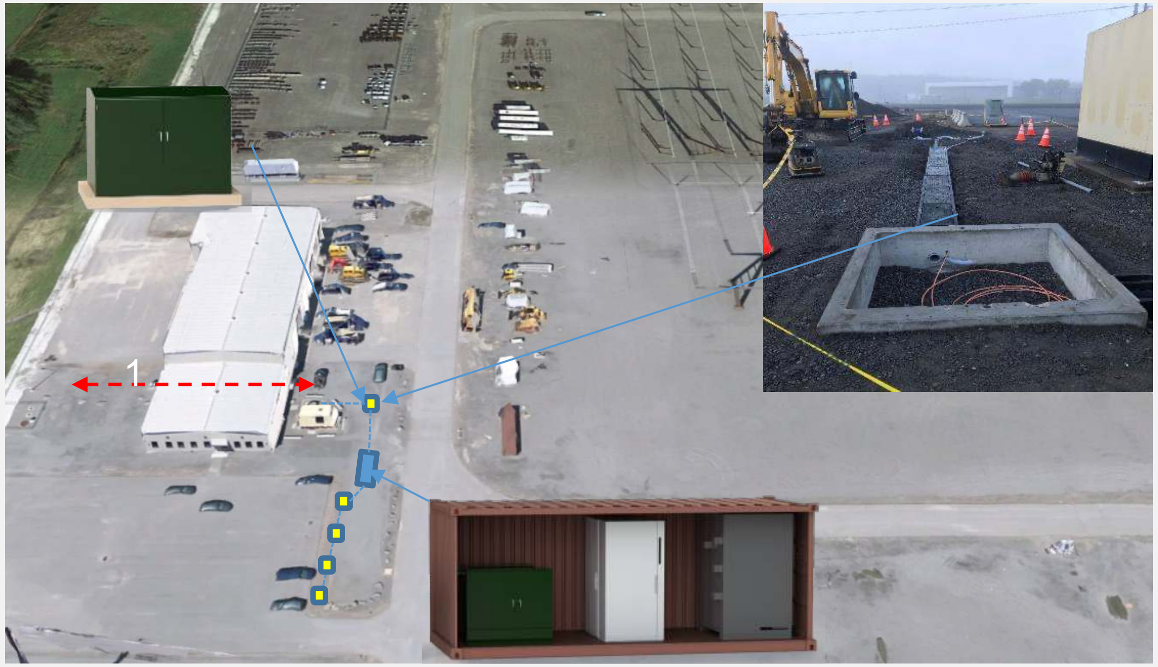
Team Introductions

- Project role: All aspects of SST Development
- Prior Experience
  - Danfoss is a leader in Medium Voltage Drives
  - MV Drives unit is headquartered in Durham, NC and performs all development and production tasks for the Danfoss MV Drives portfolio.
  - Danfoss is an Associate Member of the FREEDM Center.

Danfoss VACON 3000 Drive

Team Introductions

- Project role: Demonstration Partner
- Prior Experience: Partners on DE-EE0008450*
  - Provided a Demonstration Site for the demonstration of Baseline System
  - Will provide data from the site throughout this project
  - Self Permitting Entity



Team Introductions

comed
AN EXELON COMPANY

- Project role: Demonstration Partner
- ComEd is the largest electric utility in Illinois and the sole electric provider in Chicago.
- ComEd is a unit of the Chicago-based Exelon Corporation, one of the nation's largest electric and gas utility holding companies.
- ComEd provides electric service to more than 3.8 million customers.

Team Introductions

- Project role: Demonstration Partner
- Research Triangle Regional Public Transportation Authority, provides bus service to the Research Triangle region of North Carolina in Wake, Durham, and Orange counties. The organization owns and operates a fleet of electric buses and has identified a site where the team will demonstrate the proposed technology.

Team Introductions

Name	Organization	Role	Title
Srdjan Lukic	NCSU/FREEDM	PI	Professor
Wensaong Yu	NCSU/FREEDM	SST Development	Professor
Iqbal Husain	NCSU/FREEDM	SST Development	Professor
Ken Dulaney	NCSU/FREEDM	Tech Transfer	Insutrdy Director
Heather Brutz	NCSU/NCCETC	Lead/Cost Analysis	Clean Transportation Finance and Operations Manager
Lisa Poger	NCSU/NCCETC	Cost Analysis Team	Senior Clean Transportation Specialist
Brian Lips	NCSU/NCCETC	Cost Analysis Team	
Richard Sapienza	NCSU/NCCETC	Cost Analysis Team	Director, Clean Transportation Program
Autumn Proudlove	NCSU/NCCETC	Cost Analysis Team	Senior Policy Program Director
Isaksson Dan	Danfoss	Lead/SST Development	Head of Medium Voltage Drives,
Stefan Schroeder	Danfoss	SST Development	Chief-Engineer for MV Drives
Marko Laitinen	Danfoss	SST Development	HW Development manager
Joseph Rowny Jr.	Danfoss	SST Development	Engineering Manager
Alan Ettlinger	NYPA	Lead/ Demo Partner	Director, Research, Tech Dev and Innovation
Greg Pedrick	NYPA	Demo Partner	Senior RTD&I Engineer I,
Aleksandar Vukojevic	ComEd	Lead/ Demo Partner	Senior Manager, Smart Grid
Dino Lelic	ComEd	Demo Partner	Distribution Planning, Smart Grid & Innovation
Patrick Stephens	GoTriangle	Lead/ Demo Partner	Director
Vinson Hines	GoTriangle	Demo Partner	Asst director at GT
Brian McLean	GoTriangle	Demo Partner	Maintenance Manager

DOE Team

- Adrienne Riggi, Program Manager
- Fernando Salcedo, Program Manager
- Steven Boyd, Program Manager
- Lee Slezak, Program Manager
- Andrew Meintz
- Shane Buchanan, Contract Specialist

Timeline

Development

BP1

Cost Analysis, Cost of Ownership Targets & Initial Prototyping

4/22 - 4/23

Optimization

BP2

System Optimization & Finalized Power Cell Design

4/23 - 4/24

Integration

BP3

System Packaging, Reliability & Standards Testing

4/24 - 4/25

Deployment

BP4

Demons tration

4/25 - 4/26

BP: Budget Period

Project Summary

1. Cost Analysis, BOM, Cost of Ownership Targets and Initial Prototyping
2. System Optimization and Finalized Power Cell Design
3. System Packaging, Reliability, and Standards Testing
4. System Demonstration

Ultra-low Cost, All-SiC Modular Power Converters for DC Fast Charging Equipment Connected Directly to Medium Voltage Distribution System

Phase 1: Year 1, Year 2, Year 3 (Q1 Q2 Q3 Q4 each); Phase 2: Year 4 (Q1 Q2 Q3 Q4)

SOPO Task#				Task #	Task Description
				1	**Project Management**
1.1				1.1	Project Kickoff Meeting
				1.2	PMP Development
1.1	2.1			2	**System Design to Meet Total Cost of Ownership Targets**
1.1.1				2.1	SST Simulation and Analysis for Modularity and Scalability
1.1.2				2.2	BOM Cost
1.1.3				2.3	Reliability Analysis
1.1.4	2.1.1			2.4	Total Cost of Ownership Analysis
				M2.1	TCO Report showing 50% cost reduction vs baseline
1.2	2.2			3	**System Design**
1.2.1	2.2.1			3.1	Power Cell Design and Evaluation
1.2.2	2.2.2	3.1		3.2	System Level Mechanical Design
1.2.3	2.2.3			3.3	Medium Frequency Transformer Design
1.2.4	2.2.4	3.2		3.4	Firmware Development and Testing
1.2.5	2.2.5	3.3		3.5	Design for Safety and Applicable Standard
				M3.1	Power Cell Meets Performance Targets
		3.4		4	**System Performance Evaluation**
1.2.6	2.3			4.1	Transformer Testing
1.2.7	2.4			4.2	Power Cell Testing
	2.5	3.4.1		4.3	SST Performance Evaluation
	2.6	3.5		4.4	EVSE Communication and Control
				M4.1	System Meets Performance Targets
1.3	2.7	3.6		5	**Outreach Initiatives**
1.3.1	2.7.1	3.6.1		5.1	Summer Research Internships
1.3.2	2.8	3.7		5.2	Design of EVSE of the Future
				M5.1	Measurable Goals for SRIU/SBP Cohort Met
		3.8		6	**Technology Transfer and Planning**
		3.8.1		6.1	List of Potential Licensees and Competitors
		3.9		6.2	Identify Highest Impact Markets
				M6.1	Report Detailing findings
			4.1	7	**System Commissioning and Testing**
			4.1.1	7.1	System Commissioning and Testing
				M7.1	SST-based EVSEs operational in the field

NCSU Task | Team Task | Milestone

Go/No-Go Milestones

Title	Budget Period	Description
TCO Report defines cost/performance targets	Budget Period 1	SST-based EVSE cost analysis showing ≥50% cost reduction over the baseline system; TCO analysis specifying cost/performance targets and optimal product insertion points into the marketplace complete
Power cell meets performance targets	Budget Period 2	Power cell meets performance targets, including meeting the EMI limits, efficiency target of >98%, bidirectional power flow, and black-start capability. SST BOM meets cost targets
SST-based EVSE meets performance targets	Budget Period 3	SST-based EVSE meets performance targets, including EMI limits and efficiency target of >98%; demonstration sites identified.

BP1

Cost Analysis, BOM, Cost of Ownership Targets and Initial Prototyping: The Recipient will design the low-cost power cell that stacks to make up the SST-based EVSE, determine the cost targets for each power cell subsystem, and iterate the power cell design until the cost targets are met. The Recipient will also investigate the system reliability and set redundancy targets to meet reliability goals. The Recipient will conduct a total cost of ownership analysis, with input from industry stakeholders and project demonstration partners. An initial prototype of the transformer, the power cell, system level mechanical assembly, and system level control firmware will be developed, and the Diversity, Equity, and Inclusion Plan will be launched.

Milestone	Type	Description
SST simulation and analysis for modularity and system scalability	Technical	Demonstrate efficiency, meeting the target of ≥98%; BOM target costs ≤$90,000
Bill of materials (BOM) cost analysis	Technical	Sub-system cost targets validated to meet the BOM cost ≤$90,000
TCO analysis	Technical	Quantify TCO and identify use cases where the MV solution outperforms the LV solution
Outreach initiatives	Diversity	Launch SRIU and SBP programs
TCO Report	Go/No Go	SST-based EVSE cost analysis showing ≥50% cost reduction over the baseline system; TCO analysis specifying cost/performance targets and optimal product insertion points into the marketplace complete

BP2

System Optimization and Finalized Power Cell Design: The Recipient will finalize the design of the low-cost power cell that stacks to make up the SST-based EVSE and meet cost and performance targets, including testing benchmarks. The Recipient will develop and finalize the design of the power cell, the system-level mechanical design, and the system firmware as well as demonstrate a power cell charging an electric vehicle or vehicle emulator. The Recipient will finalize the total cost of ownership analysis, with input from industry stakeholders and project demonstration partners.

Milestone	Type	Description
Power cell design and evaluation	Technical	Final design of power cell meets cost of ≤$3,900, efficiency >98%, and power density of ≥3kW/L
Transformer Testing	Technical	Transformer passes IEEE C57.12.01TM standard tests and meets cost targets
Power Cell testing	Technical	Power cell meets performance targets, including EMI limits, efficiency of >98%, and power density target ≥3kW/L
Outreach initiatives	Diversity	Administer SRIU and SBP programs
Go/No Go Decision	Go/No Go	Power cell meets performance targets, including meeting the EMI limits, efficiency target of >98%, bidirectional power flow, and black-start capability. SST BOM meets cost targets

BP3

System Packaging, Reliability, and Standards Testing: The Recipient will finalize the design of the SST-based EVSE and packaging the power cells. The SST-based EVSE will be tested against all relevant standards and sites for system demonstrations will be identified.

Milestone	Type	Description
3.2 System level mechanical design	Technical	Final SST racked, tested, and meeting performance targets (cost ≤$90,000, efficiency >98%, and power density ≥3kW/L.)
4.4 EVSE dispenser communication and control development	Technical	Demonstration of complete SST charging an electric vehicle or vehicle emulator; system passes all safety tests and is ready for deployment
5.1 Outreach initiatives	Diversity	Administer SRIU and SBP programs
5.2 Design of the EVSE of the future	Diversity	Thematic focus of SRIU and SBP programs
Go/No Go Decision	Go/No Go	SST-based EVSE meets performance targets, including EMI limits and efficiency target of >98%; demonstration sites identified.

BP4

Demonstration: The Recipient will test the unit against a test plan generated from the review of the standards.

Milestone	Type	Description
System commissioning and testing	Technical	Ship, install, test, and commission EVSE system at partner sites
Outreach initiatives	Diversity	Administer SRIU and SBP programs
Design of the EVSE of the future	Diversity	Thematic focus of SRIU and SBP programs
Operational in Field and tested	Technical	SST-based EVSEs operational in the field

Budget Period 1: Cost Analysis, BOM, Cost of Ownership Targets and Initial Prototyping

					Ultra-low Cost, All-SiC Modular Power Converters for DC Fast Charging Equipment Connected Directly to Medium Voltage Distribution System	Phase 1												Phase 2			
						Year 1				Year 2				Year 3				Year 4			
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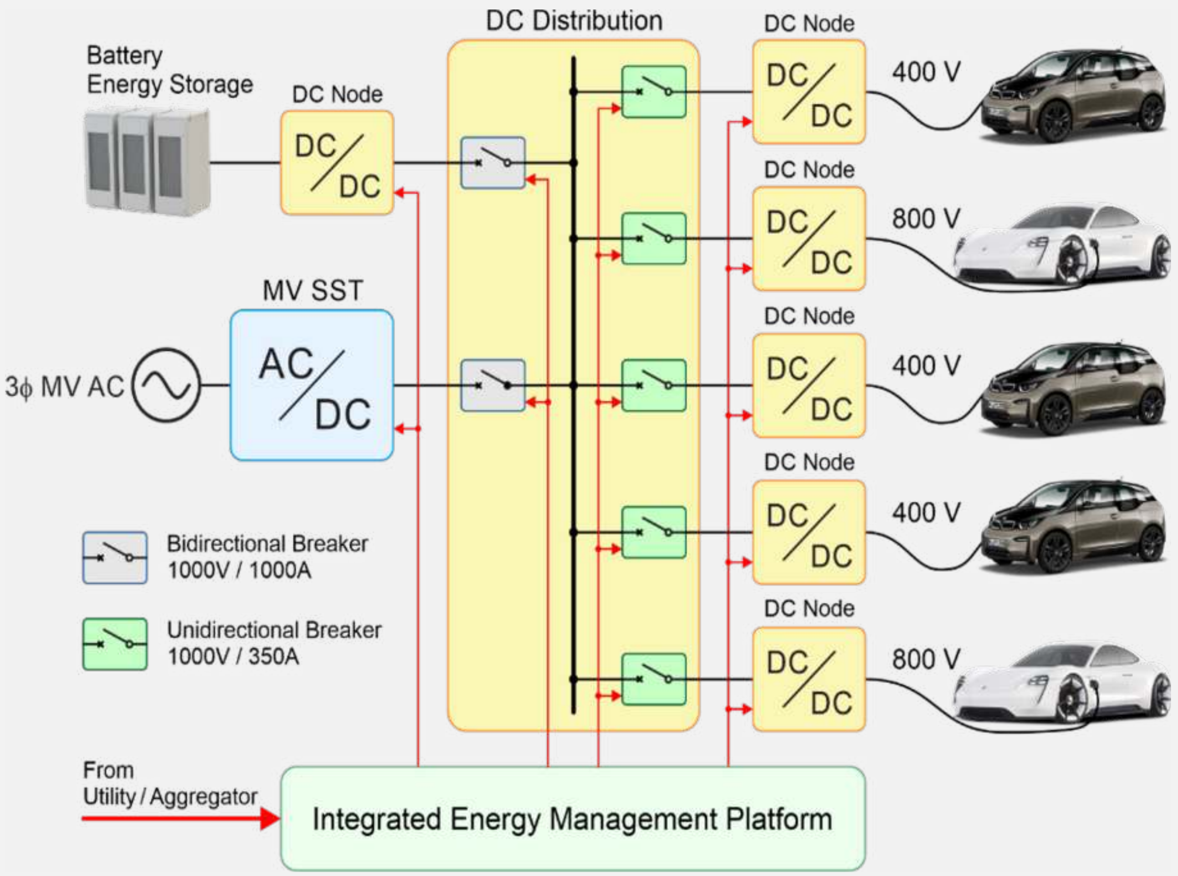
Baseline EVSE Design

Result of DE-EE0008450*:

- Shared bi-directional Solid State Transformer (SST) connecting directly to the medium voltage (MV) distribution system
- DC distribution network with solid-state DC protection
- Energy management platform
- Head-ends for local isolation and DC/DC conversion



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Baseline EVSE Design

Proof of Concept: Highly Flexible Design
Not Optimized for Cost

NCSU 1MVA SST

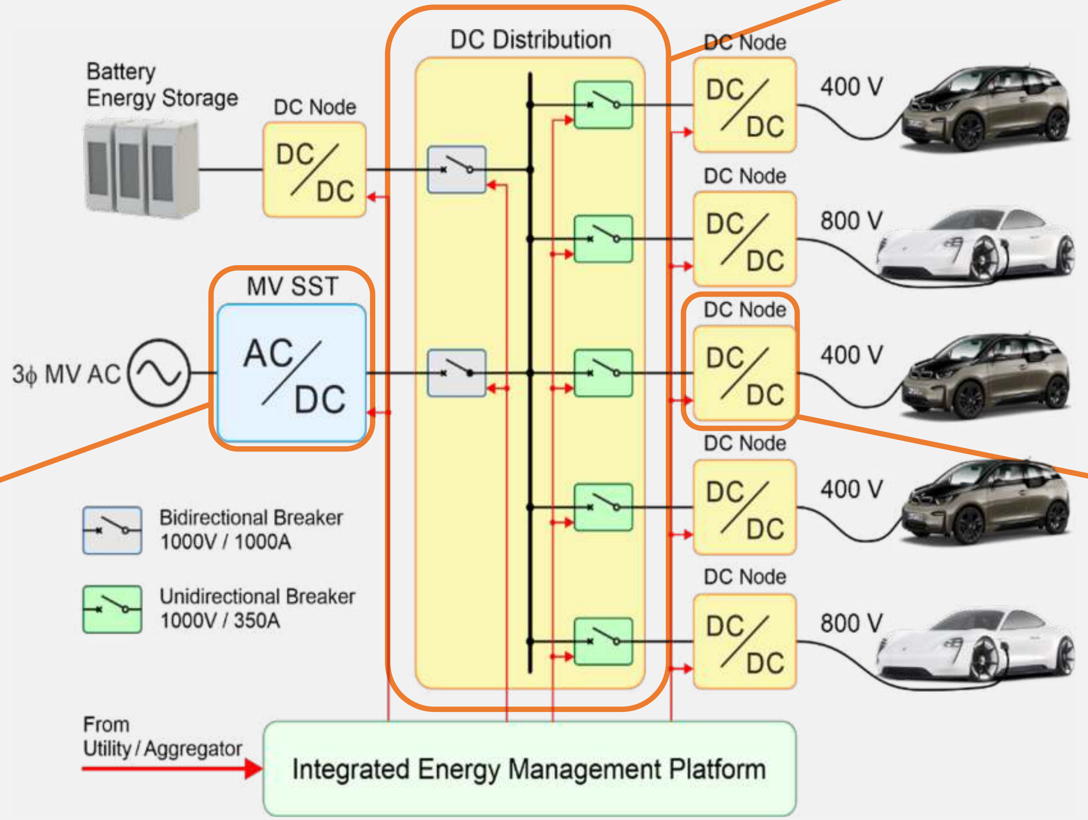


ABB Switchgear

COTS Isolated DC/DC

Approach to Cost Reduction Over Baseline System

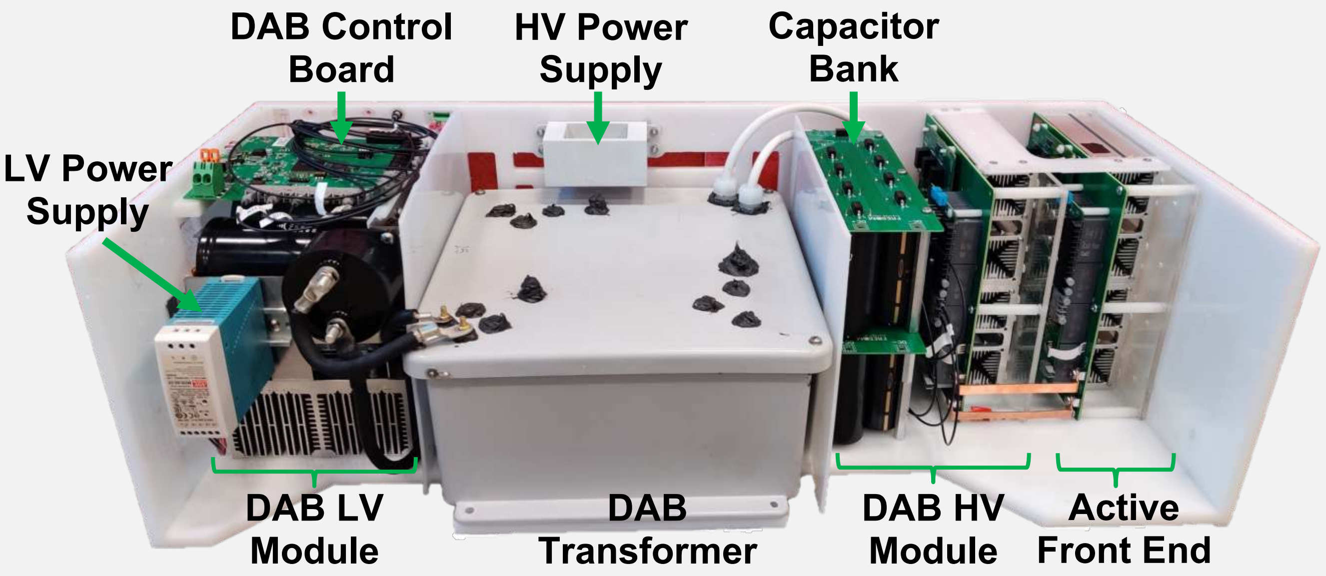
- Driven by Total Cost of Ownership Analysis
- Main focus: minimize the cost of SST and integrate functionality to reduce the cost of the balance of system
  - Minimize cost of DC protection (at the expense of flexibility/speed of response)
  - Minimize cost of DC nodes by providing galvanic isolation from the SST (at the expense of flexibility, but potentially with higher efficiency)
  - Minimize SST BOM by moving to lower cost TO 247 devices and using high volume components cost-optimized in other applications
  - Minimize Power Cell cost through design for manufacturing optimization

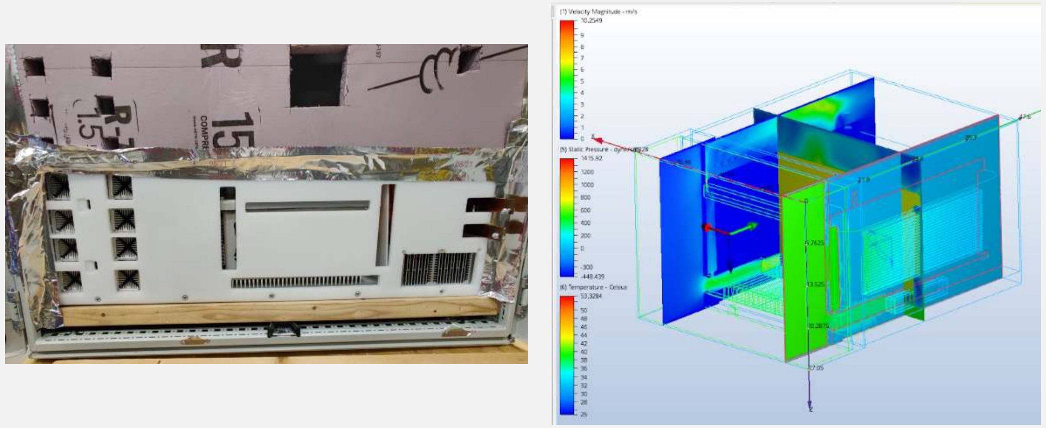
Baseline Prototype

- System made of 21 identical modules, each rated at 57kW
- Each L-N phase made of 7 modules in a single rack
- SST dimensions 1x1.5x2m (3,000L)
- Weight is approximately 2,000kg
- Peak Efficiency 97.9%

SST Module Design

- 1MVA SST single module built and tested
- Module rated at 57kW to deliver 1MW from 18 modules (3 spares)
- Cabinet level thermal test and computational fluid dynamics (CFD) simulation validate the system cooling performance

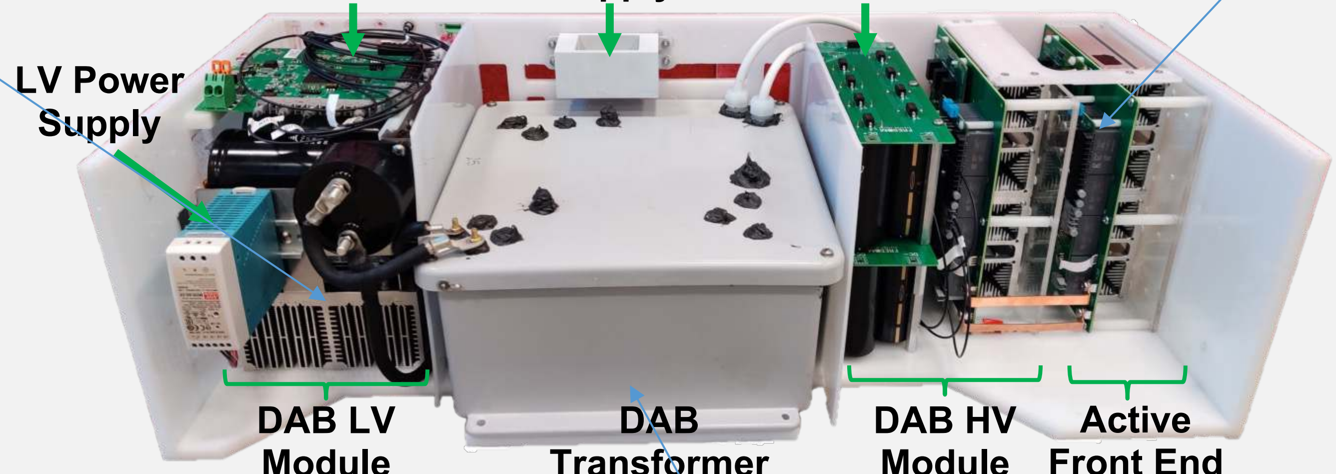




Module thermal test with cabinet cooling, and CFD simulation to identify equivalent flow resistance

New SST Module Design

Eliminate use of expensive SiC modules

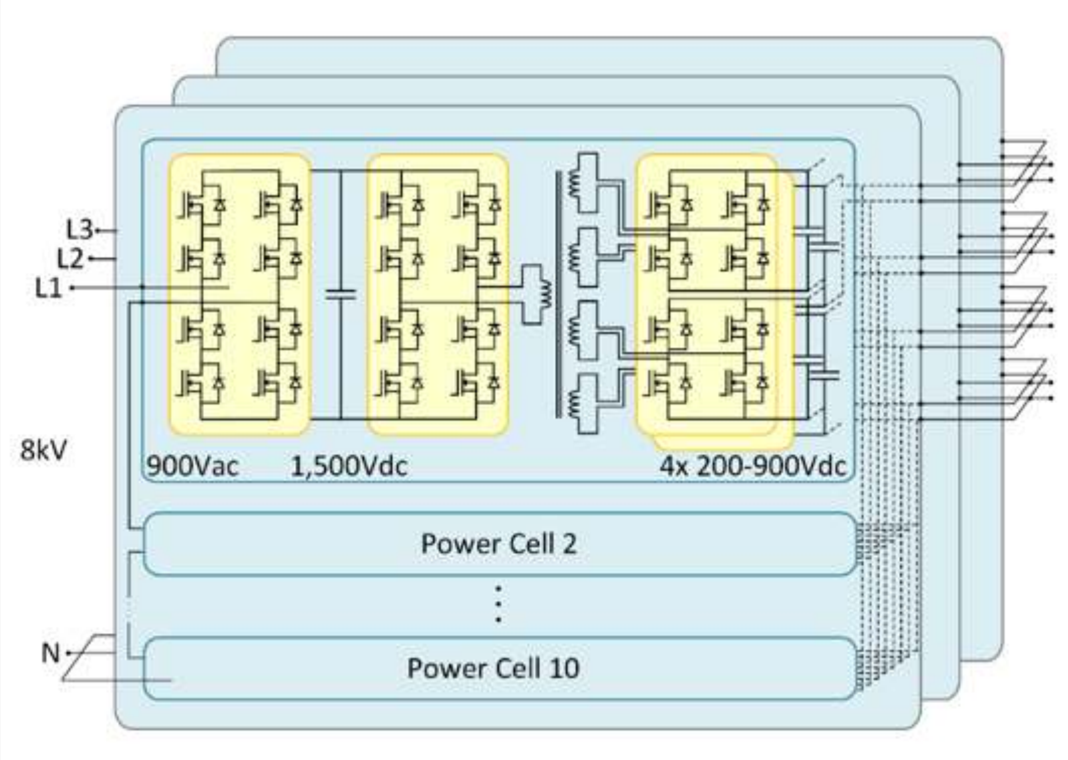


Adopt use of low-cost TO-247 SiC devices throughout the system

Revert to dry-type transformer design while addressing partial discharge issues faced in earlier designs

Proposed SST Topology

- Proposed SST-based EVSE design provides 4 independent outputs delivering 200-900V at up to 350kW each.
- Sub-module design relies on H8 topology on high voltage side
- Each power stage will use the same device/cooling construction resulting in economies of scale and simplified mechanical assembly.



Comparison of the Proposed SST to Baseline SST

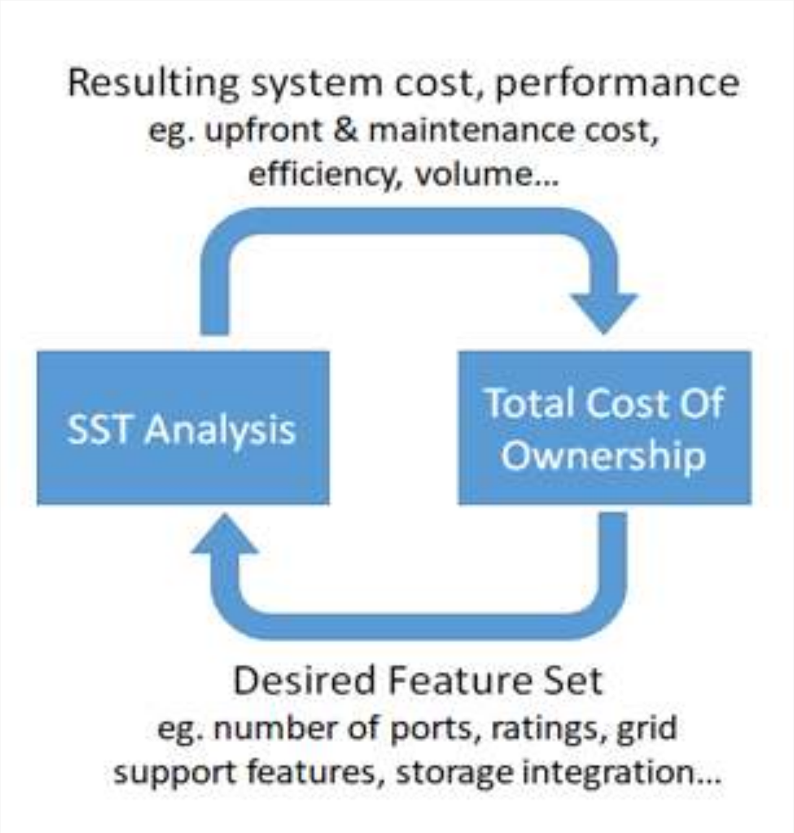
Metric	Baseline	Proposed	Comments
Input Power/Voltage	1MVA at 13.2kV	1MVA at 13.2kV	Short-term goal is $90,000; long-term goal is under $50,000
Output Power/Voltage	1,000kW at 750Vdc bus	4 x 200-900Vdc at 300kW or 2 x 400-1800Vdc at 600kW	New system will feature four galvanically isolated ports
SST Volume	2200L	400L	Our existing design of DC/DC stage for this application reaches 6kW/L
Power Cell kW/L	0.5kW/L	3kW/L	
Devices Used	SiC TO-247 and SiC Modules	SiC TO-247 Exclusively	Leads to significant cost reduction
System Efficiency	98%	98%	No penalty at reduced cost
BOM Cost for 1MVA System	$230,000	<$90,000	Short-term goal is $90,000; long-term goal is under $50,000

Cost Comparison of the Proposed SST to Baseline SST

Baseline System		New System		Cost Reduction Strategy
Items	**Price**	**Items**	**Price**	
AFE	$2,462	AFE	$950	Cost estimate based on H8 and DC/DC design
DABHV	$2,462	DABHV	$950	
DABLV	$3,898	DABLV	$950	
Sensors	$2,019	Sensors	$500	Use fewer & lower cost sensors
Transformer	$4,200	Transformer	$500	Cost estimate based on raw material cost
Fiber optic cables	$131	Fiber optic cables	$50	Use lower cost isolators
Total for 1 module	$15,173	Total for 1 module	$3,900	
Total for 21 modules	$318,624	Total for 30 modules	$117,000	
Enclosure	$7,124	Enclosure	$7,000	
Central Control Board	$3,725	Central Control Board	$2,500	Use distributed control
Total cost for 1MW XFC	**$329,473**	**Total cost for 1MW XFC**	**$126,500**	
Mass production cost	$230,631	Mass production cost	$88,550	Assumes 70% of single unit cost

EVSE Optimization Through TCO Optimization

- Determine relative costs between the medium voltage extreme fast charger and a conventional approach.
- Quantify capital, operating costs over the lifespan including: capital or initial costs; installation, including land purchase requirements; total energy consumption for an assumed power level, EVSE efficiency and vehicle use case; revenue from ancillary services; reliability; and future expansion costs.
- Document difference in components and installation procedures and labor needed for future upgrades and expansions for the two systems.
- Document needs and technology solutions targeting underserved communities.
- Create a series of total cost of ownership models based on considered variables.
  - Costs will vary across utility territories and geographic regions.
  - Target is to identify the scenarios where the extreme fast charger is most financially viable.



Iterative Process Defining the Optimal SST Design Using the Total Cost of Ownership Analysis

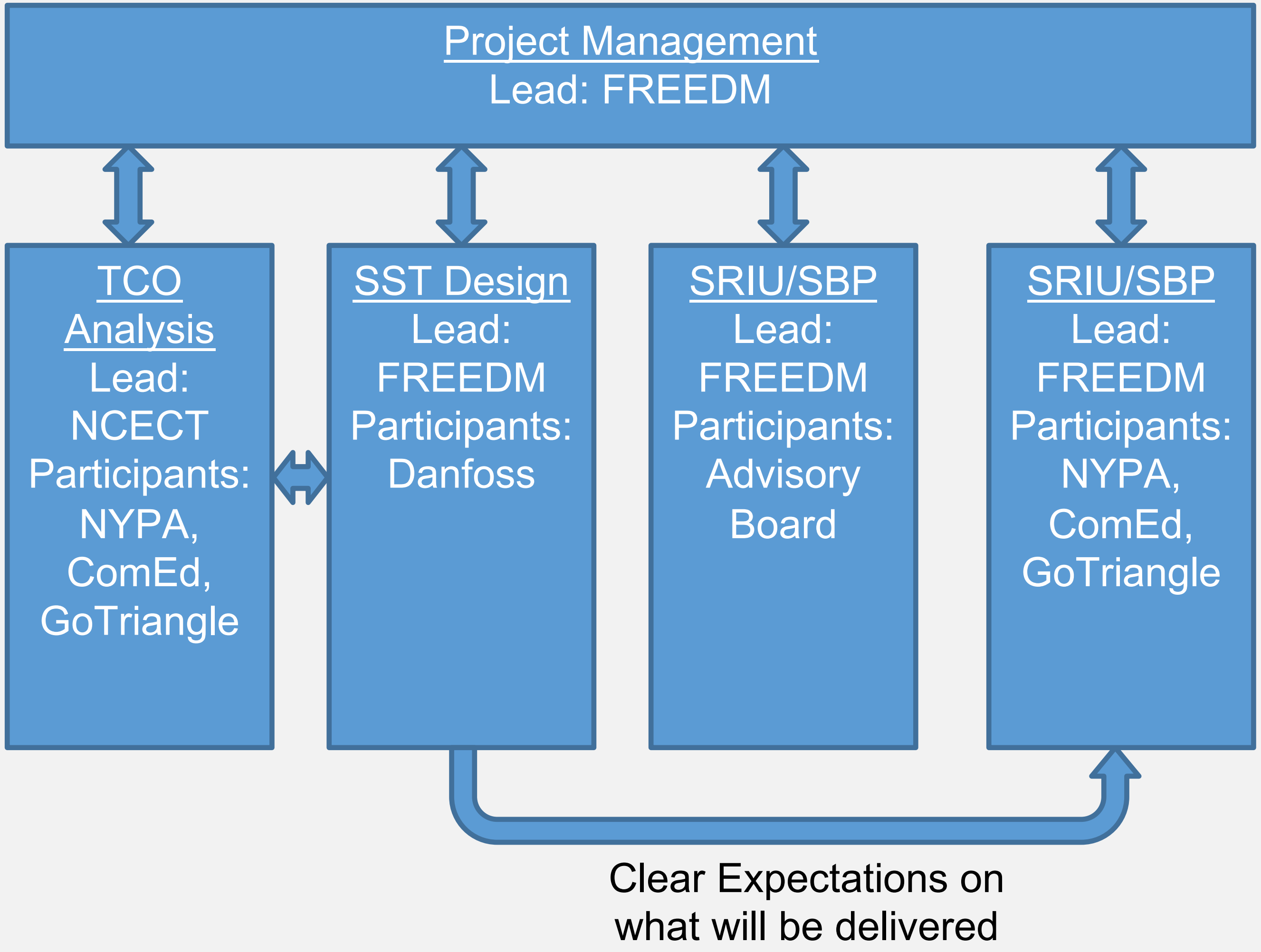
Workforce Development

- At NCSU, expect to engage 16 PhDs and 10 Undergrads in the project.
- Builds on successful track record: currently 2 PhDs from FREEDM are doing internships at Danfoss and one participant DE-EE0008450 in is now a Danfoss employee.
- Establish Summer Research Internship for Undergraduates (SRIU) and Summer Bridge Programs (SBP);
  - SRIU will be open to NCSU and undergrads from minority serving institutions that participate in the SPB program
  - Participants will create EVSE adaptations for people with disabilities that are Americans with Disabilities Act (ADA) compliant.

Project Management

In BP1, focus on Total Cost of Ownership Analysis:

- Quarterly Team Meetings
- Weekly Total Cost of Ownership Meetings
- Weekly SST Development Meetings



Technology Transfer Plan

- NCSU plans to follow multiple paths to market for the MV SST Technology licensing and startup formation.
- Plan to protect the Intellectual Property though Patent filings working with North Carolina State University’s Office of Research Commercialization (ORC).

Risks and Risk Mitigation

- SST design requires flexibility in initial stages to account for findings of TCO analysis. Mitigated by focusing on more generic and systematic challenges initially, including transformer design, protection requirements and design, and system level control.
- A reliable transformer design and manufacturing with multiple outputs and without the use of oil is a major challenge. Rely on know-how and industry connections for manufacturing from Danfoss.
- Supply chain constraints present an issue even for prototyping and cause major delays. To mitigate the issue, the team will pre-order hard to source items such as SiC MOSFEETS.
- Supply chain constraints and inflation present a risk to the overall budget. Scope of the demonstration plans may need to be reevaluated in the later stages of the project.