EVs@Scale

U.S. Department of Energy

Nov. 2024 EVs@Scale High-Power Charging Deep Dive Technical Meeting

12 November 2024

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

NREL/PR-5400-92274

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Consortium Overview and Stakeholder Engagement

Andrew Meintz

12 November 2024

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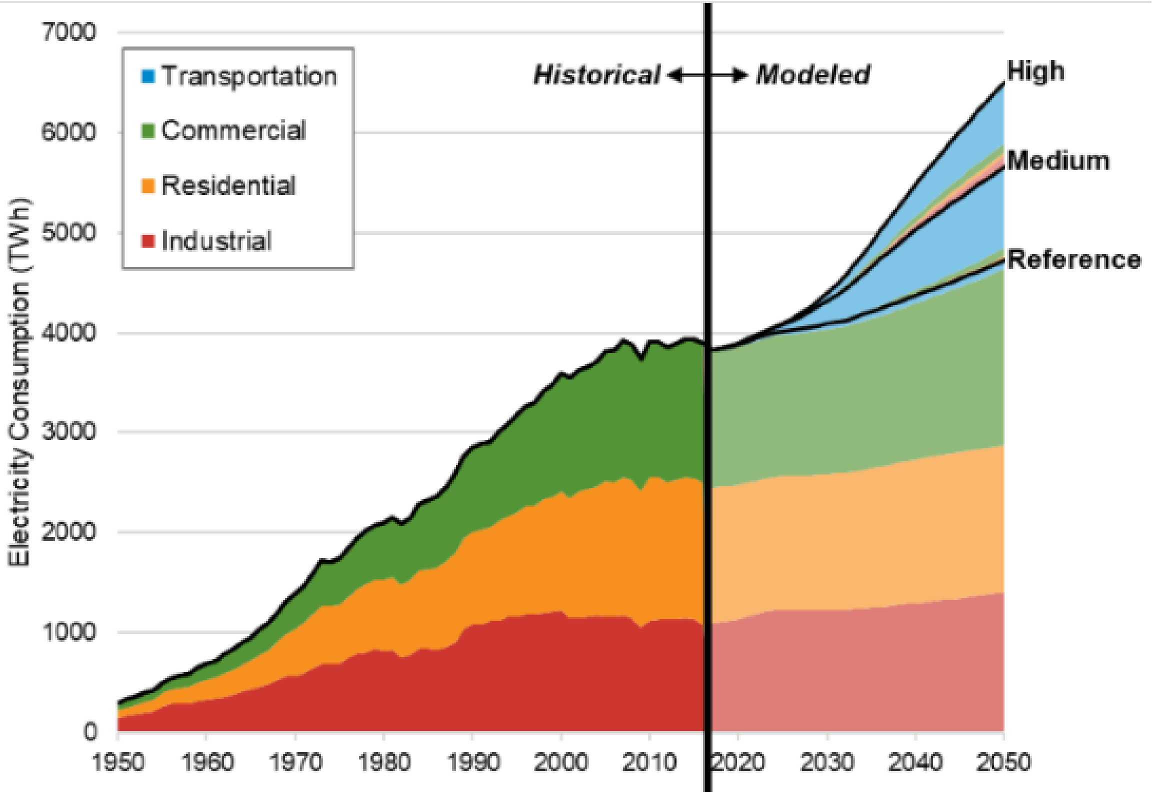
Impact of Transportation Electrification



Historical and Projected annual electricity consumption

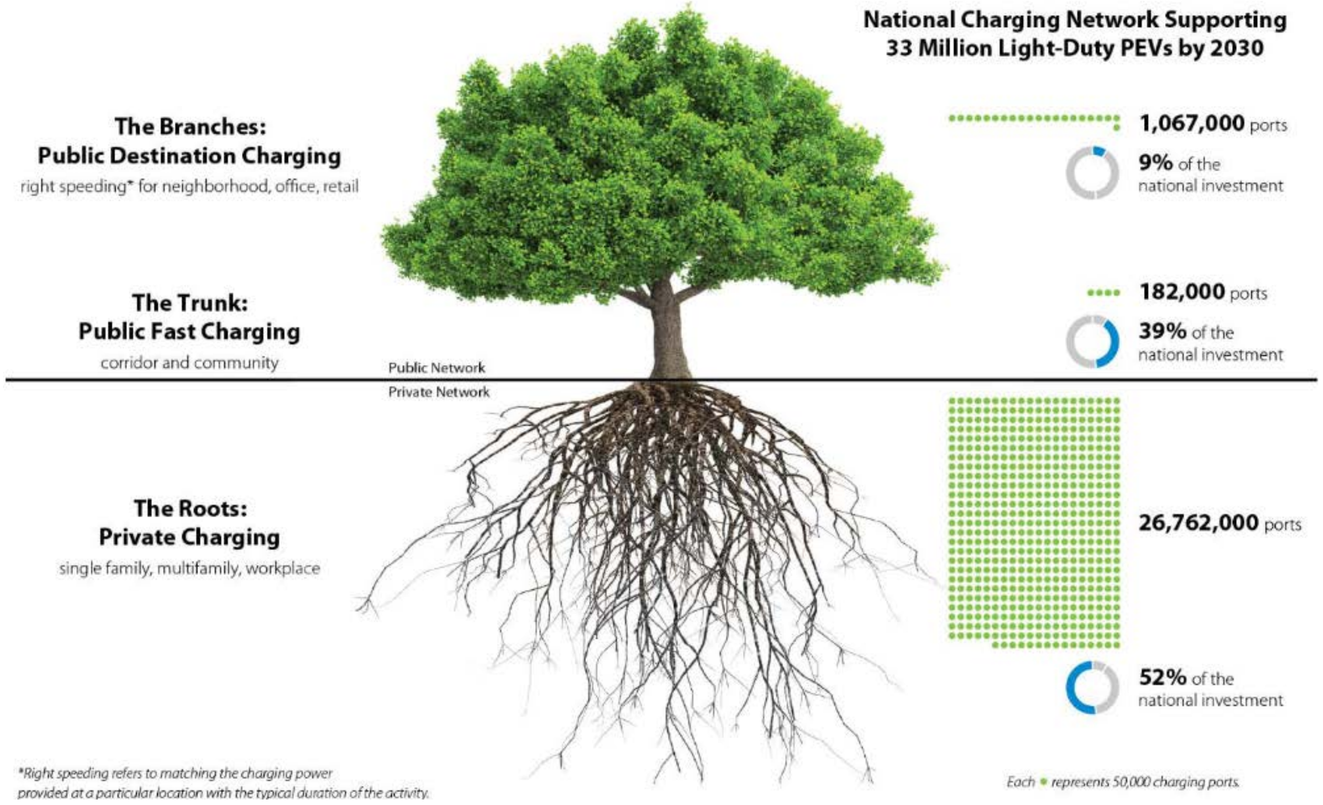
EVs@Scale Consortium RD&D will support electrification by answering:

- How will electricity generation and the transportation sectors work together?
- What research can we do to ensure a safe, smooth, and seamless transition?
- How could a grid-integrated charging network support intermittent generation?

Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States. NREL/TP-6A20-71500

Building the 2030 National Charging Network

27 million new charging ports are required which has been estimate that a $53–$127-billion cumulative national charging infrastructure investment, including $31–$55 billion for publicly accessible charging infrastructure, is necessary to support charging infrastructure needs under the baseline scenario.



The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure; NREL https://www.nrel.gov/docs/fy23osti/85654.pdf

Consortium Objectives

- **Vehicle-Grid Integration:** Achieve seamless integration and charging for EVs@Scale to enable synergistic coupling of the energy and transportation sectors.
- **Interoperability:** Advance the connectivity, compatibility, and scalability of systems and technologies operating across the interfaces of an open, standards-based EV charging ecosystem.
- **Reliability and Resiliency:** Improve the reliability of charging and enhance the ability of the electric grid to provide dependable power and robustly react and recover from adverse events
- **Cybersecurity:** Advance the cyber-physical security posture across the EV charging ecosystem.

Installation of smart charging system at NREL's Flatirons Campus (Dennis Schroeder / NREL)

Consortium Structure

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Leadership Council

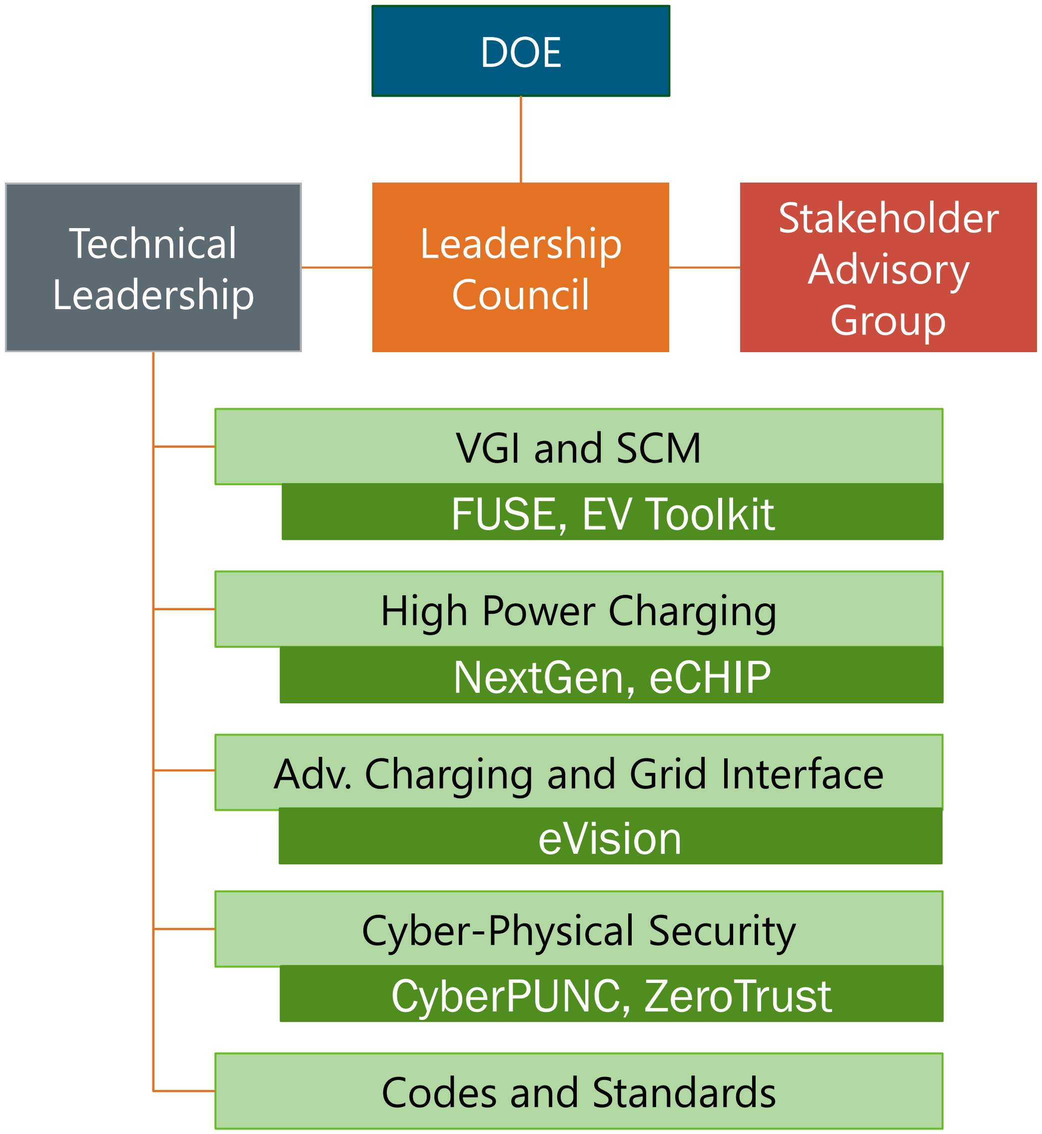
- Andrew Meintz (NREL, chair), Tim Pennington (INL, rotating co-chair), Don Stanton (ORNL), Summer Ferreira (SNL), Lori Ross (PNNL), Dan Dobrzynski (ANL), Tom Kirchsetter (LBNL)

Stakeholder Advisory Group

- Utilities, EVSE & Vehicle OEMs, CNOs, SDOs, Gov't, Infrastructure

Consortium Pillars and Technical Leadership

- Vehicle Grid Integration and Smart Charge Management (VGI/SCM): Jesse Bennett (NREL), Jason Harper (ANL)
- High Power Charging (HPC): John Kisacikoglu (NREL)
- Advanced Charging and Grid Interface Technologies (ACGIT): Madhu Chinthavali (ORNL)
- Cyber-Physical Security (CPS): Richard "Barney" Carlson (INL), Craig Rodine (SNL)
- Codes and Standards (CS): Ted Bohn (ANL)



Upcoming Stakeholder Engagement Events

We have the following upcoming stakeholder engagement events planned and will send out invites to registrants of this event for the deep-dives next week.

Fall 2024: Deep Dive Meetings

- Codes & Standards Pillar
  - October 21, 2024
- SCM&VGI Pillar
  - FUSE
  - October 31, 2024
- Cyber-Physical Security Pillar
  - CyberPunc, and ZeroTrust Projects
  - November 6, 2024
- High-Power Charging Pillar
  - NextGen Profiles and eCHIP Projects
  - November 12, 2024
- Advanced Charging and Grid Interface Tech. Pillar
  - November 19, 2024

Spring 2025: Semi-Annual Meeting

- Sandia will host in Albuquerque, NM
- Late March or early April

Thanks for attending!

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EVs@Scale High-Power Charging (HPC) Pillar Deep-Dive Technical Meeting

John Kisacikoglu, NREL

November 12, 2024

Introduction and Overview of High-Power Charging Pillar

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EVs@Scale Lab Consortium addressing challenges, developing solutions and enabling technologies for transportation electrification ecosystem

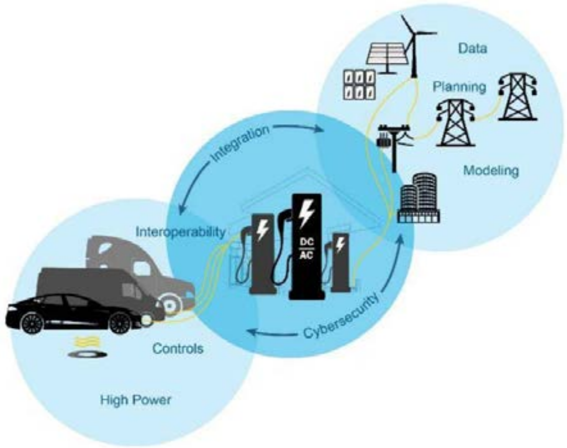
High-Power Charging: Bring together hardware and software expertise, capabilities, and facilities related to high power EV charging, charge management and grid integration

Deep-dive technical meetings providing opportunity for more industry engagement and technical feedback

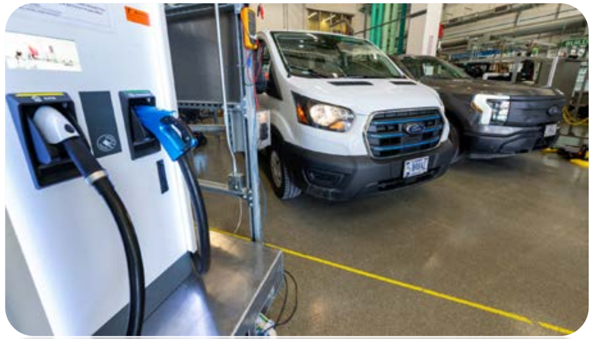
Industry partnership is key for success.

High-Power Charging Pillar has two projects:

- Next-Gen Profiles (NGP)
- High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP)



The EVs @ Scale Lab Consortium will consider these key components of the transportation electrification ecosystem



Next-Gen Profiles (NGP) – Project Overview

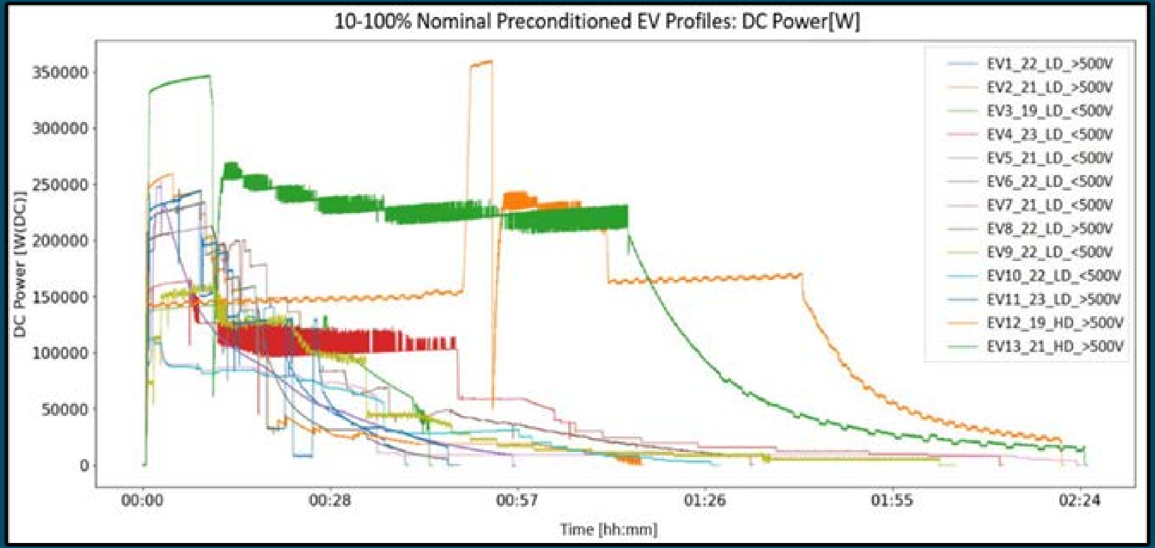
Objective: Assess a portfolio of EVs, EVSEs, and Fleets that are expected to utilize High Power Charging (>200kW) to understand charging rates, time, grid impacts, and asset utilization. Provide DOE, project partners, stakeholders, and the public with insight into the capability of HPC and performance of today's charging infrastructure.

NGP PI: Sam Thurston: sthurston@anl.gov

Outcomes:

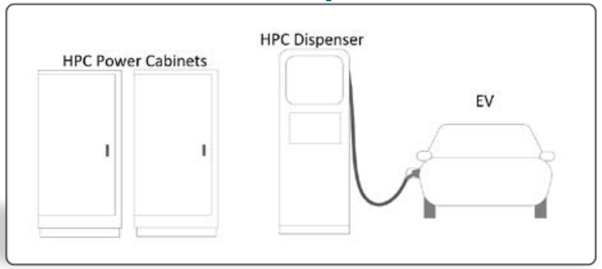
- Assessment of assets under Nominal & Off-nominal conditions
- Assessment of conductive vs non-conductive systems
- Assessment of EV/EVSE fleet utilization & performance
- System responses to grid disturbances & charging management
- Unique & thoughtful methods of performance characterization
- Collaboration with OEMs & industry for:
  - Procedures development
  - Testing Assets
  - Report feedback

EV Profile Capture: 10-100% Nominal Preconditioned DC Power[W]



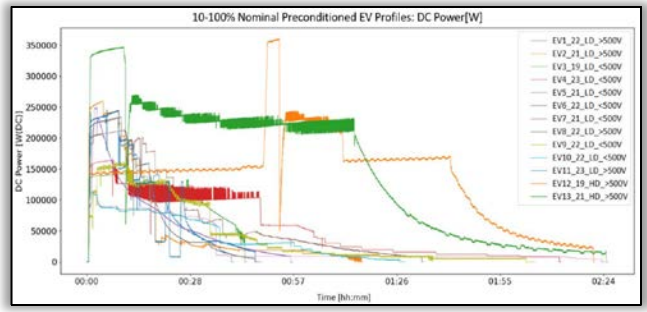
Next-Gen Profiles – Three Focus Areas

1. EV Profile Capture

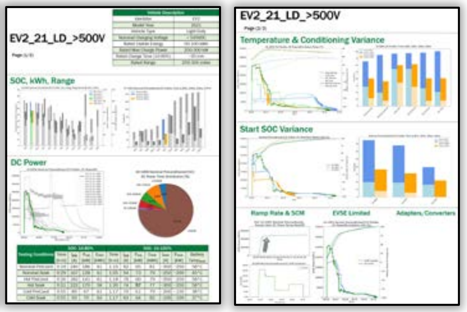


- **Assets**: Production EVSEs, Production EVs
- **Conditions:** SOC, Batt Temp, Vehicle Cond
- **Edge Cases:** Power/voltage limited, SCM, Adapters, WPT
- **Cadence:** 10Hz data, lab collected & processed

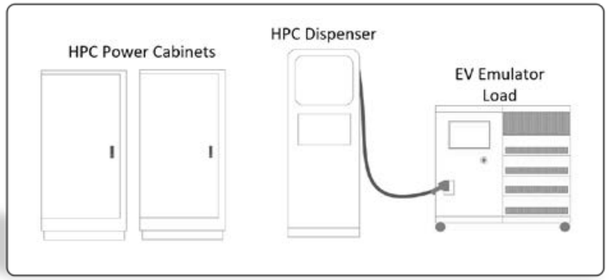
EVs Charge Profile



EV Boundary Condition Analysis

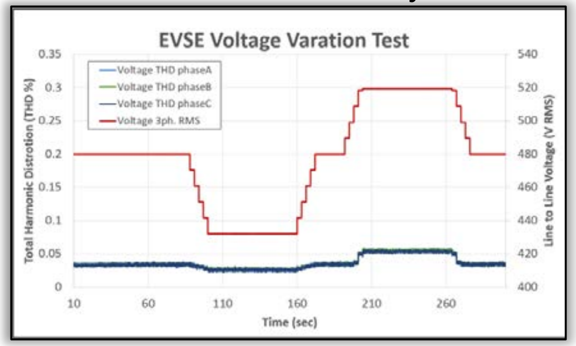


2. EVSE Characterization

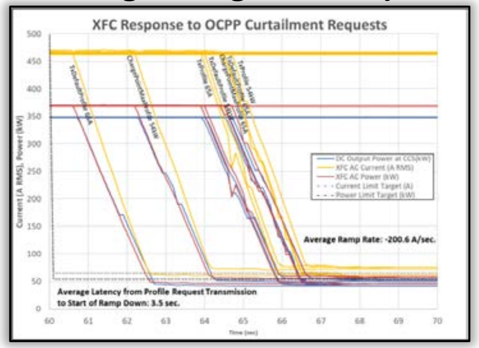


- **Assets**: Production EVSEs, Emulated EVs
- **Conditions**: Voltage, Current, Ambient temperature, Grid supply
- **Edge Cases:** Voltage deviation, Frequency deviation, Harmonics injection, High utilization, V2X, SCM
- **Cadence:** 10Hz data, lab collected & processed

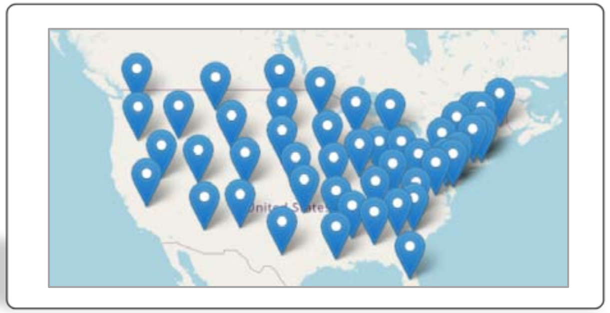
Grid Disturbance Analysis



Charge Management Analysis

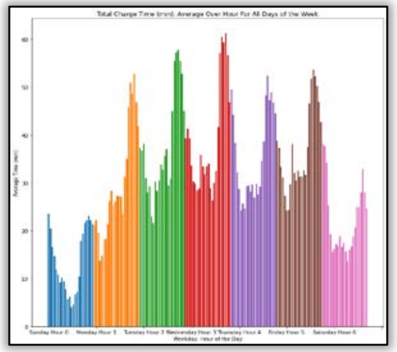


3. Fleet Utilization Analysis

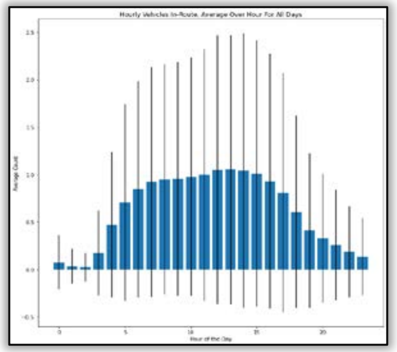


- **Assets**: Production EV and/or EVSE Fleet
- **Analysis**: Fleet description, Meta-data,
- **Time-series Categories:** Charging, Routing, Other
- **Cadence:** 1-minute data, fleet collected & lab processed in post
- **Analysis Types:** Hourly, Daily, Weekly, yearly, Totals and Averages

Weekly Charge Time Average



Daily In-Route Time Average



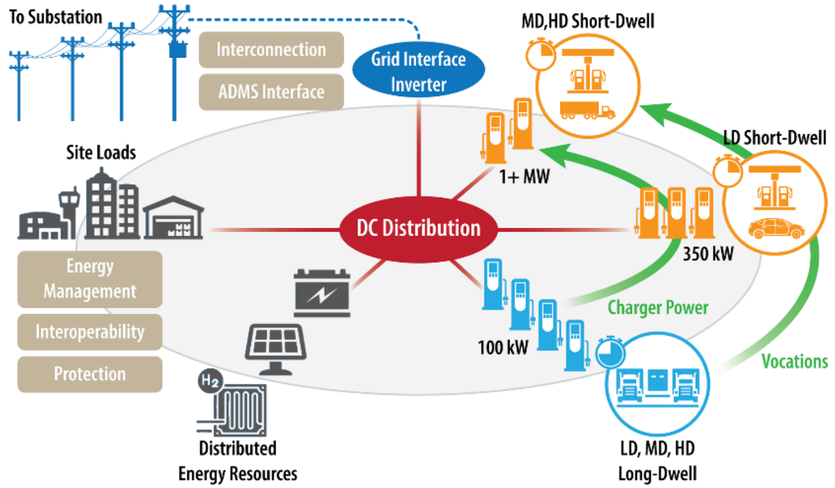
eCHIP – Project Overview

High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP)

Objective: Develop plug-and-play solution allowing charging site to organically grow with additional chargers and DERs through predefined compatibility with standards that will ensure interoperability

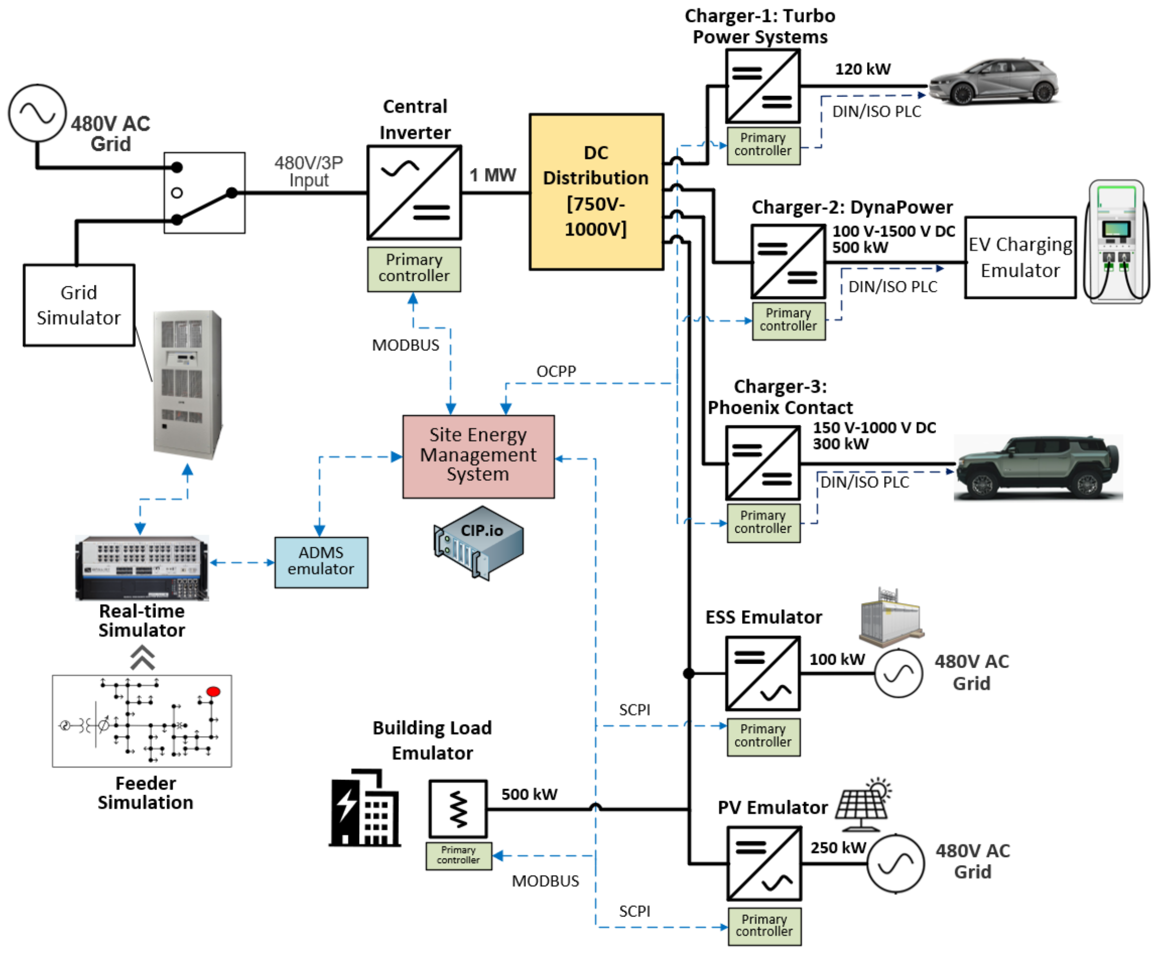
Outcomes:

- Determine interoperable and scalable hardware, communication, and control architectures for high-power charging facilities
- Broadly identify limitations and gaps in DC distribution and protection systems that allow for modular HPC systems
- Develop and demonstrate solutions for efficient, low-cost, and high-power-density DC-DC for kW- and MW-scale charging

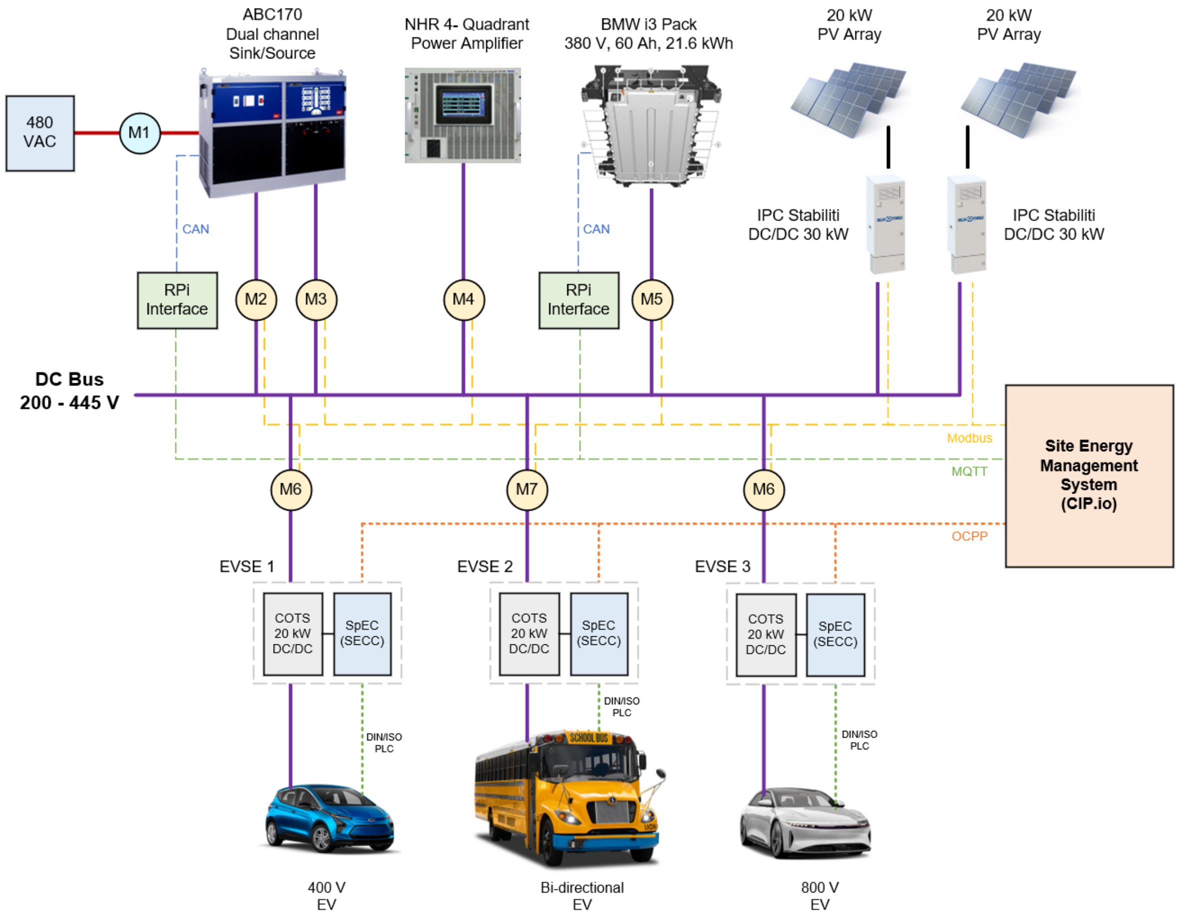


eCHIP PI: John Kisacikoglu: john.kisacikoglu@nrel.gov

DC Charging Hub Overview



NREL

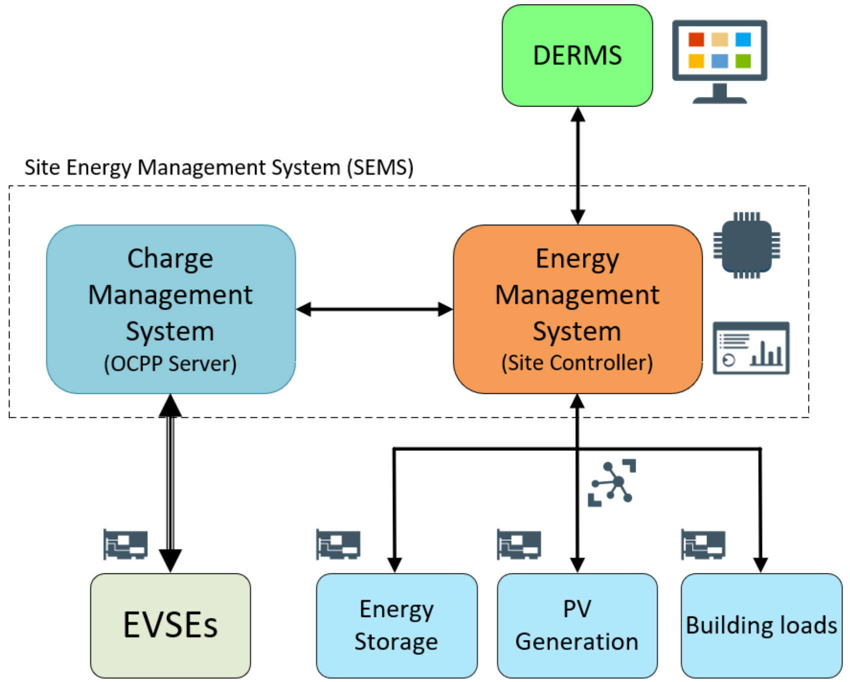


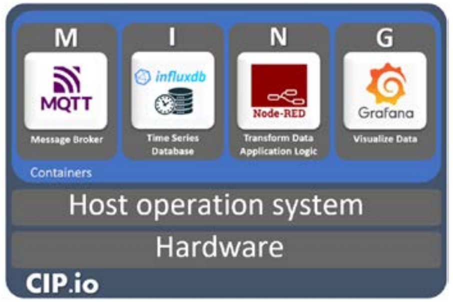
Argonne NATIONAL LABORATORY

Site Energy Management System (SEMS) Platform

SEMS platform is developed by Argonne and NREL

- **Real-time monitoring and control of DC hub**
- **OCPP 1.6J and 2.0.1 for EV charging**
- **MQTT for non-standardized DC hub integration monitoring and control**
- **Controllers will handle communication for DC chargers and EV**
  - SpEC module, Vector, Pionix, Raspberry Pi, etc.
- **Custom site-control applications are created in Node-RED, Python and C/C++**





https://github.com/Argonne-National-Laboratory/CIP.io

Publications

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Technical Reports:

[1] R. Carlson, O. Onar, “EVSE Characterization, A Next-Gen Profiles Project Report,” INL/RPT-24-76181-Rev000, INL, 2023

[2] L. Wells, S. Thurston, “EVs@Scale Next-Gen Profiles - Fleet Utilization 2023,” ANL/TAPS-24/2, ANL, 2023

[3] K. Davidson, N. Kogalur, I. Tolbert, E. Watt, A. Meintz, “EVs@Scale NextGen Profiles: High Level Analysis and Procedures Report,” NREL/TP-5400-88898, NREL, 2024

[4] S. Thurston, L. Wells, “EVs@Scale Next-Gen Profiles - EV Profile Capture 2023,” ANL/TAPS-24/1, ANL, 2024

[5] J. Kisacikoglu, et al. “High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP): Design Guidelines and Specifications for DC Distribution-Based Charging Hub,” NREL/TP-5400-86326, NREL, 2024

Conference Papers:

[1] M. S. U. Khan, et al. "Development of a DC distribution testbed for high-power EV charging," IEEE Energy Conversion Congr. Expo. (ECCE), Oct. 2023

[2] E. Ucer, et al. “Controller Hardware-in-the-loop Modeling and Operation of a High-power DC Charging Hub,” ECCE, Oct. 2023

[3] E. Ucer, et al. “Hybrid Energy Management with Real-Time Control of a High-Power EV Charging Site,” ECCE, Oct. 2024,

[4] D. Jackson, E. Ucer, M. J. Kisacikoglu, and A. Thurlbeck “A Comparison of AC and DC Distribution Architectures for EV High Power Charging Facilities,” ECCE, Oct. 2024

bitly

https://bit.ly/3AGaK1V

Publications, Coming Soon

Technical Reports:

- **NGP:** Updated Results on EVSE Characterizations; Additional EV characterizations with new vehicles.
- **eCHIP:** Site Energy Management System Platform Development

Partnership Opportunities - eCHIP

- **Site Operators**
  - Fleet, depot, port operators interested in looking DC hub operations and providing operational data
- **Site Energy Management System Developers**
  - SEMS or building energy management system developers
  - Developing SEMS platforms and integrate solutions in the field
- **Hardware Integration for EVSE and Site**
  - Power electronics hardware developers to integrate our control solutions to your hardware.
  - Implementing MCS solutions
  - Implementing site integration and connectivity
- **DC Microgrid and DC as a service**
  - DC microgrid and DC as a service field implementations
- **Automotive Sector Opportunities**
  - Implementation of bidirectional power transfer

Interested in partnering with us?

Contact eCHIP PI: John Kisacikoglu, NREL

John.Kisacikoglu@nrel.gov

Partnership Opportunities - NGP

- **EV Profiles: High power EV/EVSE**
  - HPC (150-400kW) EVSE & EVs
  - Megawatt-level (800-1000kW+) EVSE & EVs
- **EVSE Characterization: High power and/or Bi-directional EV charging infrastructure**
  - EV emulator capable of high-power charging up to 400kW (500A max., 920V DC max.)
  - EV emulator capable of CCS-1 bi-directional charging up to 120kW using ISO 15118-2 (2015)
- **Fleet telematics data**
  - Looking to add another fleet to our portfolio, granting access to data portal for NGP specific analysis
- **Data Analysis**
  - Lots of data collected within NGP. Partner would use data to perform different areas of analysis for EV, EVSE, and/or Fleet pillars with an industry perspective.

Interested in Partnering with NGP?

Contact NGP PI: Sam Thurston, ANL

sthurston@anl.gov

Industry Partnerships

Power Electronics/EVSE

- Dynapower
- Turbo Power Systems

Site Operation

- Total Energies

Utility

- Colorado Springs Utilities

Automotive

Lion Electric

Energy Management

- Eaton

Agenda for Today

Time (EST)	Session	Presentation
11:20AM-12:30PM	**Session 1:** Characterization of High-Power Chargers	• NextGen Profiles: EVSE HPC Characterization (20 min), **Namrata Kogalur (NREL)** QandA and Discussion (15min) • NextGen Profiles: EVSE V2X Characterization (20 min), **Barney Carlson (INL)** QandA (15min)
5-min Break		
12:35PM-1:45PM	**Session 2:** Control and Hardware Demonstration of High-Power DC Charging Hub	• Optimized and Robust Energy Management for DC Charging Hub: A Hybrid Controller Approach (20 min), **Emin Ucer (NREL)** QandA (15min) • Exploring Decentralized Site Control in the DC Charging Hub Testbed (20 min), **Alastair Thurlbeck (NREL)** QandA (15min)
Closing Remarks		

- **Meeting is recorded.**
- Slides will be available online after this meeting.
- **QandA Session:** Raise your hand to be unmuted to ask question.
- **Chat:** Write your questions to the chat anytime and we will try to answer.

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NextGen Profiles - EVSE HPC Characterization

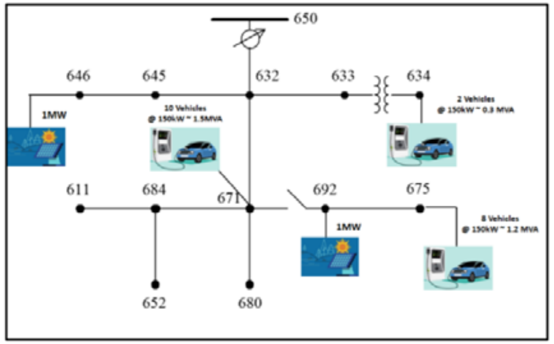
Namrata Kogalur, NREL

12 Nov 2024

EVSE Characterization Overview

Objective:

- To evaluate performance of High Power Charging (>200kW) infrastructure and further understand recent technological capabilities and grid impacts of these EVSEs under various environmental conditions and grid disturbances.
- To integrate findings and high-fidelity data into grid modeling tools for improved infrastructure development, better VGI decisions and optimization.



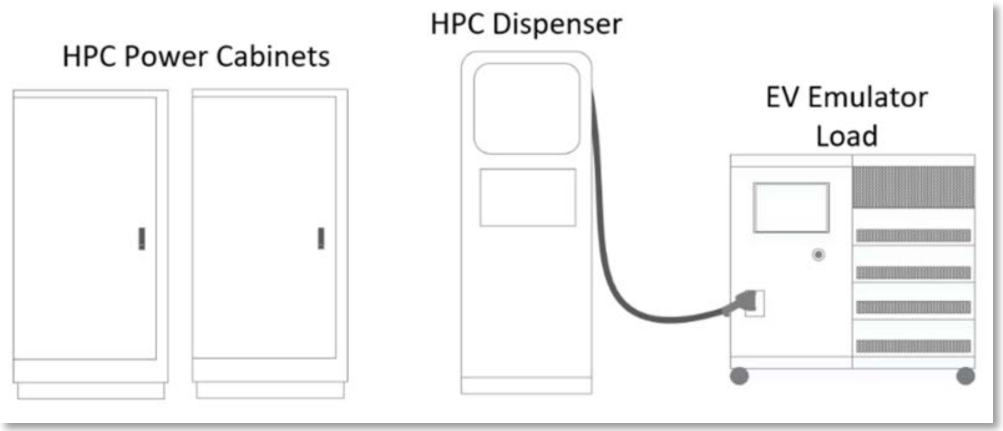
Grid modeling and standards development
EVI-X Charging Infrastructure Tools

EVSE Test Setup and Hardware Configuration

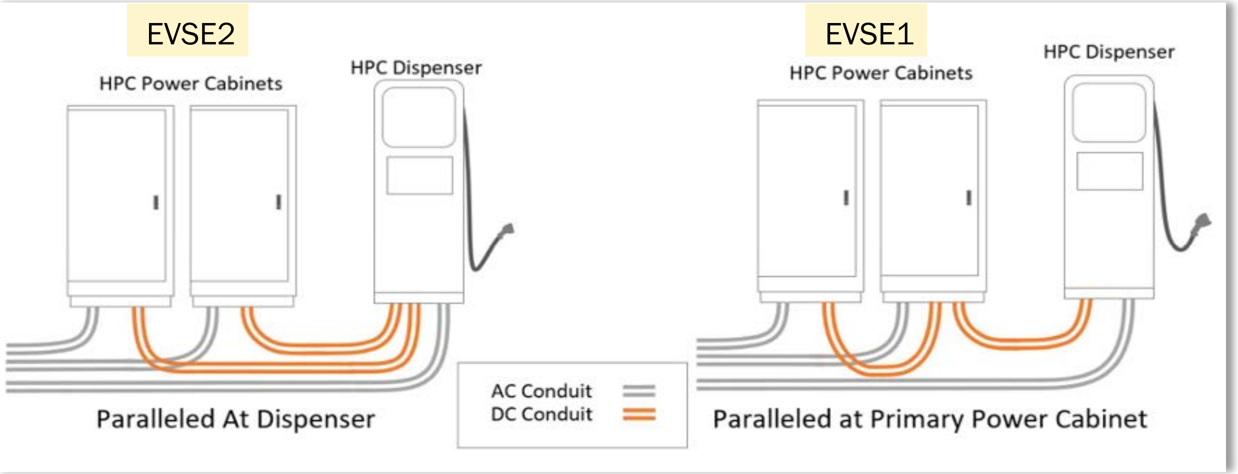
Characterization studies were performed on two conductive EVSEs rated 350kW consisting of 2 paralleled power cabinets each.

- The power cabinets come in two paralleling configurations:
  - Paralleled at Dispenser
  - Paralleled at Primary power cabinet
- The 2 EVSEs also differ in isolation methods
  - Low frequency transformer at the AC input before the PFC stage
  - High frequency isolation in the DC-DC converter stage

Carlson, Richard, and Onar, Omer. EVSE Characterization, A Next-Gen Profiles Project Report. United States: N. p., 2023. Web. doi:10.2172/2328073.



EVSE characterization configuration



EVSE system topologies

EVSE Characterization Test Conditions

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EVSE characterization boundary conditions →

Condition Category	Condition Sub-Category	Condition Metric	Tolerance
Temperature	Ambient Temperature	Nominal: 23°C	+/- 2%
		Hot: 40ºC	+/- 2%
		Cold: -7ºC	+/- 2%
Grid Condition	Voltage	Nominal: 480VAC	+/-25VAC
		Swelled: 528VAC (110% nominal)	+/-25VAC
		Sagged: 432VAC (90% nominal)	+/-25VAC
	Harmonics	Nominal: No Harmonics	
		5% Voltage Distortion	+/- 1%
	Frequency	Nominal: 60 Hz	+/- 0.2 Hz
		Increased: 61.2 Hz	+/- 0.2 Hz
		Decreased: 58.8 Hz	+/- 0.2 Hz
Charge Management	Smart Charge Request	Nominal: None	-
		TxProfile	-
		TxDefaultProfile	-
		ChargePointMaxProfile	-
	Smart Charge Request Duration	Nominal: None	-
		2 minutes	+/- 1 minute
	Smart Charge Request Scheduling	Nominal: None	-
		1 minute into charge session	-
	Current or Power Request	Nominal: None	-
		65A (total AC input current)	-
		54kW (AC or DC as implemented by manufacturer)	-

Power transfer characterization test conditions

Test Condition Category	DC Current Test Conditions	DC Voltage Test Conditions	Tolerance
Nominal test conditions	50 to 500 AMP in 10A increments (up to maximum power)	300 V, 400 V, 650 V, 750 V, 850 V	+/-2%
Off-nominal test conditions	150 AMP, 500 AMP (or full power if 500 AMP is not possible)	400 V, 850 V	+/-2%

EVSE Off-Nominal Temperature Test Setup

540kW Grid Simulator

480VAC Input

EVSE and Power Cabinets in Thermal Chamber

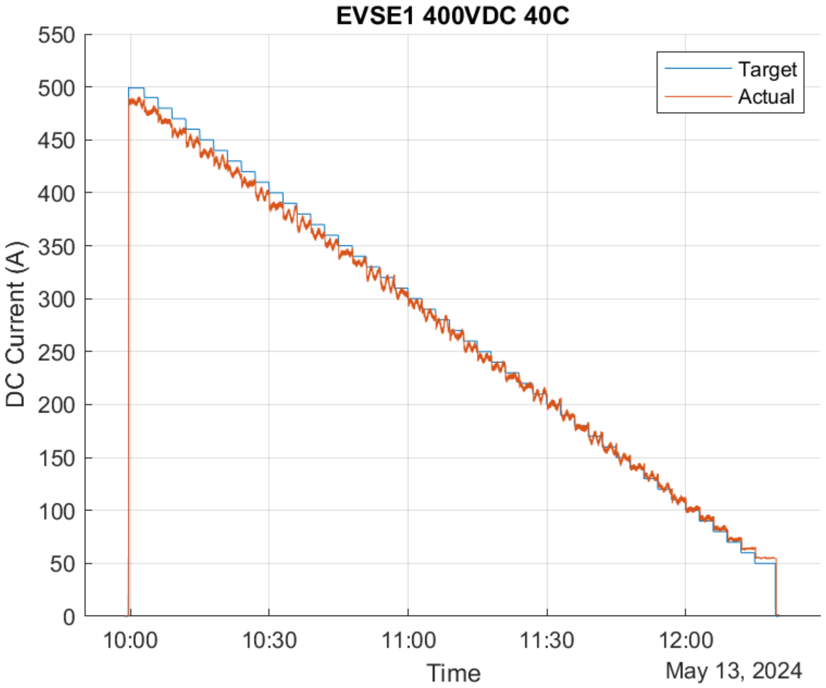
CCS

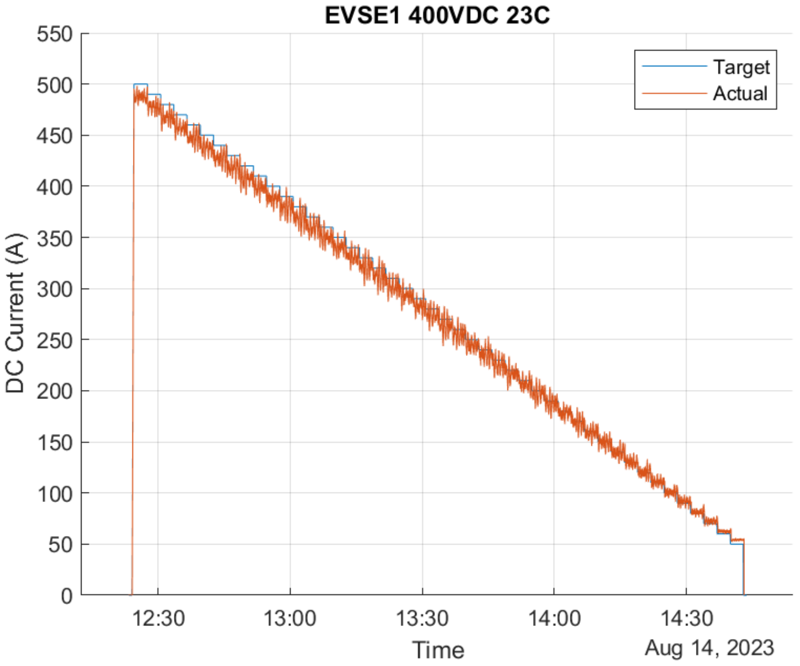
Charge Control Box (CCB)

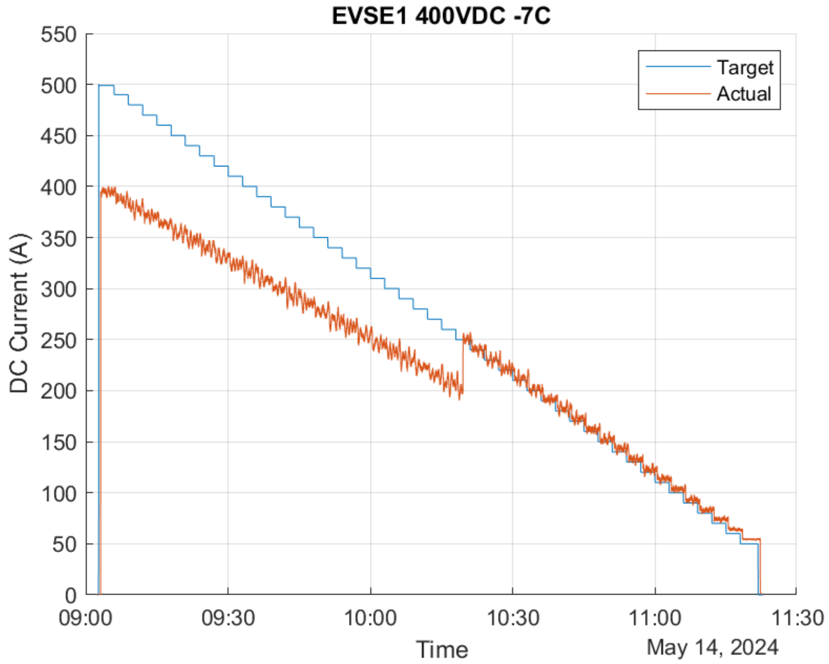
DC Output

DC Emulator Load

EVSE1 Power Transfer Characterization

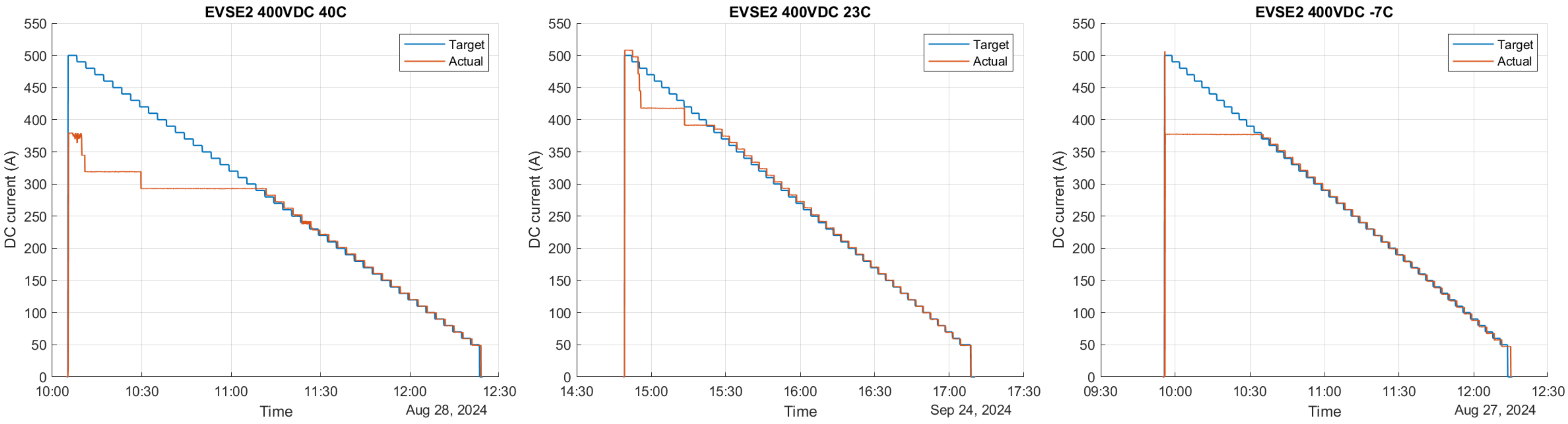






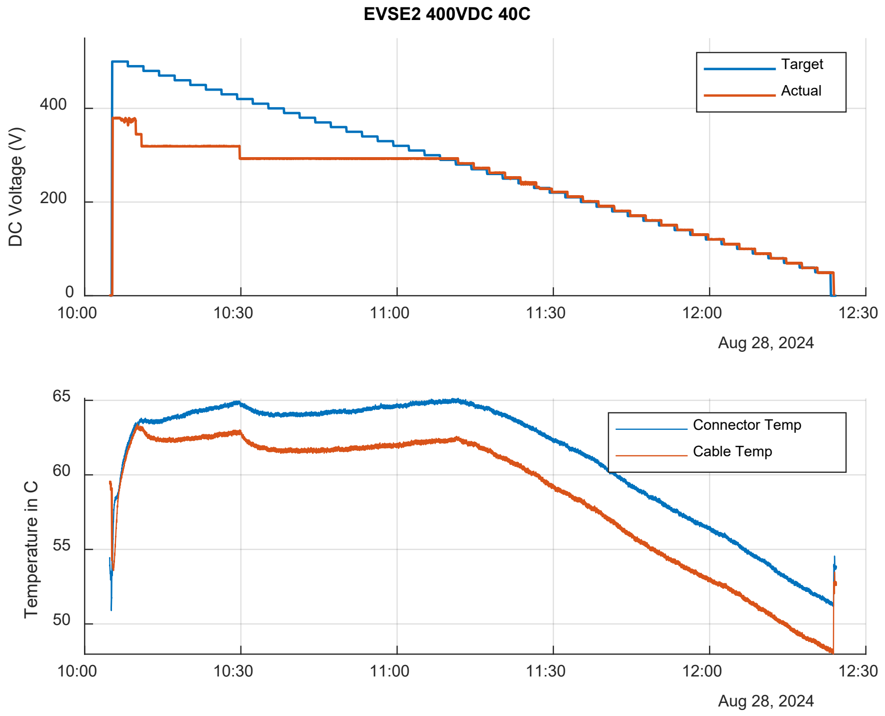
- Test Conditions: 400VDC, 500-50ADC output across ambient temperatures (-7C, 23C, 40C)
- While we suspect higher ambient temperature to likely derate, EVSE is able to achieve targets at 40C but limits power at -7C till 85kW DC output.
- This test captures the derating behavior of the EVSE since it was tested to the charging connector's maximum current rating (500A), which has been observed to be the thermal limitation so far.

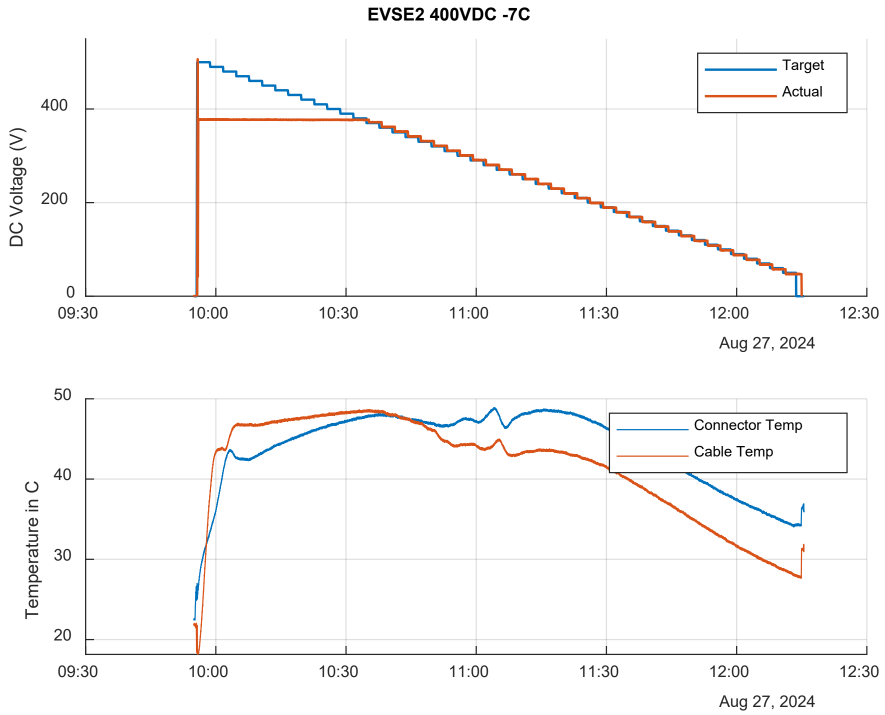
EVSE2 Power Transfer Characterization



- Test Conditions: 400VDC, 500-50ADC output across ambient temperatures (-7C, 23C, 40C)
- Charger was observed to not engage secondary cabinet during both off-nominal tests at -7C and 40C.
- 40C derating is more significant and prolonged due to excessive heating and reaching the temperature threshold more quickly.

EVSE2 Derating and Device Temperatures

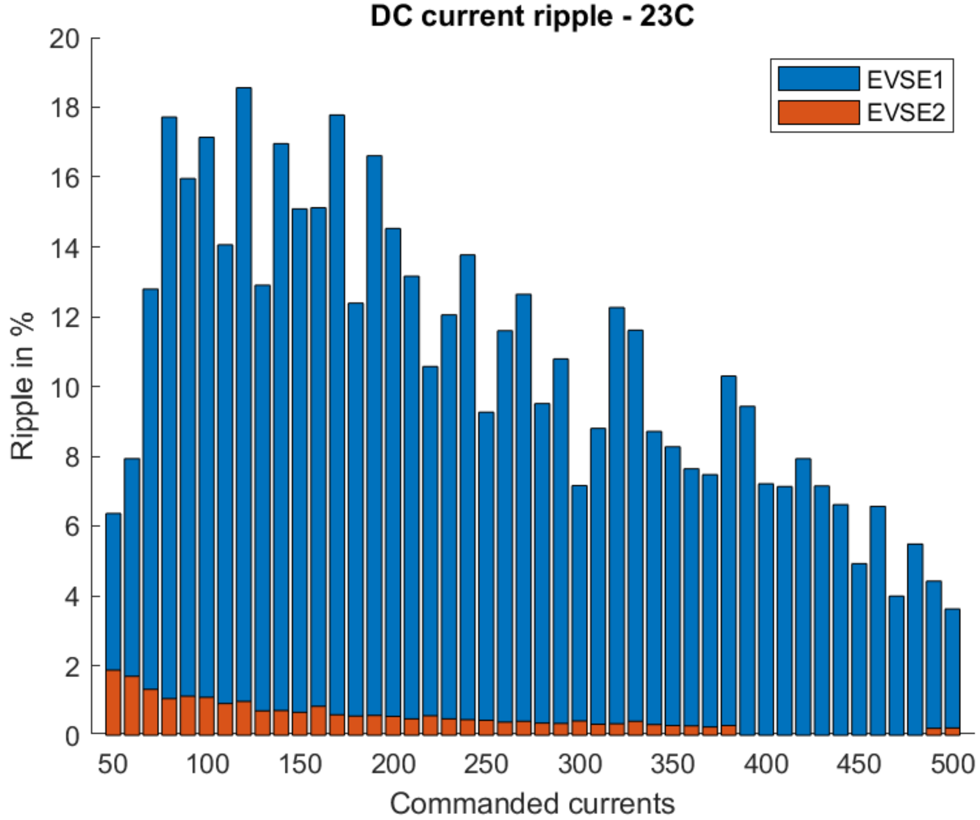


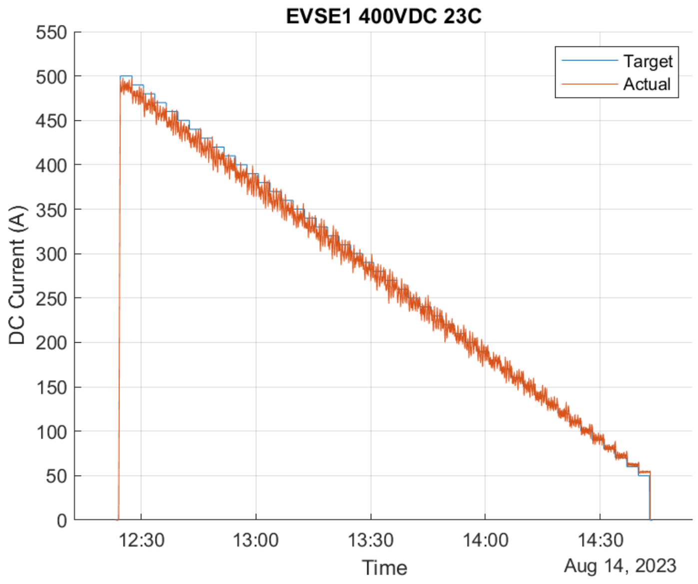


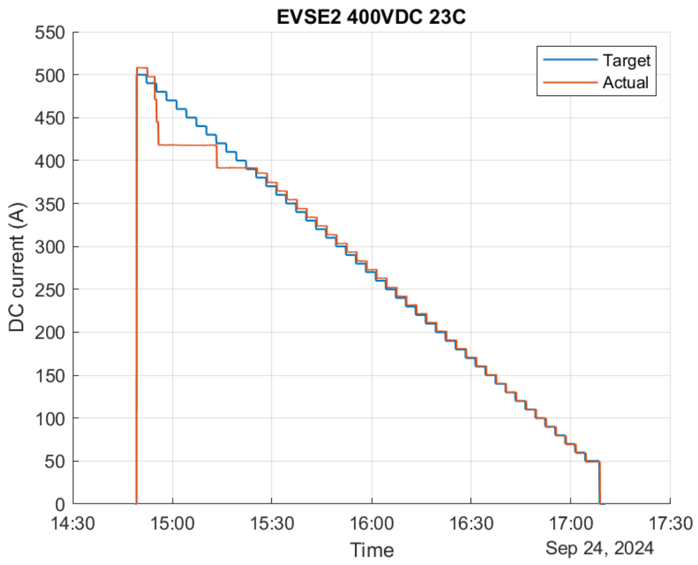
- 40C results show that the temperatures of the cable and connector rise significantly during the first 5 minutes and reaches the maximum threshold thereby curtailing the allowed current even further.
- During -7C test, cable temperature is well within temperature max limit but still shows curtailment. This could be due to effect of cold temperature on thermal properties of the coolant, flow rate and limitation with liquid cooled cables.

EVSE DC Output Regulation

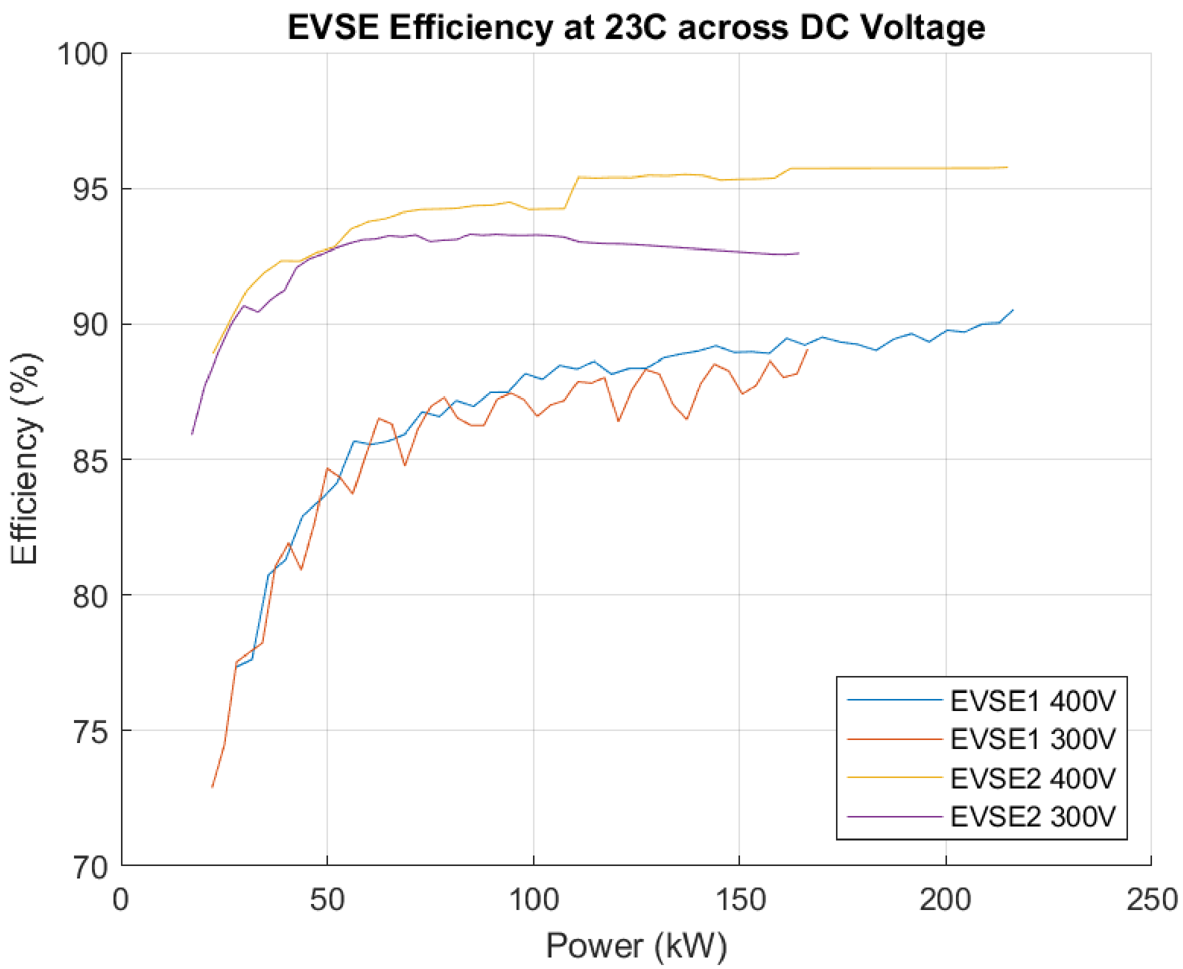
- Test Conditions:
  - 400VDC, 500-50ADC @23C
- EVSE2 has better current regulation than EVSE1
- Current ripple reduces at higher currents





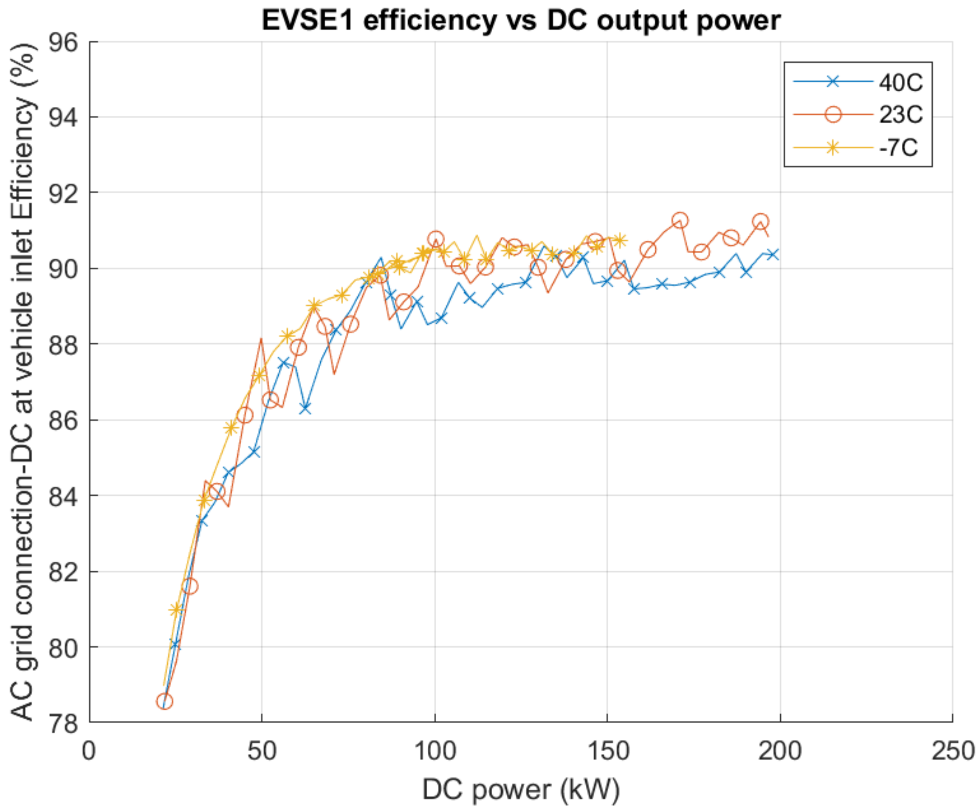


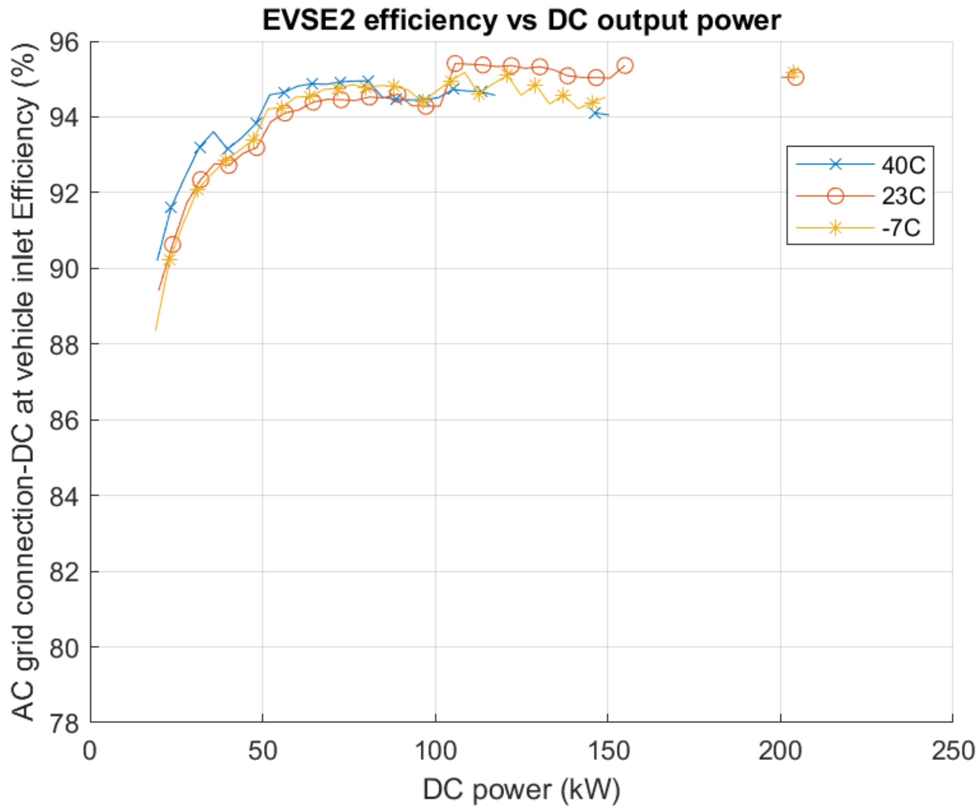
EVSE1 characterization - Efficiency



- Test Conditions:
  - DC Voltage: 300Vdc and 400Vdc
  - DC Current: 500-50Adc output
  - Ambient temperature: 23C
- EVSE2 demonstrates higher efficiency across all power levels compared to EVSE1, with a notable increase in efficiency at 400V beyond 50kW.
- EVSE1 efficiency across both output voltages are very similar across power levels.

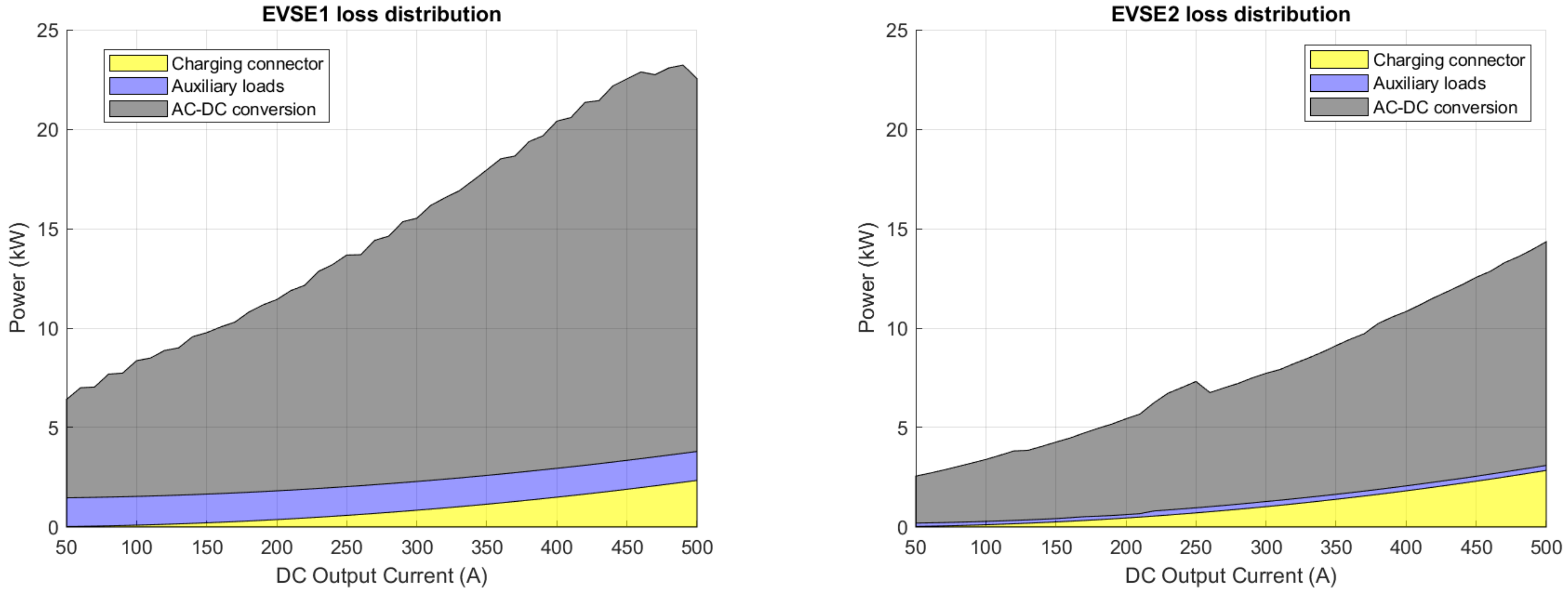
EVSE Efficiency: Off-Nominal Temperatures





- Test Conditions: 400VDC, 500-50ADC output across ambient temperature (-7C, 23C and 40C)
- EVSE1 successfully reaches the entire target range under both 23°C and 40°C conditions whereas EVSE2 derates between the 150-200kW levels.
- At the power levels achievable by the EVSEs, individual efficiencies show minimal variation with changes in ambient temperature

EVSE Power Loss Distribution



- Test Conditions: 400VDC, 500-50ADC @23C
- Both EVSEs exhibit similar losses in the CCS connector but EVSE2 seems to be limited by thermal constraints in cable cooling leading to derating at higher current levels despite being the more efficient unit overall

EVSE Power Factor: Off-Nominal Temperatures

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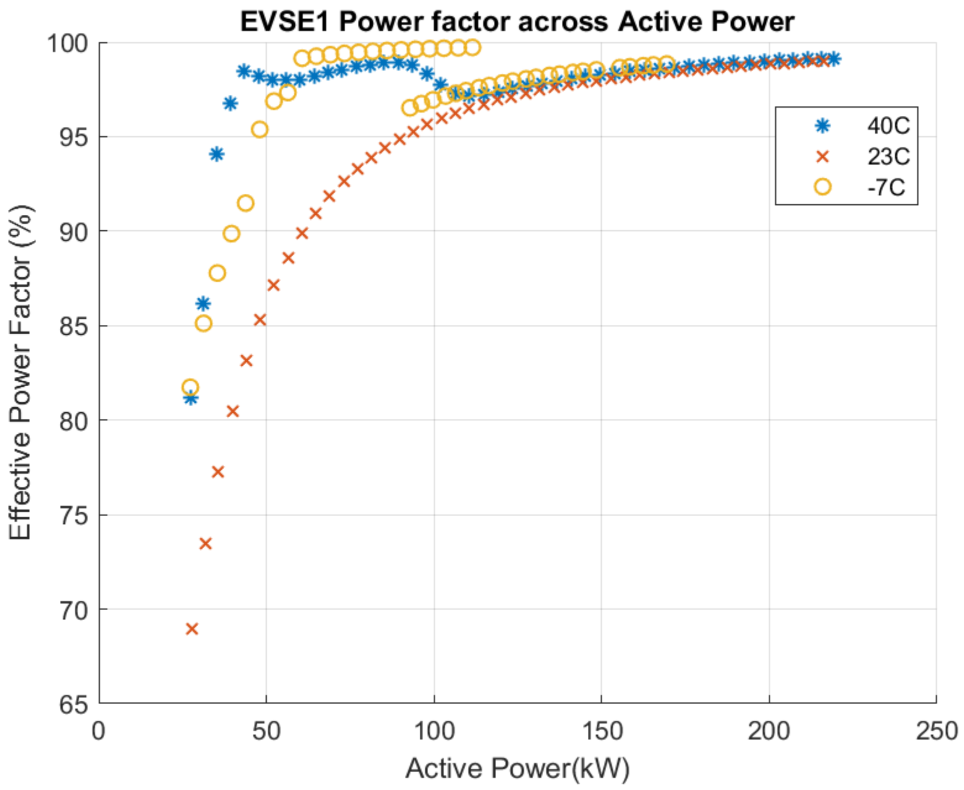
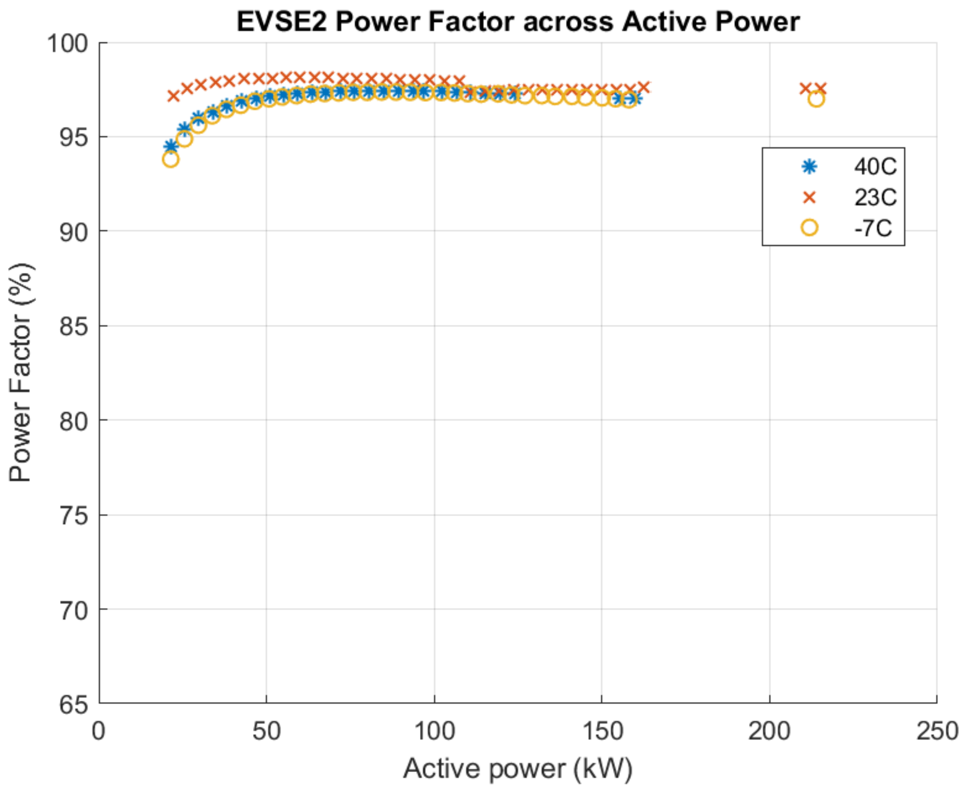
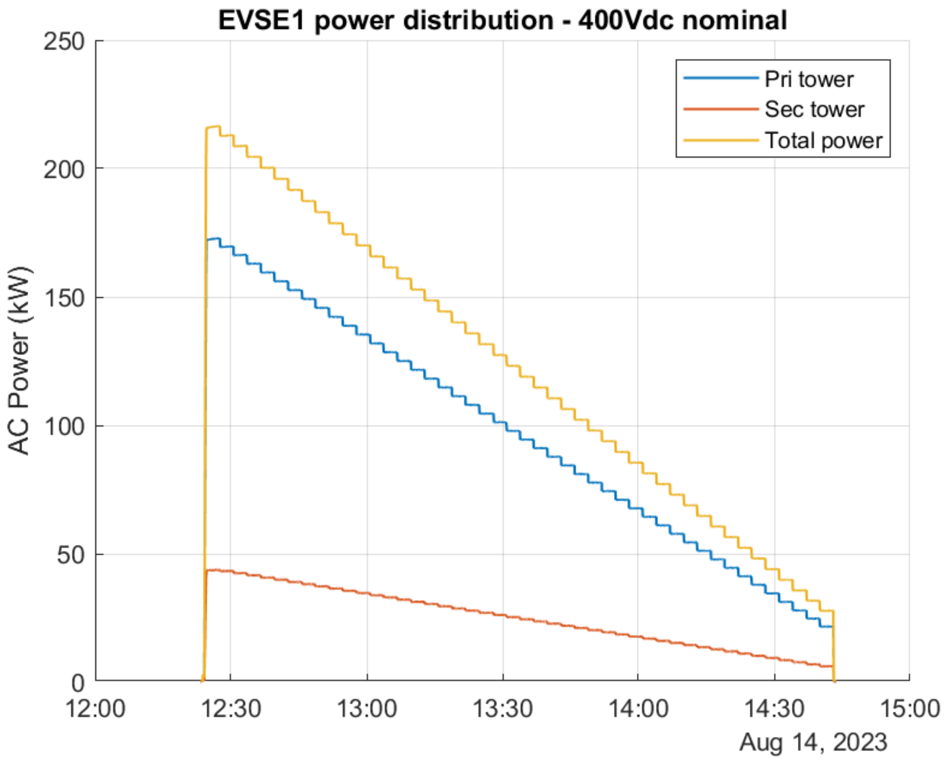
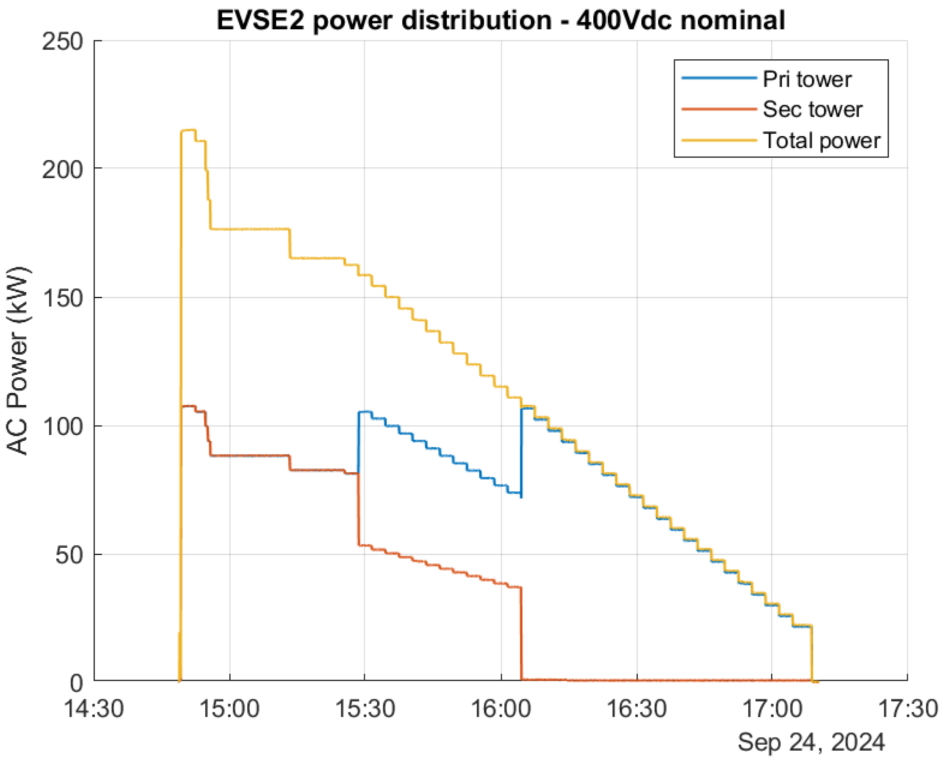




- Test Conditions: 400VDC, 500-50ADC across temperature
- Total power factor is calculated as total active power from the two cabinets over net apparent power. The estimation uses harmonic components also in calculation. Hence there is a factor of THD in this unit which is visible at lower power levels where THD rises significantly
- Power factor of EVSE2 is greater than 93.8% across tested range

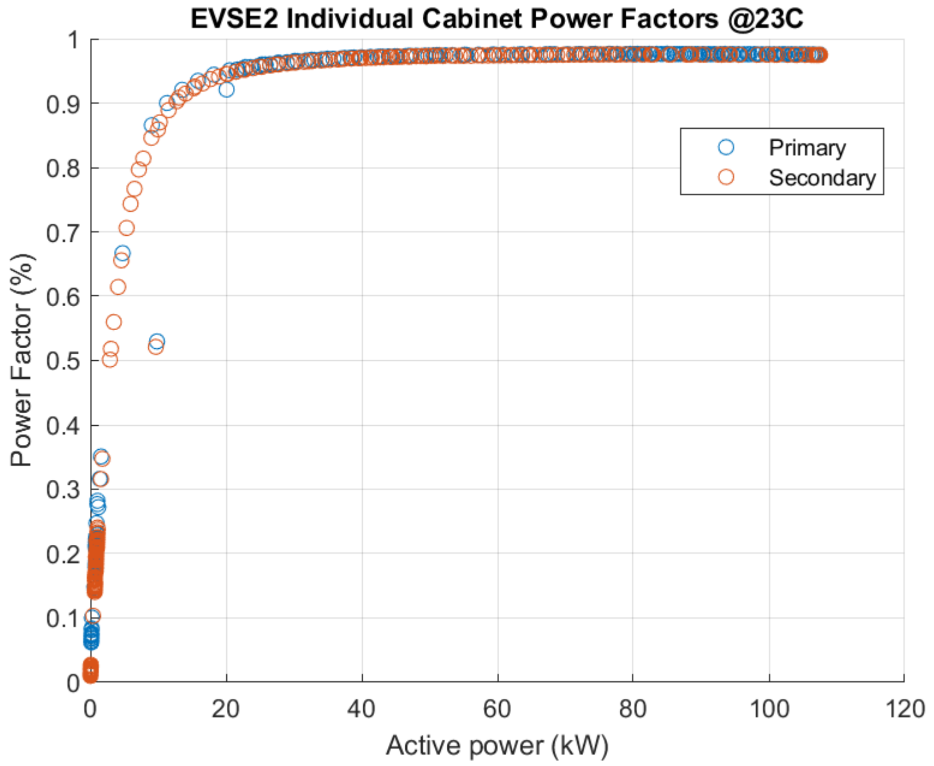
EVSE Power Sharing Between Cabinets

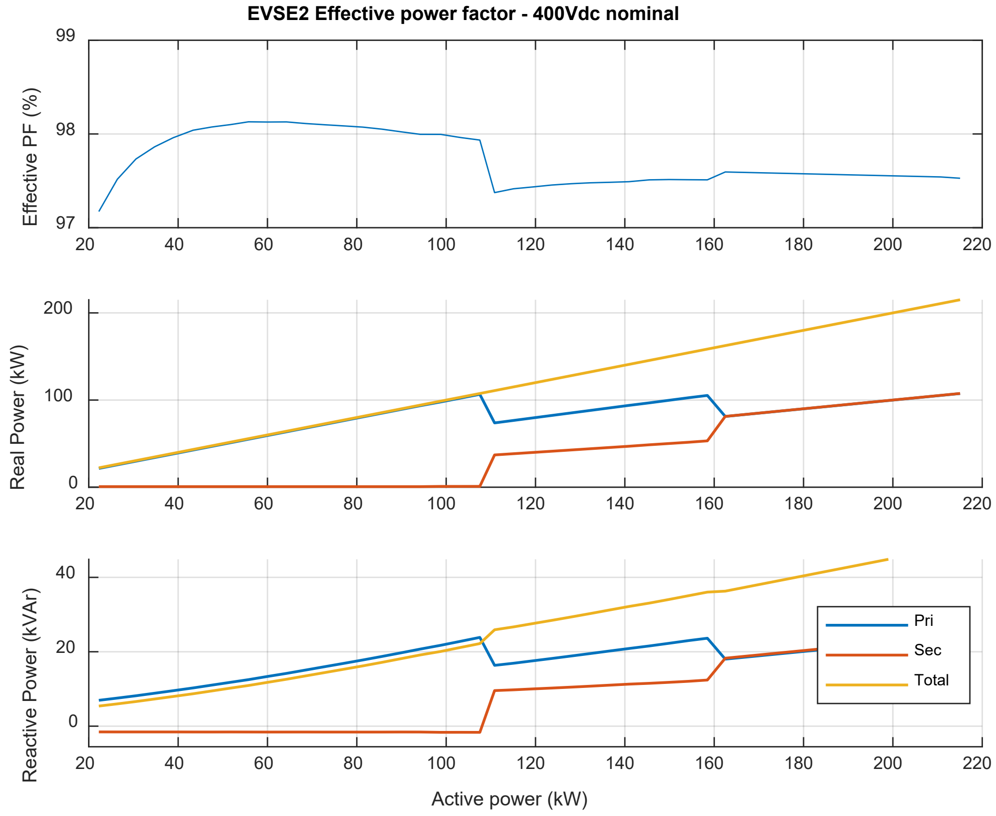




- EVSE1 always maintains about 4:1 ratio of power sharing between cabinets.
- EVSE2 does not operate a tower below 50A, it redistributes it to single tower.
- EVSE2 seems to optimize performance by splitting power requested across the cabinets in such a way to avoid lower power operating regions of the individual cabinets. It could be a factor for better power factor at lower powers compared to EVSE1.

EVSE Power Factor – Dynamic Power Sharing

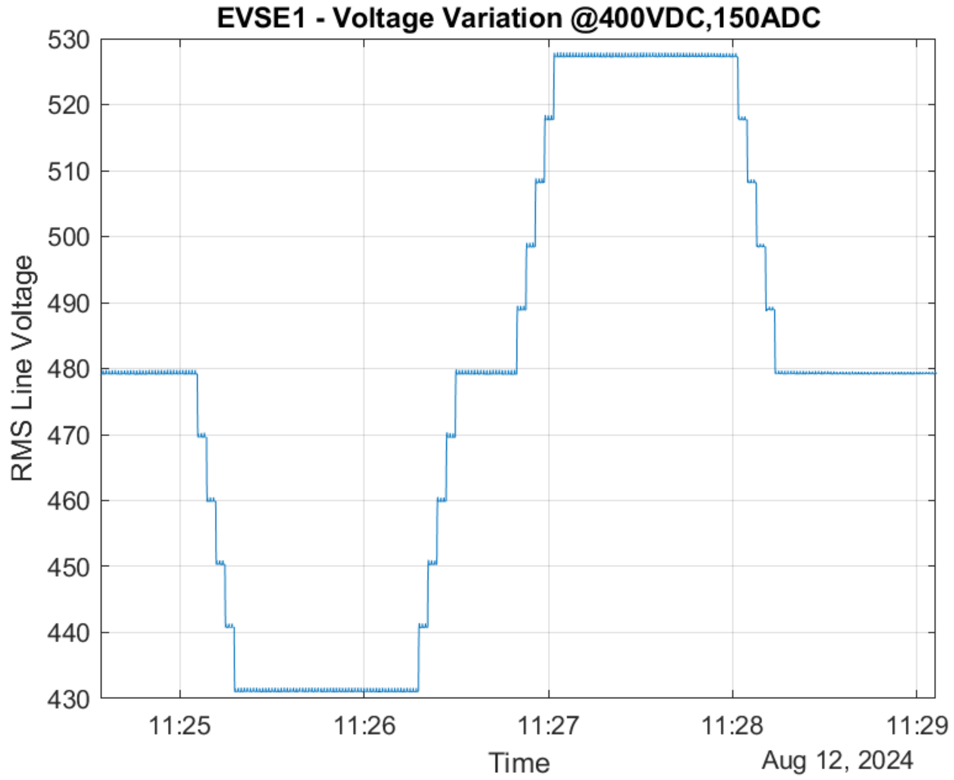




- Test Conditions: 400VDC, 500-50ADC, 23C
- Power factor drastically reduces at powers lower than 20kW at individual cabinet level
- Changes in power factor seem to align with the way EVSE2 does power sharing between cabinets and utilizes the secondary to provide reactive power support in lower power region.

Voltage Variation Tests

- Goal: To evaluate EVSE’s response to a variation in source voltage within the limits of SAE J2894 -1 and -2
- Both EVSEs operate fully satisfactorily without interruption across the 90-110% voltage range
- Additional test was conducted per ANSI C84.1 for sustained voltage levels categorized by,
  - Range A: Utilization equipment shall be designed and rated to give fully satisfactory performance throughout the range
  - Range B: As far as practicable, utilization equipment shall be designed to give an acceptable performance in the extremes of the range of utilization voltages, although not necessarily as good as in Range A.
- EVSE1 input voltage specifications are within Range B for 480V nominal system
- EVSE2 input voltage specifications does not cover below 90% but it was tested to operate satisfactorily to Range B



Voltage Category	Min utilization voltage (% of 480V)	Max utilization voltage(% of 480V)
Range A	432V (90%)	504V (105%)
Range B	416V (86.67%)	508V (105.8%)

Conclusions

- Thermal testing demonstrates the effects of both hot and cold temperatures which can limit the equipment's ability to reach its full power rating.
- Operating EVSEs at low powers leads to poorer performance and impacts power quality and efficiency.
- Dynamic power sharing between cabinets can improve charger operation at lower power levels which is crucial to consider since EVs spend over 50% of charge time below 50kW and only 12.1% above 200kW.[1]
- The test results provide valuable insights into the equipment’s derating, output regulation, thermal behavior, power factor, efficiency, and its performance under varying load conditions
- Understanding these characteristics is crucial for grid planning, seasonal assessments of charging sites and optimization of fleet charging.

[1] Thurston, Sam, and Wells, Landon. EVs@Scale Next-Gen Profiles - EV Profile Capture 2023. United States: N. p., 2023. Web.

Thank You!

Contact Info:

Namrata.Kogalur@nrel.gov

EVs@Scale

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Deep Dive Meeting

Next-Gen Profiles:

Bidirectional (V2G) EVSE Characterization

Barney Carlson

Nov. 12, 2024

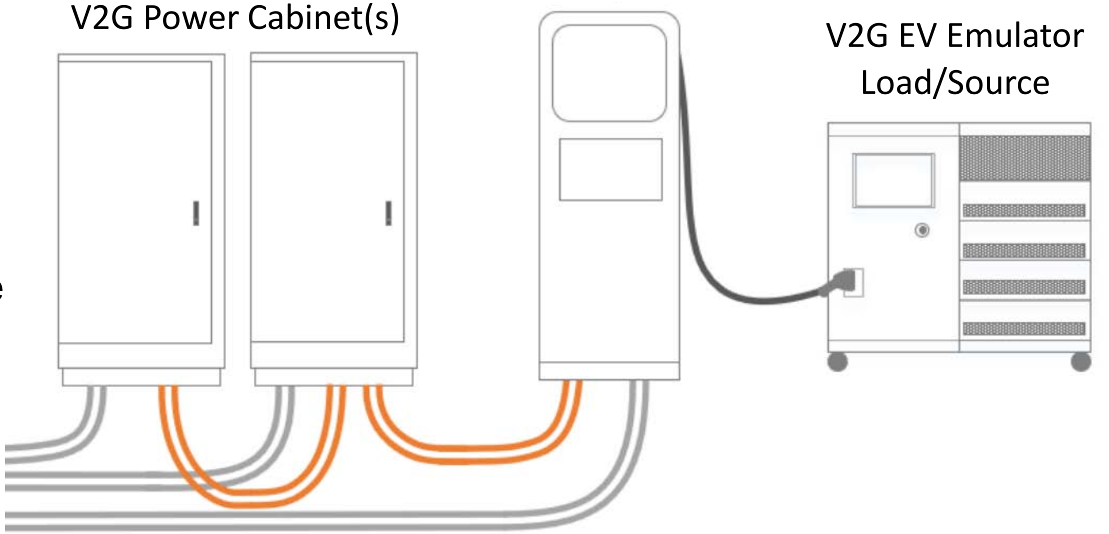
Bidirectional (V2G) EVSE Characterization Overview

- **Characterization results from two V2G EVSE (still underwa**
  - 50kW-class V2G bidirectional chargers

- **Nominal test conditions**
  - AC voltage: 277.1 Vrms L-N (480.0 Vrms L-L, 3-ph.), 60.0 Hz, voltage total harmonic distortion <0.5%
  - Ambient temperature: 21^{o}C (inside laboratory)

- **Off-nominal test conditions**
  - AC voltage deviation (+/- 10%)
  - AC frequency deviation (+/- 2%)
  - AC voltage total harmonic distortion (THD) up to 5%

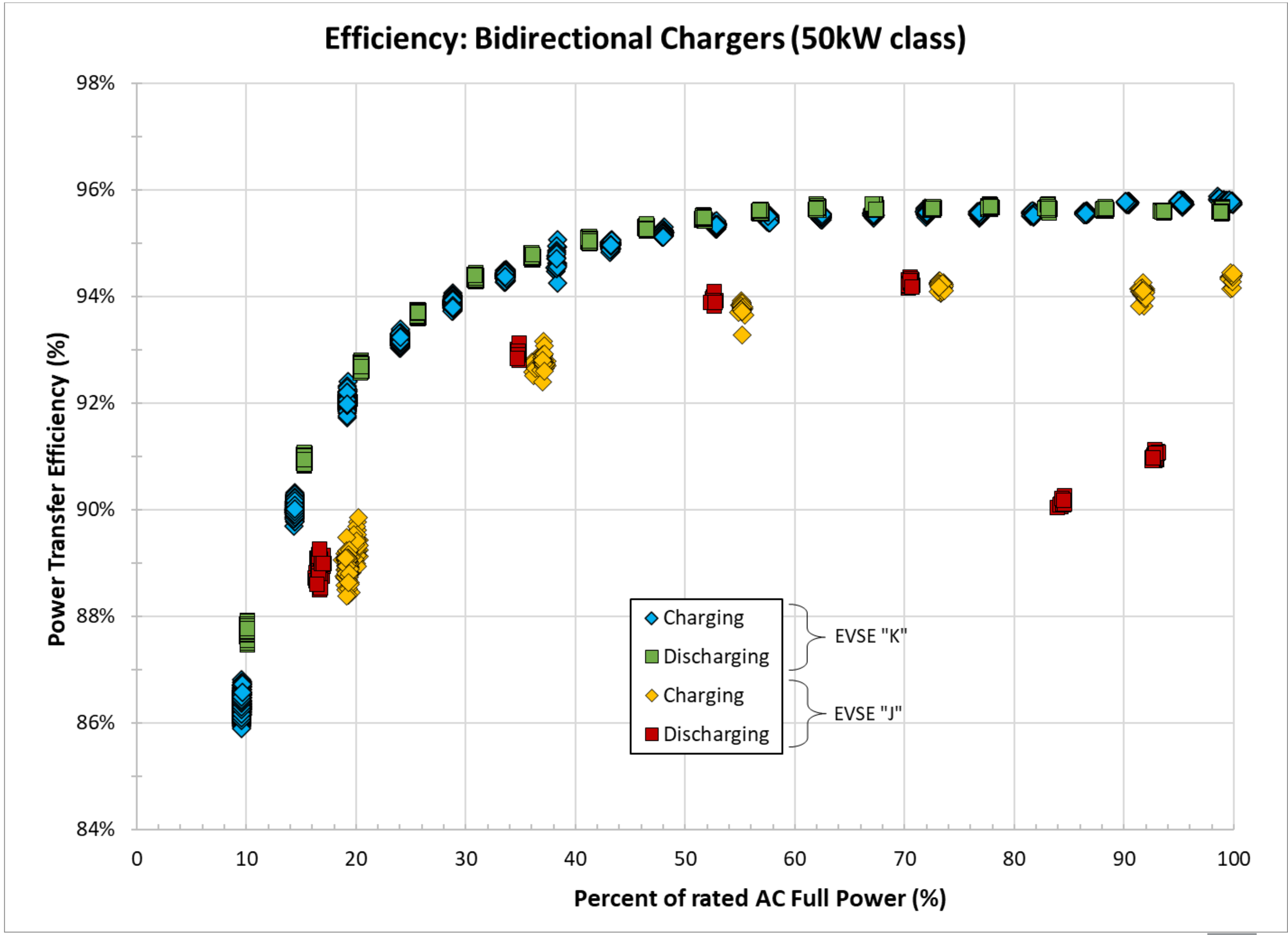
- **EV emulator and production EV utilized for characterization**
  - EV emulator with ISO 15118-2 (2015), CCS inlet port, and 120kW battery emulator (DC source / load bank)
  - Production V2G CHAdeMO capable EV with ~375V battery



Nominal Test Condition Results

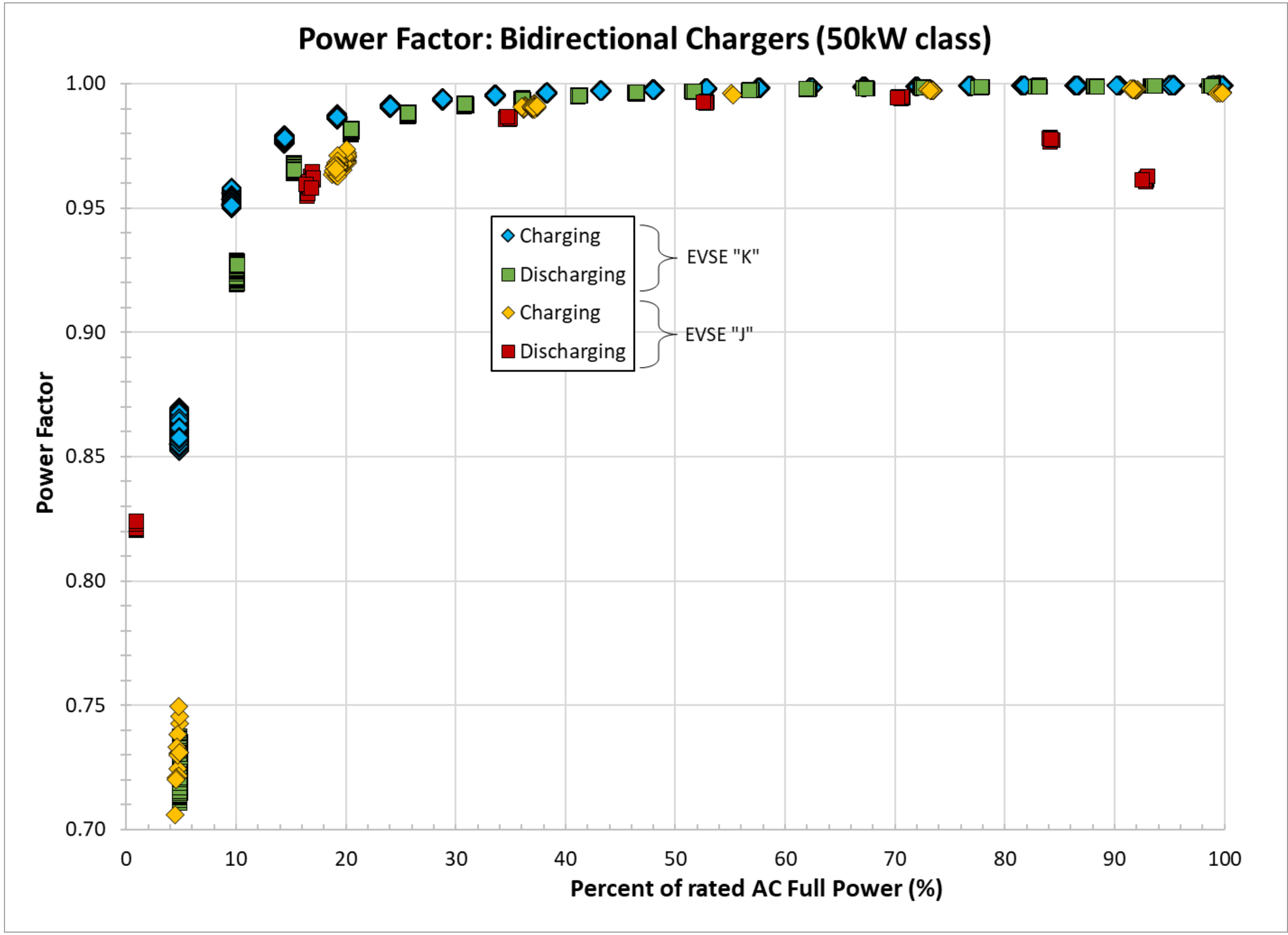
V2G Characterization: Nominal Test Conditions – Efficiency

- **Asymptotically increasing efficiency with increasing power transfer**
- **Similar efficiency for charge and discharge**
  - Except high power discharge EVSE "J"
- **Moderate difference between EVSE "K" and EVSE "J"**



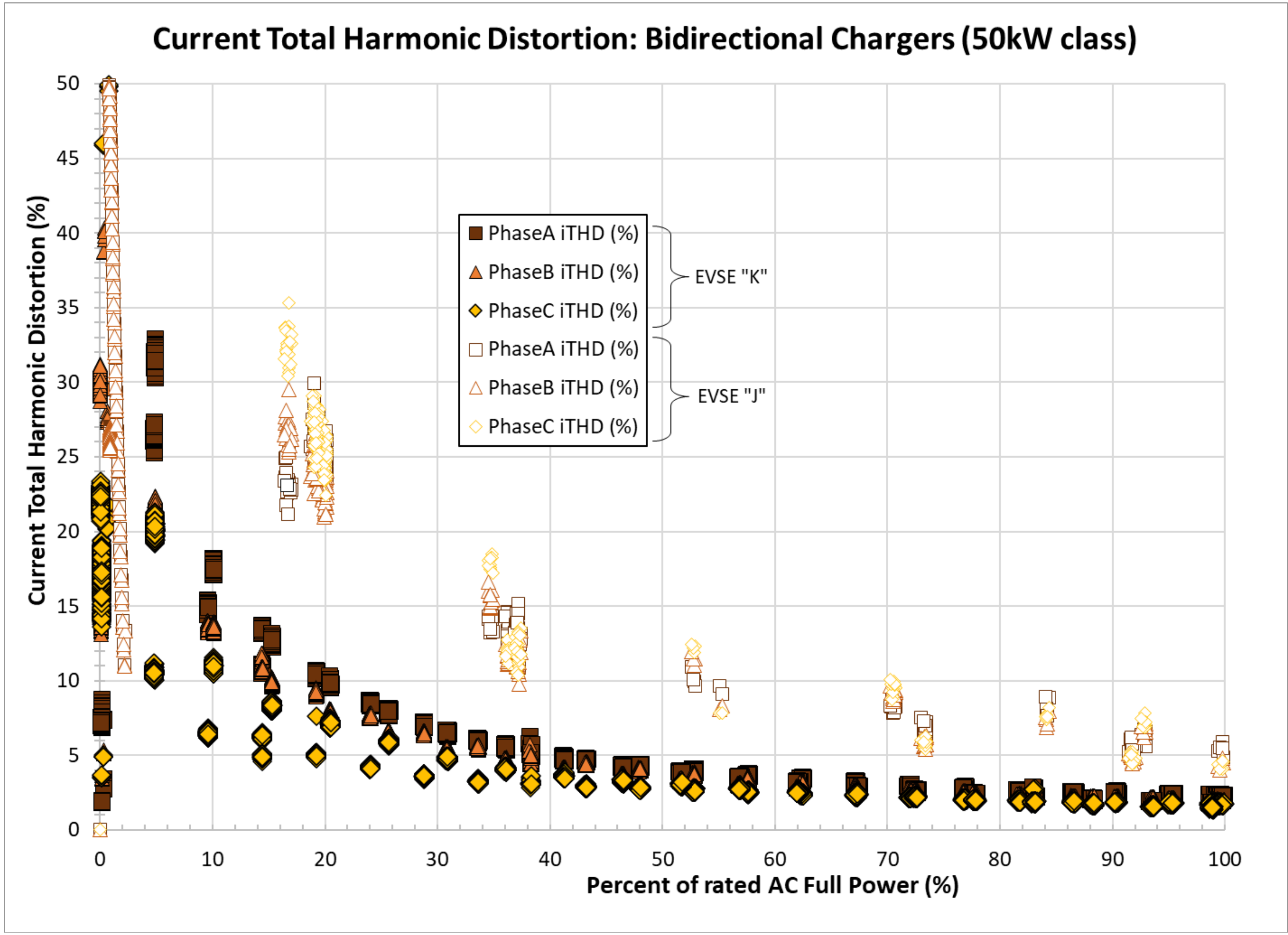
V2G Characterization: Nominal Test Conditions – Power Factor

- **Power Factor >.95 for most of operating range**
- **Similar power factor for charge and discharge**
  - Except high power discharge EVSE "J"
- **Moderate difference between EVSE "K" and EVSE "J"**



V2G Characterization: Nominal Test Conditions – Current THD%

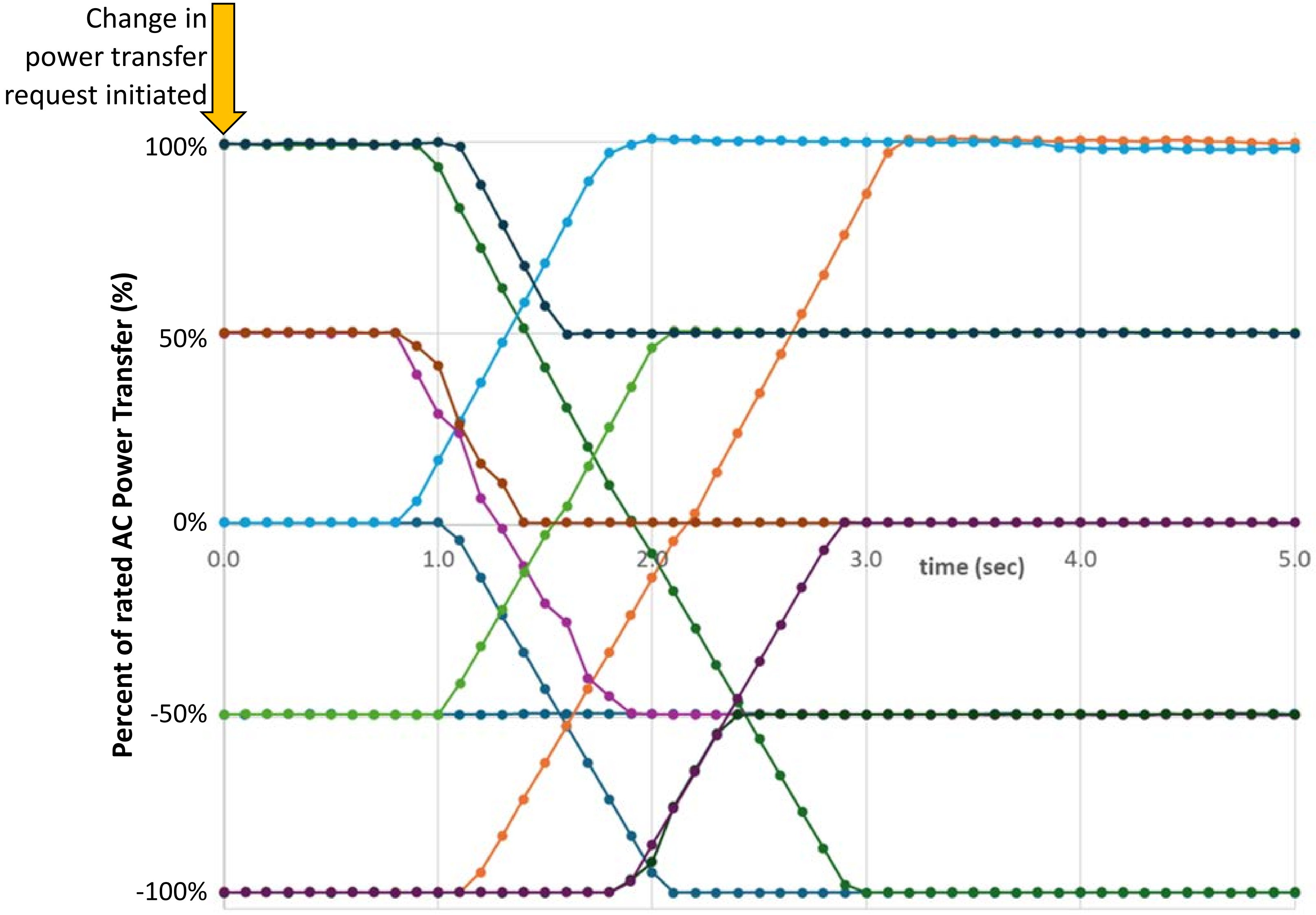
- **Decreasing current THD% with increasing power transfer**
  - EVSE “K”:
    - <5% THD above 50% rated power
  - EVSE “J”:
    - Approaching 5% THD at full rated power transfer
- **Similar current THD% for charge and discharge**
- **Notable difference between EVSE “K” and EVSE “J”**



$$Ithd(i) = \frac{\sqrt{\sum_{k=2}^{K} (I_k)^2}}{I_1} \times 100$$

V2G Characterization: Response to Energy Management Control Request

- **Cloud-based energy management system used to request change in power transfer to EVSE via cell modem**
- **Power transfer request initiated at 0.0 seconds**
- **Latency:**
  - 0.8 to 1.8 sec.
- **Ramp Rate:**
  - 95% rated power per second
  - Fairly consistent for:
    - Charging or discharging
    - Ascending or descending



V2G Characterization: Nominal Test Conditions

- **Idle power consumption while:**
  - Not plugged in
  - Plugged in (no power transfer)

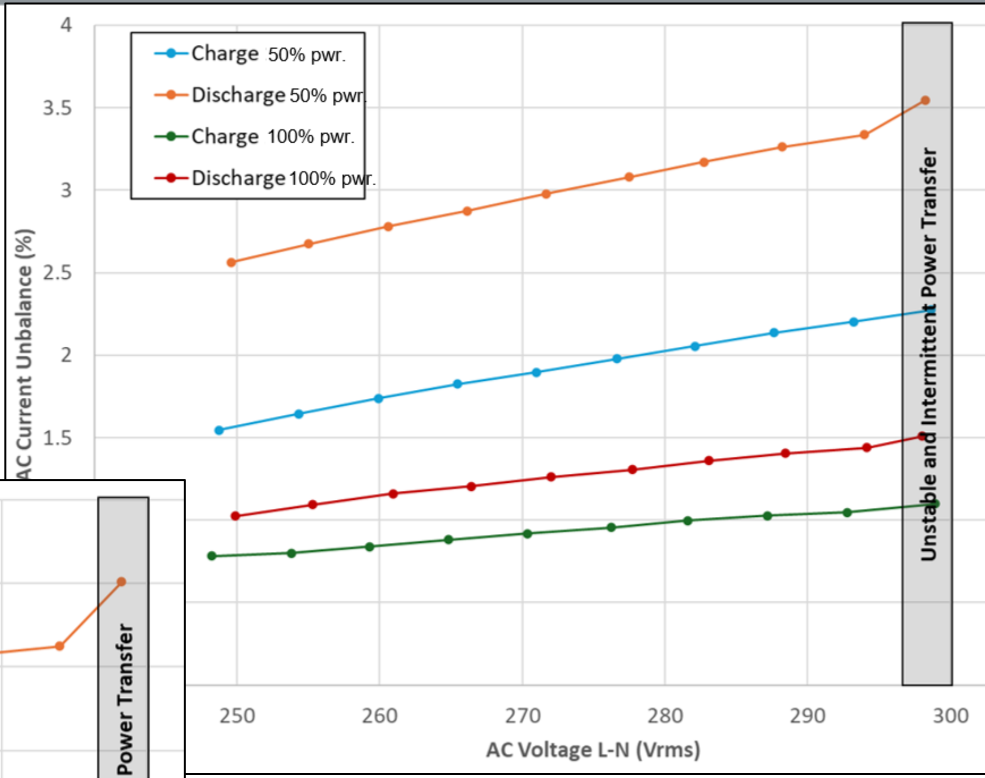
- **Auxiliary power**
  - Thermal management
  - Exterior lighting
  - Graphical user interface
  - Controls/communication modules
  - Etc.

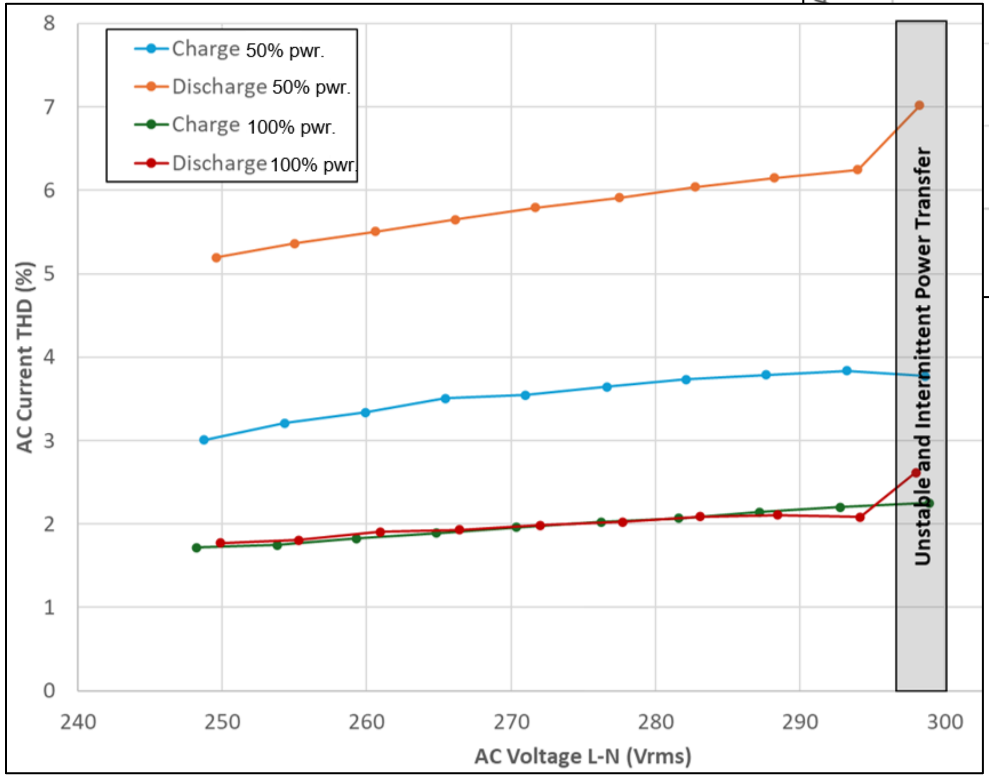
	EVSE "K"		EVSE "J"	
	Standby (not plugged in)	Standby (plugged but no power transfer)	Standby (not plugged in)	Standby (plugged but no power transfer)
Real Power (watts)	10 watts	140 watts	138 watts	554 watts
Reactive Power (VAR)	430 VAR	250 VAR	-207 VAR	-4 VAR
Auxiliary Power (watts)	25 to 40 watts during power transfer		581 to 654 watts during power transfer	

Off-Nominal Test Condition Results

V2G Characterization: Off-Nominal AC Input Voltage Deviation

- **AC voltage >298V L-N (516V L-L) resulted in:**
  - power transfer instability
  - repeated power transfer interruption with recovery after a few seconds
- **Increasing voltage had small increase in:**
  - AC current phase unbalance
  - AC current THD %
- AC voltage deviation between 249V to 298V had no impact on:
  - Power transfer
  - Efficiency
  - Power Factor
  - DC current ripple





V2G Characterization: Off-Nominal AC Frequency Deviation

- **Testing conducted between 58.8 Hz and 61.2 Hz (i.e. +/- 2% from 60.0Hz)**
  - At 100% power transfer (charge and discharge)
  - At 50% power transfer (charge and discharge)

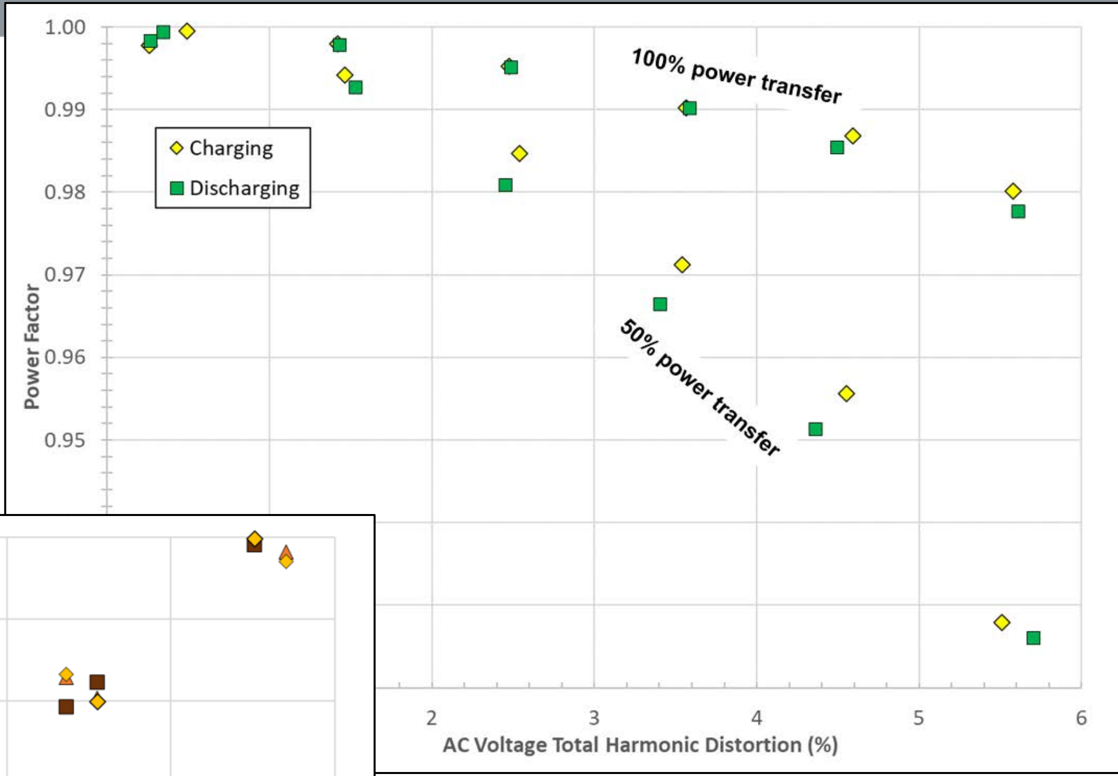
- **No notable impact on any measured performance metric**
  - Power transfer
  - Efficiency
  - DC current ripple
  - Power Factor
  - AC Current THD %
  - AC current phase unbalance

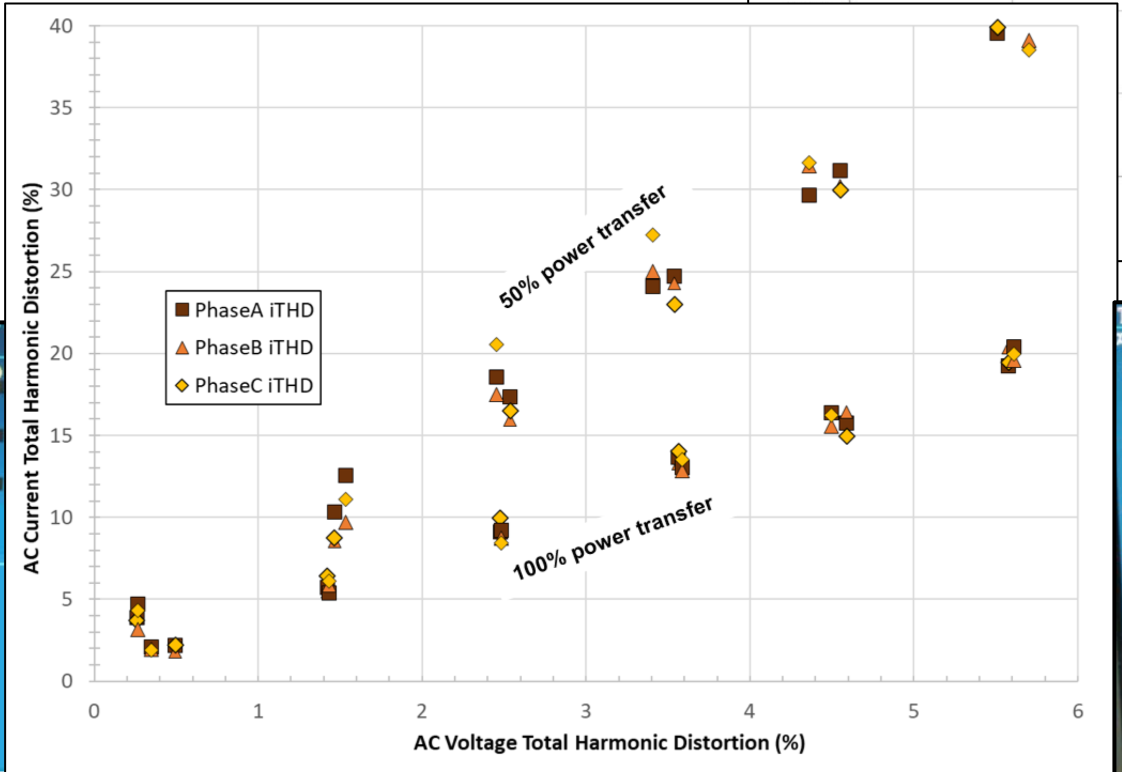
V2G Characterization: Off-Nominal AC Voltage Total Harmonic Distortion

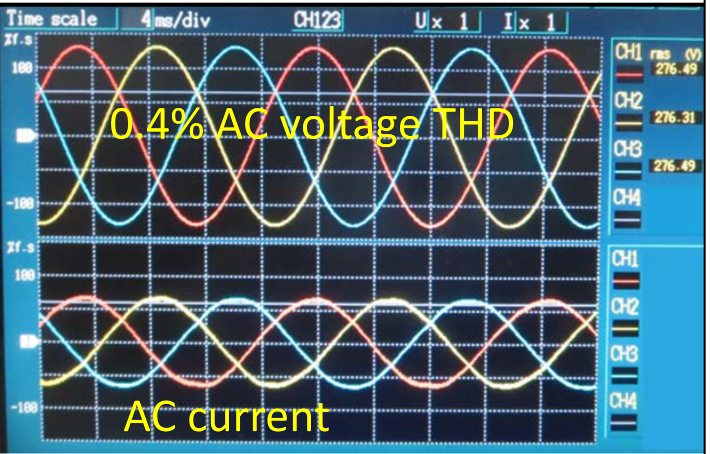
- **Power quality characteristics is impacted by AC input voltage total harmonic distortion**
  - Power factor
  - AC current THD %

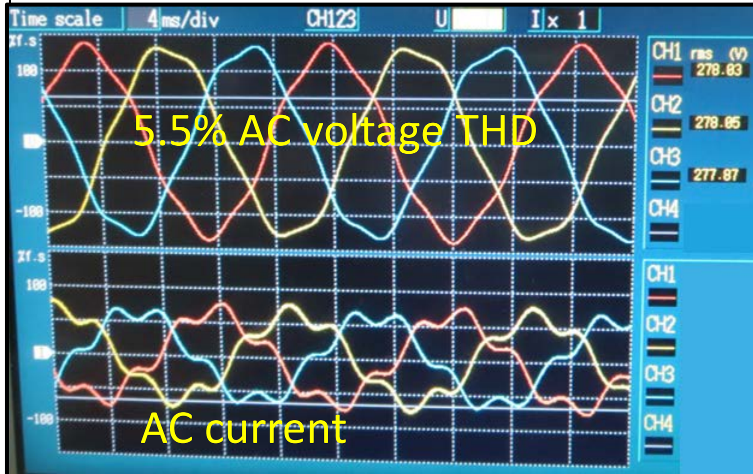
$$Ithd(i) = \frac{\sqrt{\sum_{k=2}^{K} (I_k)^2}}{I_1} \times 100$$

- **Negligible impact on:**
  - Power transfer
  - Efficiency
  - DC current ripple
  - AC current phase unbalance









Summary: Bidirectional (V2G) EVSE Characterization

- **Nominal characterization results:**
  - Charging and discharging characteristics are typically very similar (efficiency, power factor, etc.)
  - Power transfer request via cloud-base management system
    - Low latency
    - Repeatable ramp rates
- **Off-Nominal characterization results:**
  - Above 298V L-N (516V L-L) power transfer was not stable and had repeated interruptions
  - Frequency deviation had no notable impact on performance
  - Voltage harmonic distortion impacted power factor and AC current harmonic distortion
- **Testing is in progress of these two V2G charging systems**
  - Further lab evaluation is in progress to complete all remaining testing on both V2G chargers
  - Once completed, results and findings will be published in the year-end report for the Next-Gen Profiles project

Open Project Partnerships

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- EV Profiles: High power EV/EVSE partnership
  - HPC (150-400kW) EVSE & EVs
  - Megawatt-level (800-1000kW+) EVSE & EVs
- EVSE Char: High power and/or Bi-directional EV charging infrastructure partnership
  - EV emulator capable of high-power charging up to 400kW (500A max., 920V DC max.)
  - EV emulator capable of CCS-1 bi-directional charging up to 120kW using ISO 15118-2 (2015)
- Fleet telematics data partnership
  - Looking to add another fleet to our portfolio, granting access to data portal for NGP specific analysis
- Data Analysis partnership
  - Lots of data collected within NGP. Partner would use data to perform different areas of analysis for EV, EVSE, and/or Fleet pillars with an industry perspective.

Interested in Partnering with NGP?

Contact NGP PI: Sam Thurston, ANL

sthurston@anl.gov

Thank You!

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eCHIP

Optimized and Robust Energy Management for DC Charging Hub: A Hybrid Controller Approach

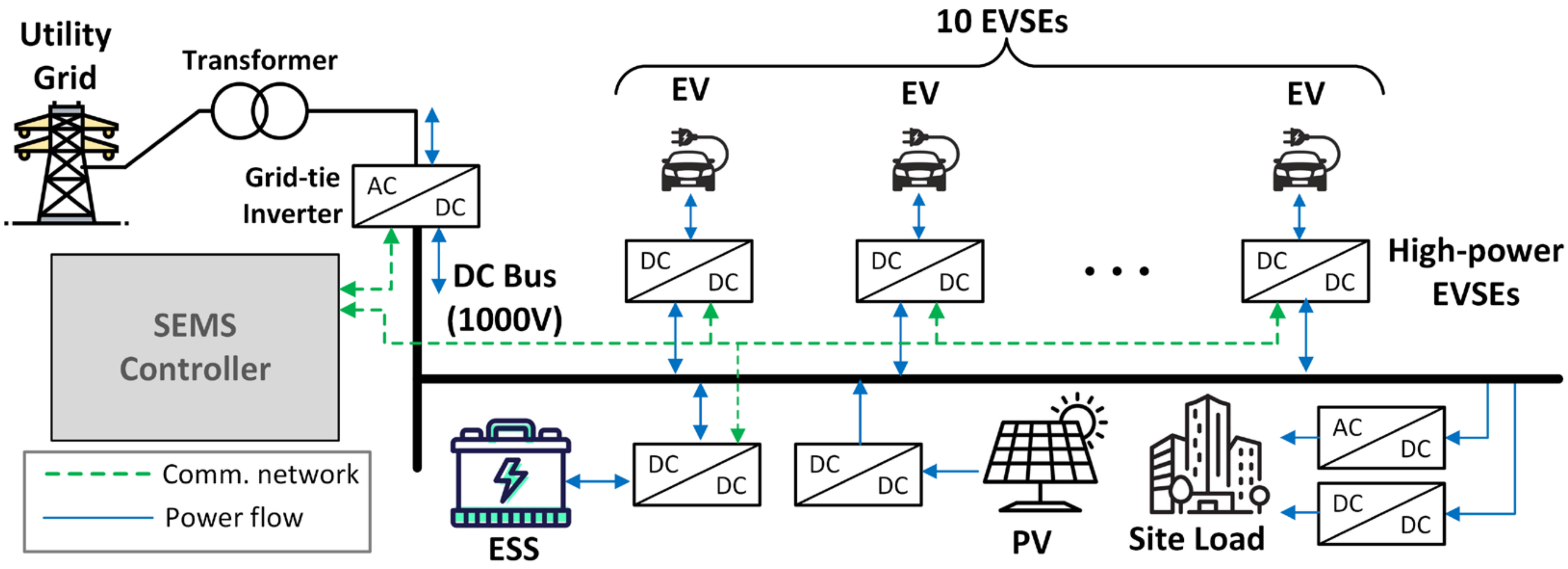
Emin Ucer, NREL

Nov 12, 2024

Outline

- **Overview of HPC DC Hub**
- **Problem Definition**
  - Energy management and robust real-time control in DC charging hubs
- **Hybrid Controller**
  - Centralized MPC-based energy management
  - Droop control
- **Offline Simulation results**
- **CHIL and SEMS platform**
- **CHIL Validation**
- **Conclusion and Future Work**
- **Q&A**

Overview of High-Power DC Charging Hub



A typical HPC DC Hub

Problem: Need for Energy Management and Control

Goal: Coordinate power flows among hub assets to achieve high-level operational objectives and benefits while ensuring robust, resilient performance under disturbances and unforeseen conditions.

Operational Objectives (Slow and long term)

- Cost minimization
- Demand response
- Customer satisfaction
- Grid interactions and services
- Renewable utilization
- Optimizing asset lifespan

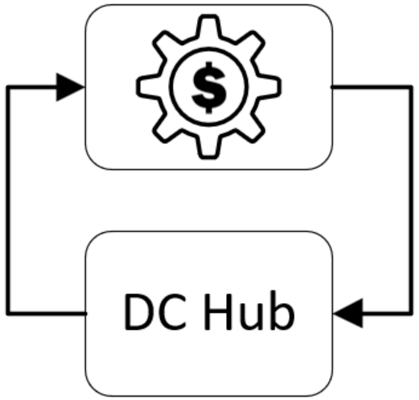
Disturbance Handling (Fast and short term)

- Load surge
- Generation drop
- Commutation failure
- Asset failure
- Faults
- Blackouts

What is the Hybrid controller?

Operational Objectives

Centralized/Optimized Control



- Optimized for long-term performance
- Customizable to support complex objectives
- Centralized and slower operation
- Real-time connectivity requirement

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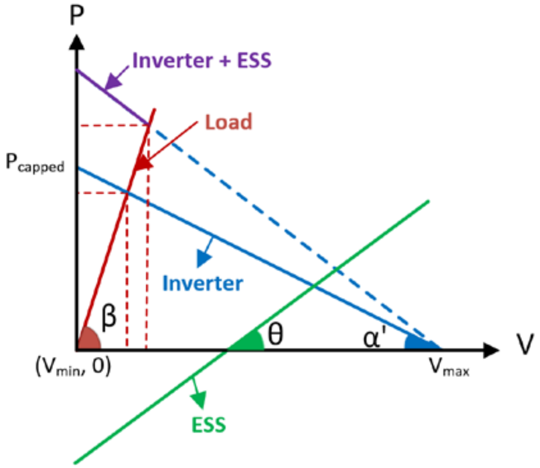
Disturbance Handling

Droop-based Control



- Decentralized and faster operation
- Minimal communication requirement
- Sub-optimal performance
- Limited scope for defining operational objectives

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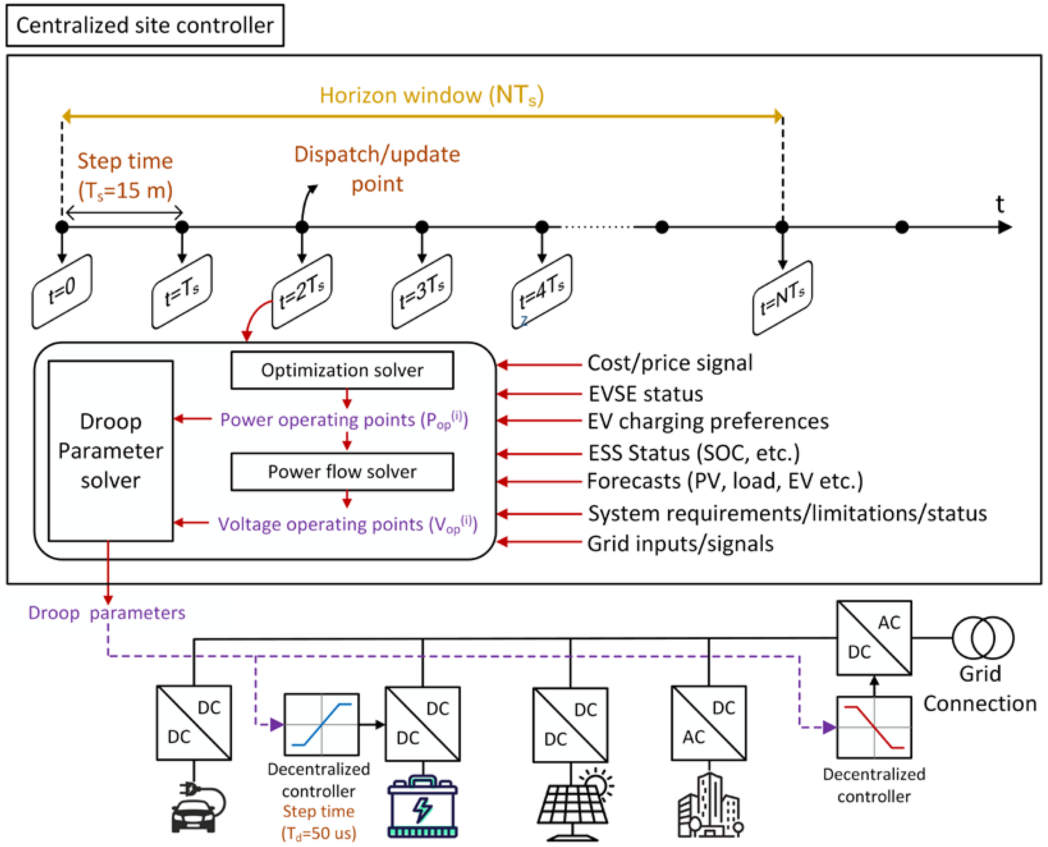
Hybrid Controller



Hybrid Controller: MPC Formulation

Goal: Minimize cost of energy received from power grid utilizing energy stored in ESS.

ESS power vector set points — Power from grid — Relaxation term

$$\min_{\mathbf{P_{ess}}} \; J(\mathbf{P_{ess}}) = \sum_{k} \left(c_k P_{inv}[k] \Delta t + \zeta s \right) \tag{1a}$$

c_k: Energy price at time k ($/kWh)

Inverter power — ESS power — Forecasted EVSE, PV & Site Load powers

$$\text{s.t.} \quad P_{inv}[k] = P_{ess}[k] + P_{evse}^{agg,(f)}[k] + P_{pv}^{(f)}[k] + P_{load}^{(f)}[k],$$

→ Power balance

$$SOC_{ess}[k+1] = SOC_{ess}[k] + \frac{(P_{ess}[k]\eta_{ess}\Delta t)}{Q_{ess}},$$

→ MPC state eq (ESS SOC)

$$P_{inv}^{min} \le P_{inv}[k] \le P_{inv}^{max},$$
$$P_{ess}^{min} \le P_{ess}[k] \le P_{ess}^{max},$$

→ Inverter and ESS power limits

$$SOC_{ess}^{min} - \zeta \le SOC_{ess}[k] \le SOC_{ess}^{max} + \zeta,$$

→ ESS SOC constraint

$$SOC_{ess}^{target} = (SOC_{ess}^{min} + SOC_{ess}^{max})/2,$$

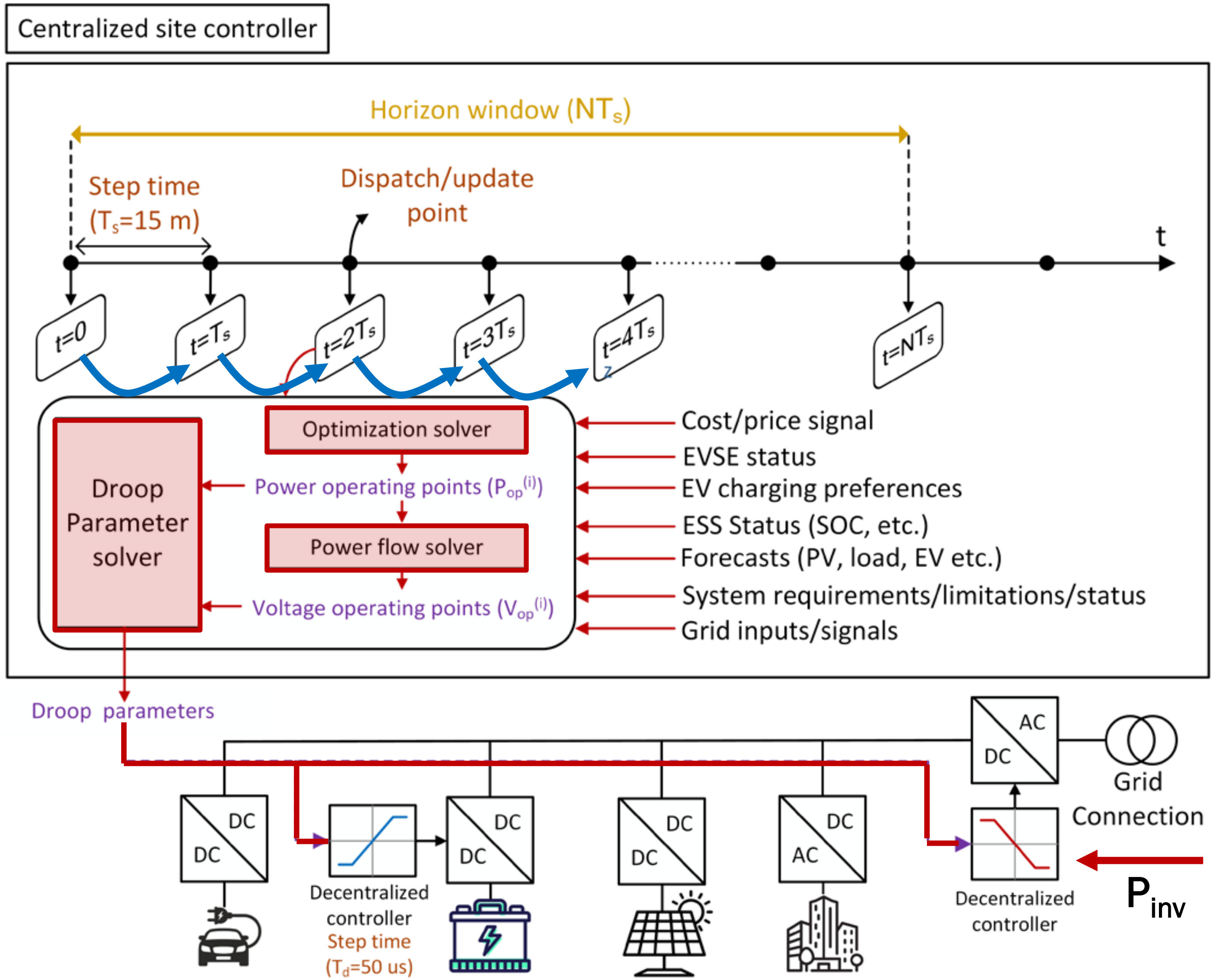
→ Target SOC (50%)

$$\frac{1}{N}\sum_k SOC_{ess}[k] \ge SOC_{ess}^{target} - 10\%,$$
$$\frac{1}{N}\sum_k SOC_{ess}[k] \le SOC_{ess}^{target} + 10\%,$$

→ Target SOC band

$$\forall k \in \Omega_k = \{0, \ldots, N-1\}$$

→ Discrete time N=24*4=96



Hybrid Controller: Droop Calculation

Assumption: Only ESS is controllable. EV and site loads as well as PV generation are uncontrolled (disturbances).

Inverter droop equation

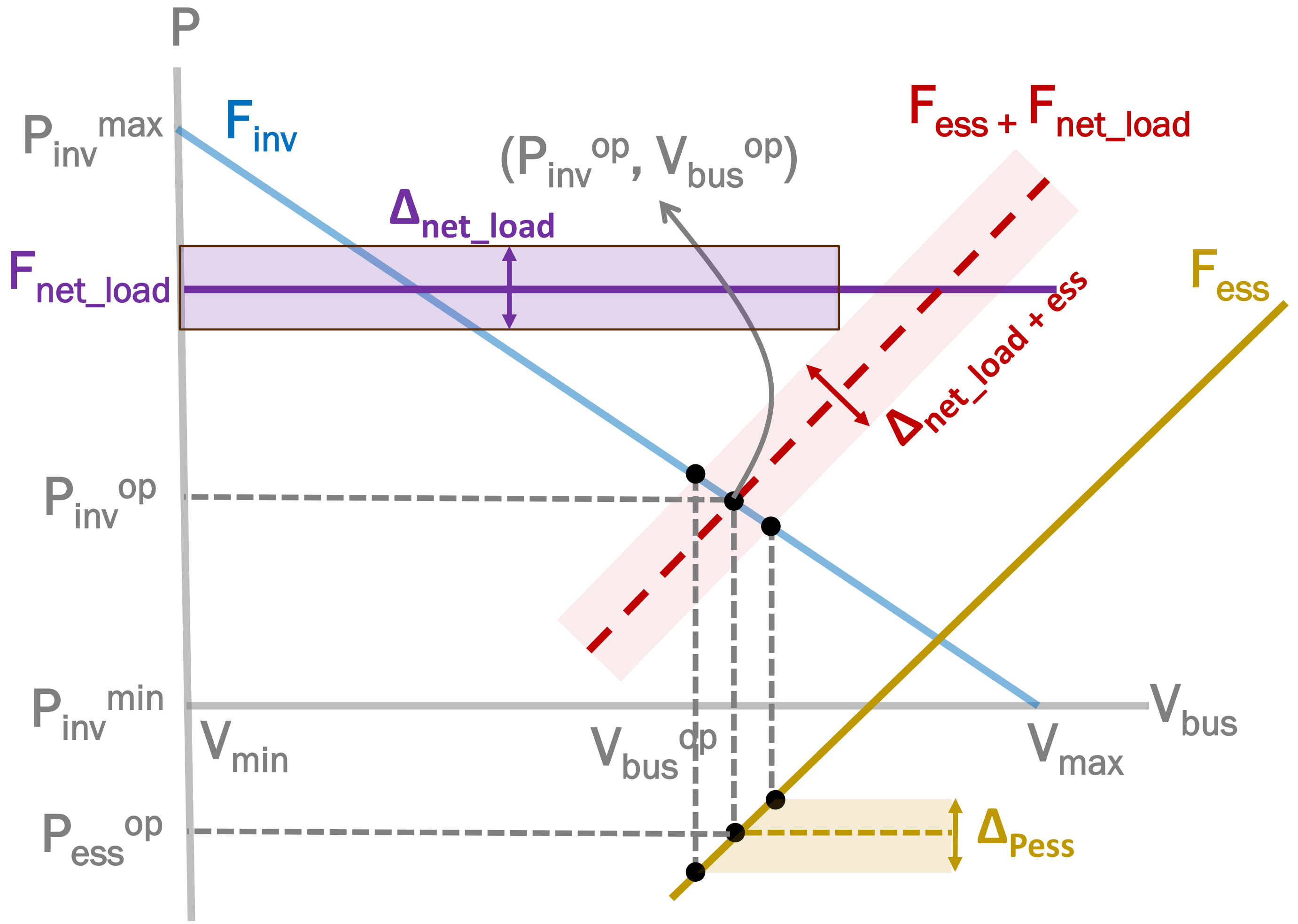
$$V_{bus} = F_{inv}(P_{inv}) = (P_{inv}^{max} - P_{inv})\kappa_{inv} + V_{bus}^{min}$$

$$P_{ess} = F_{ess}(V_{bus}) = (V_{bus} - \underbrace{V_{bus}^{op}}_{\text{Operating bus voltage}})\kappa_{ess} + \underbrace{P_{ess}^{op}}_{\text{Operating ESS power}}.$$

ESS droop equation

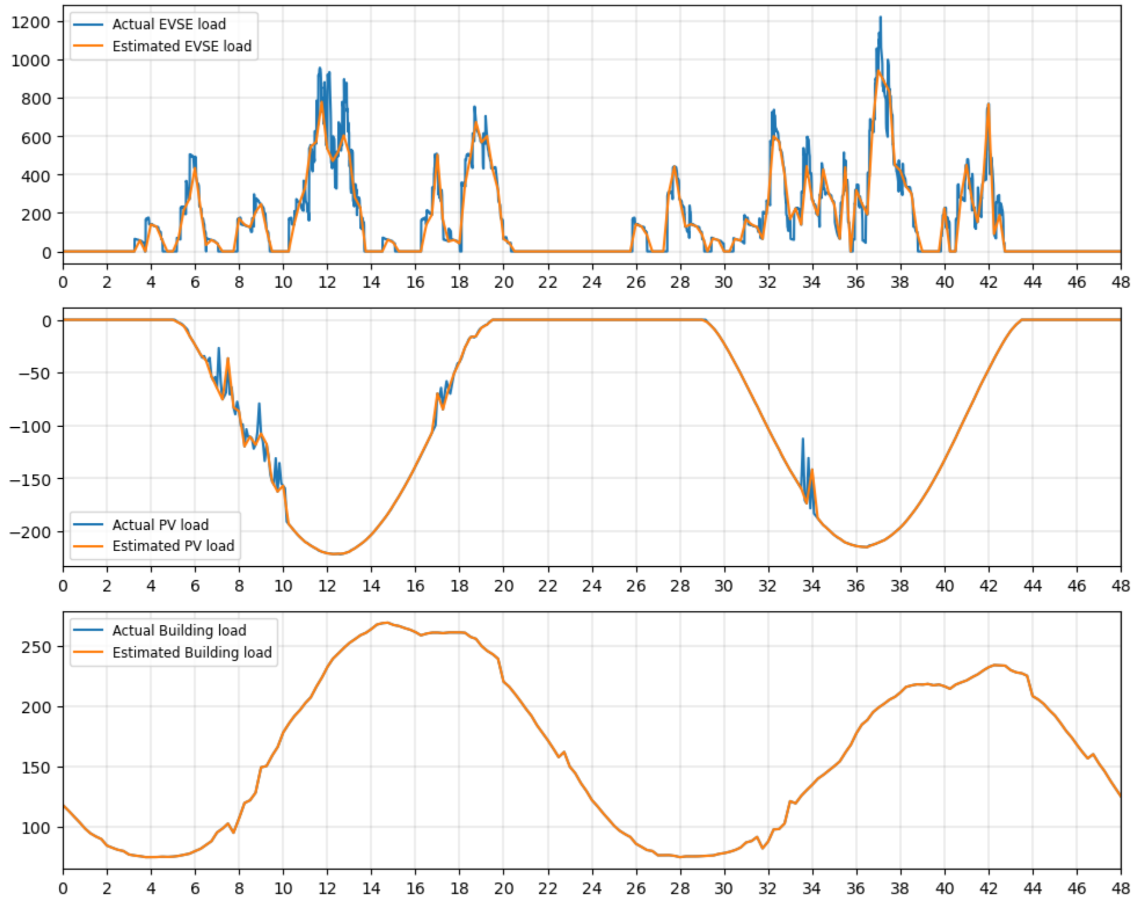
Operating bus voltage

Operating ESS power

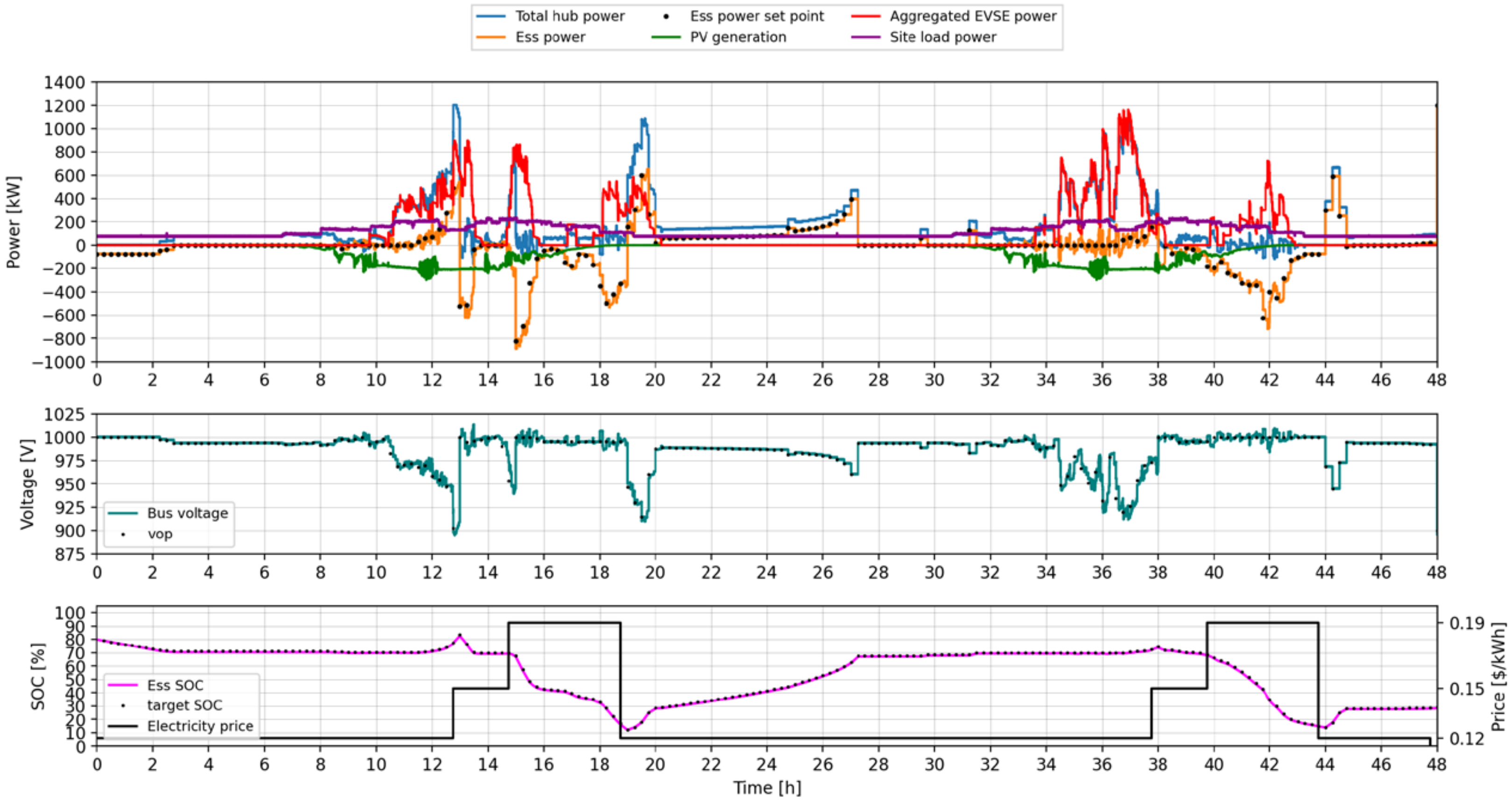


What about forecasts of uncontrolled loads and generation?

- **MPC relies on accurate forecasting of <u>uncontrolled</u> loads**
- **Aggregated loads usually follow cyclic trends that can be extracted from historical data**
  - Building load pattern
  - EV arrival and departure times
  - PV generation
- **Any mismatch between forecasted and actual load and generation will result in divergence from optimal operating point determined by MPC. Potential solutions**
  - Better and more accurate forecasting
  - Increasing controllability
    - MPPT
    - EV charge control
- **Droop control plays critical role to respond to disturbances resulting from mismatches**



Hybrid Controller in Action (2-day offline simulation in EVI-EnSitePy)



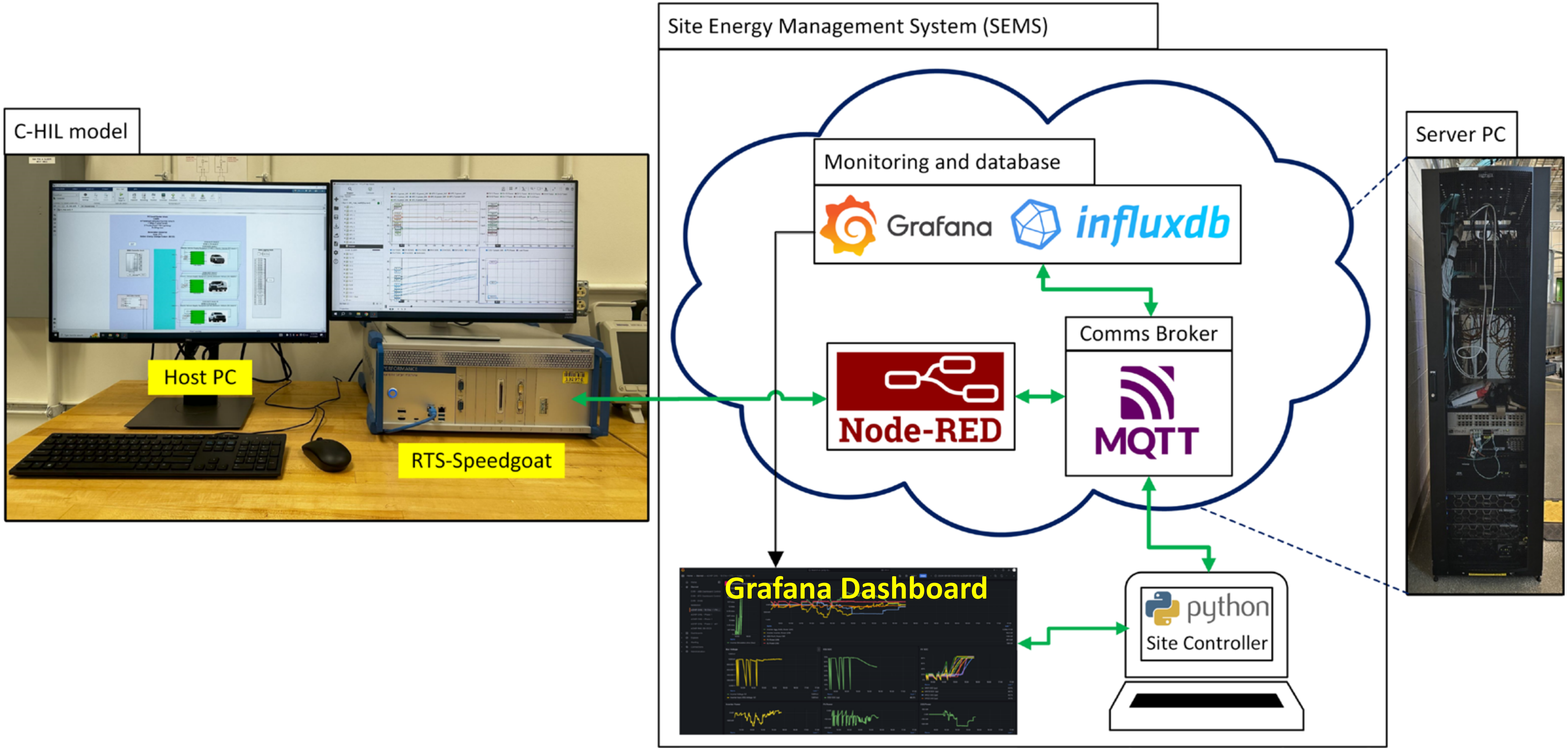
Component Type	Power Rating	Voltage/Current/Energy Ratings
Inverter	1,200 kVA	Input: 3-ϕ, 480 VAC Output: 1000 VDC
DC Bus	-	1000 VDC
(x3) EVSE Type-1	150 kW rated	Input: 1000 VDC Output: 400 VDC
(x3) EVSE Type-2	175 kW rated	Input: 1000 VDC Output: 400 / 800 VDC
(x4) EVSE Type-3	350 kW rated	Input: 1000 VDC Output: 400 / 800 VDC
EV Type-1	235 kW max	800 VDC, 70-80 kWh
EV Type-2	108 kW max	400 VDC, 60-70 kWh
EV Type-3	155 kW max	370 VDC, 90-100 kWh
ESS	1,500 kW max	1000 VDC, 2 kWh
PV	235 kW max	-
Site load	269 kW max	-

Hub consists of assets
- 10 EVSE
- 1 ESS
- 1 PV
- 1 Grid-tie inverter
- 1 Site load

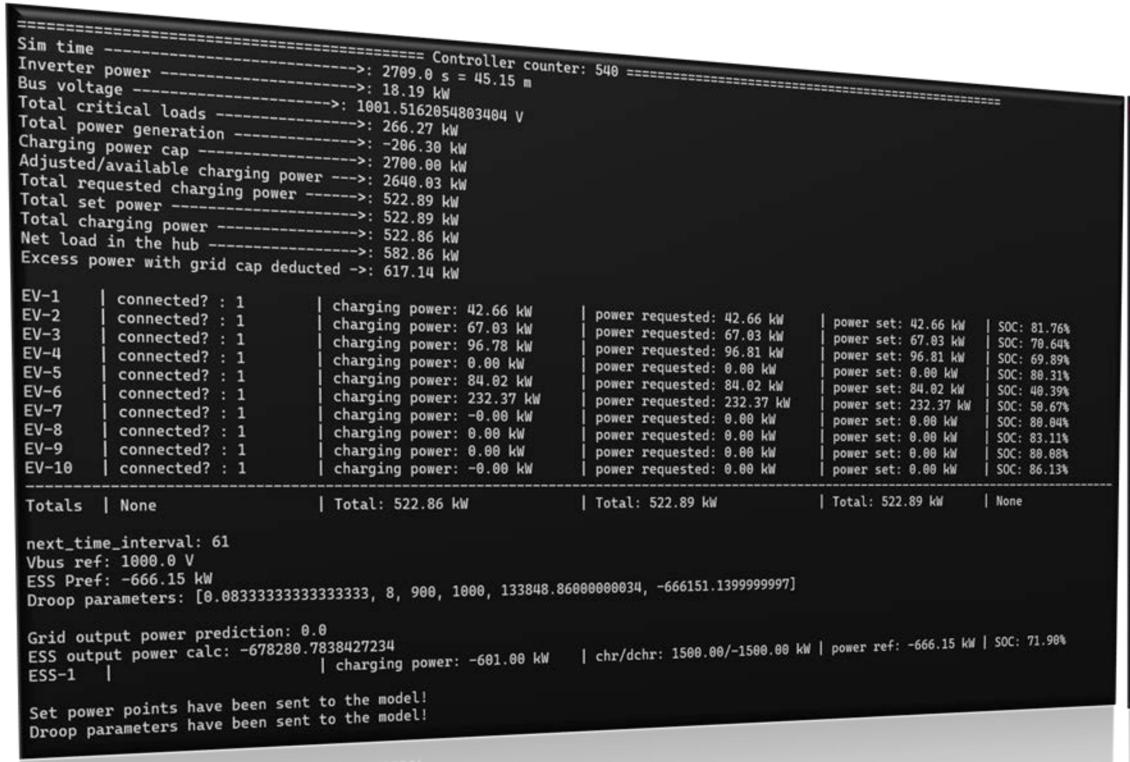
- Goal is to minimize total cost of energy received from utility grid by leveraging ESS.
- Forecasts for EVSE, PV, and site load power are incorporated into MPC
- ESS power setpoint is updated every 15 minutes, with new droop coefficients calculated based on updated operating point.
- ESS supports hub by discharging during peak price periods and charging during off-peak hours.

Publication: E. Ucer, V. Pawaskar, D. Jackson, A. Thurlbeck, E. Watt, J. Kisacikoglu, "Hybrid Energy Management with Real-Time Control of a High-Power EV Charging Site" in IEEE Energy Conversion Congr. Expo. (ECCE), 2024

C-HIL Platform and SEMS



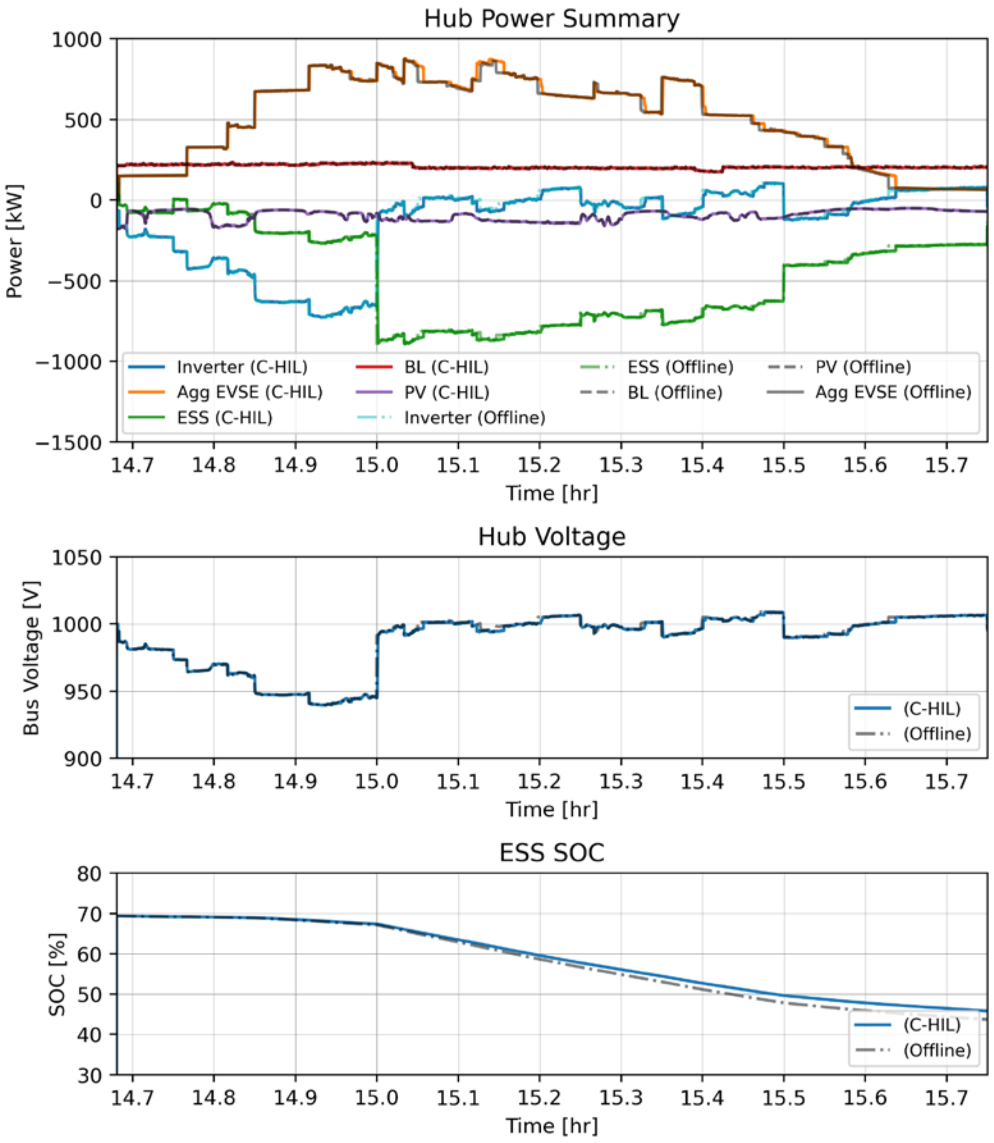
Site Energy Management System (SEMS)



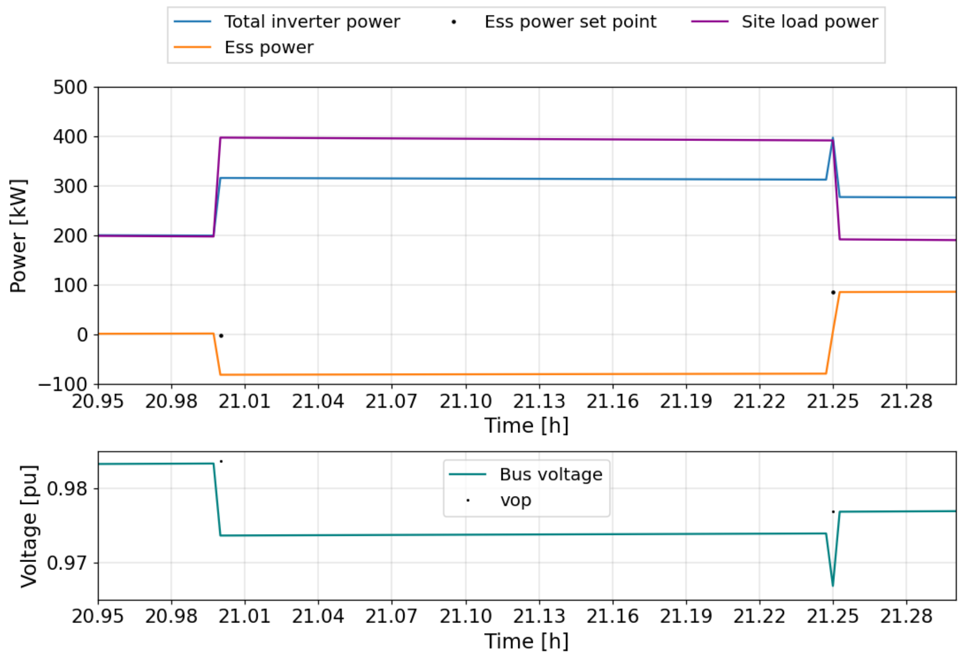
Controller console

Monitoring Console

CHIL Validation



- 1h window was selected from offline 2-day simulation for validating SEMS operation in C-HIL platform
- Results closely match offline simulation expect for some minor differences due to modeling variations



15m load surge disturbance and ESS's response

Conclusion and Future Work

Conclusion

- Hybrid approach can offer best of both worlds
  - Achieving longer time objectives and optimized operation
  - Responding to fast disturbances and fluctuations, ensuring robustness and responsiveness
- Forecasting uncontrolled loads/sources is critical for effective operation
  - More accurate forecast methods
  - Increasing number of controlled assets
- Hybrid controller verified as real-time controller
  - CHIL
  - SEMS

Future Work

- Testing new operational objectives (grid services etc.)
- Controlling EVSE and PV generation
- Testing new forecasting methods
- Implementing hybrid controller on PHIL platform

Thank You

Questions and Comments

Emin Ucer, Ph.D.
National Renewable Energy Laboratory (NREL)
Research Engineer | Center for Integrated Mobility Sciences

emin.ucer@nrel.gov

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eCHIP Project

Exploring Decentralized Site Control in the DC Charging Hub Testbed

Alastair Thurlbeck, NREL

November 12, 2024

Outline

- **Introduction to Site Control Concepts**
- **Introduction to Droop Control**
- **eCHIP “DC Hub” Experimental Test Platform Overview**
- **Droop Control Hardware Implementation**
- **Droop Control Experimental Testing**
  - Comparing droop to a centralized rules-based approach
  - Islanded operation under droop control
- **Stability Considerations**
- **Future Work**
- **Conclusions and Next Steps**

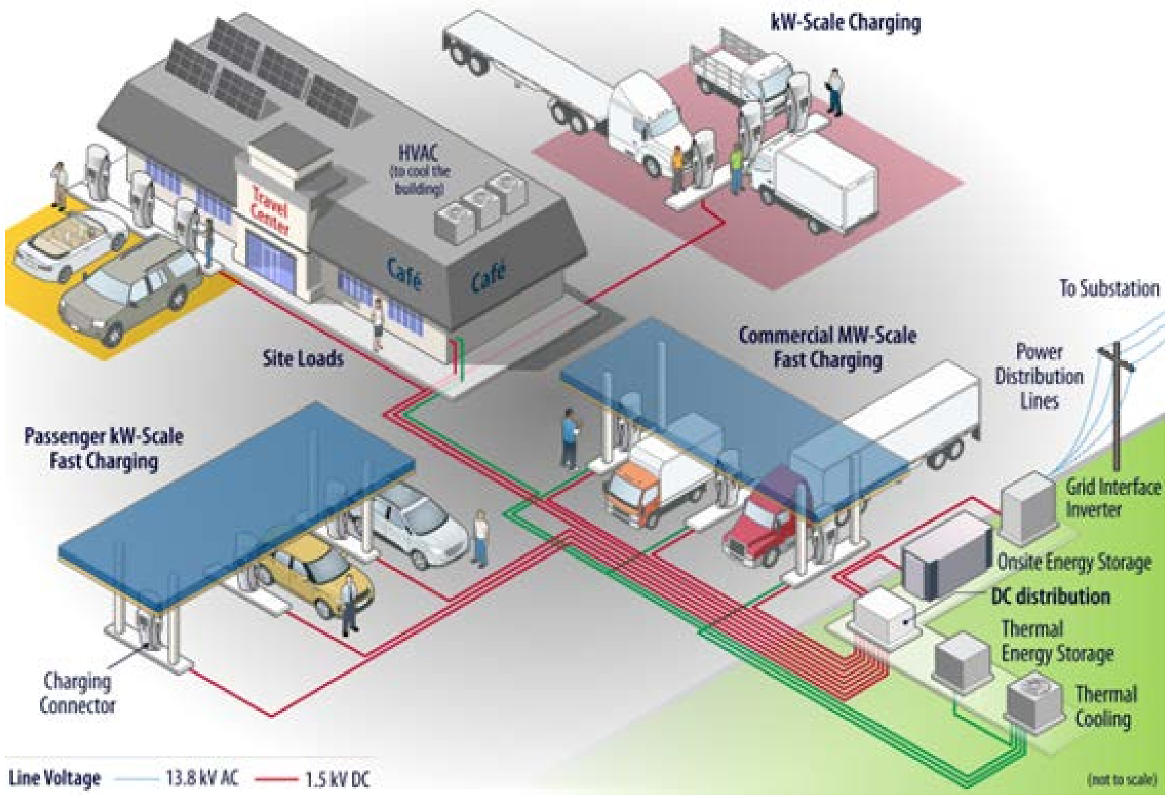
Site Level Controller Functions

Managing the fundamental power demand and generation within the hub:

- Dispatching energy storage
- Load management (including smart charge management)
- Generation curtailment
- Controlling grid power consumption and injection

Balancing broader system objectives:

- Minimize operating cost
- Minimize charging times
- Maximize charging station resiliency



eCHIP's DC Hub architecture enables decentralized DC droop control.

Example Site Control Approaches

- **Centralized**
  - Rules-based (heuristics)
  - Optimized
- **Decentralized**
  - DC Droop Control (continuous voltage)
  - DC Bus Signaling (voltage zones)
  - Power-line Communication (signal injection)
- **Hybrid**
  - Local Droop + Central Optimization

Introduction to Droop Control

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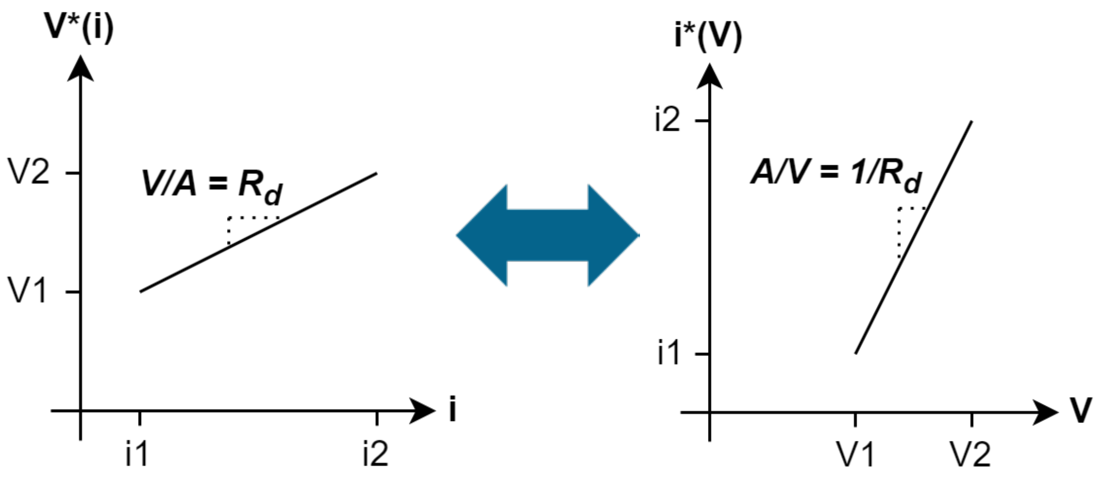
Droop Control Basics

- Sources and loads (nodes) in the system are given a "droop function" to actively participate in the droop control system. Not all nodes need to actively participate in droop control. i.e. they can operate as uncontrolled generation / load.
- A droop function defines a relationship between a node's output voltage and current (output = DC distribution bus connection)
  - There are two fundamental forms of droop function:
    - V*(i) = Voltage setpoint as a function of measured current
    - i*(V) = Current setpoint as a function of measured voltage

      Note: Droop functions can also use power instead of current, using V(P) or P*(V).*
- Regions of constant slope in the V*(i) and i*(V) functions have a direct equivalency. However, dead zones / plateaus do not and must be designed differently.
- Dynamic behaviors of the V*(i) and i(V) functions are not the same [1].

Sign Convention:
+ve Current = LOAD (sinking current from the bus)
-ve Current = GENERATION (sourcing current to the bus)



V*(i) and i*(V) Droop Function Equivalency

Droop Behavior	V*(i) Slope	i*(V) Slope
Linear slope	e.g. Rd = 0.2	1/Rd = 5
Voltage plateau	Rd = 0	1/Rd = ∞ (not permitted)
Current plateau	Rd = ∞ (not permitted)	1/Rd = 0

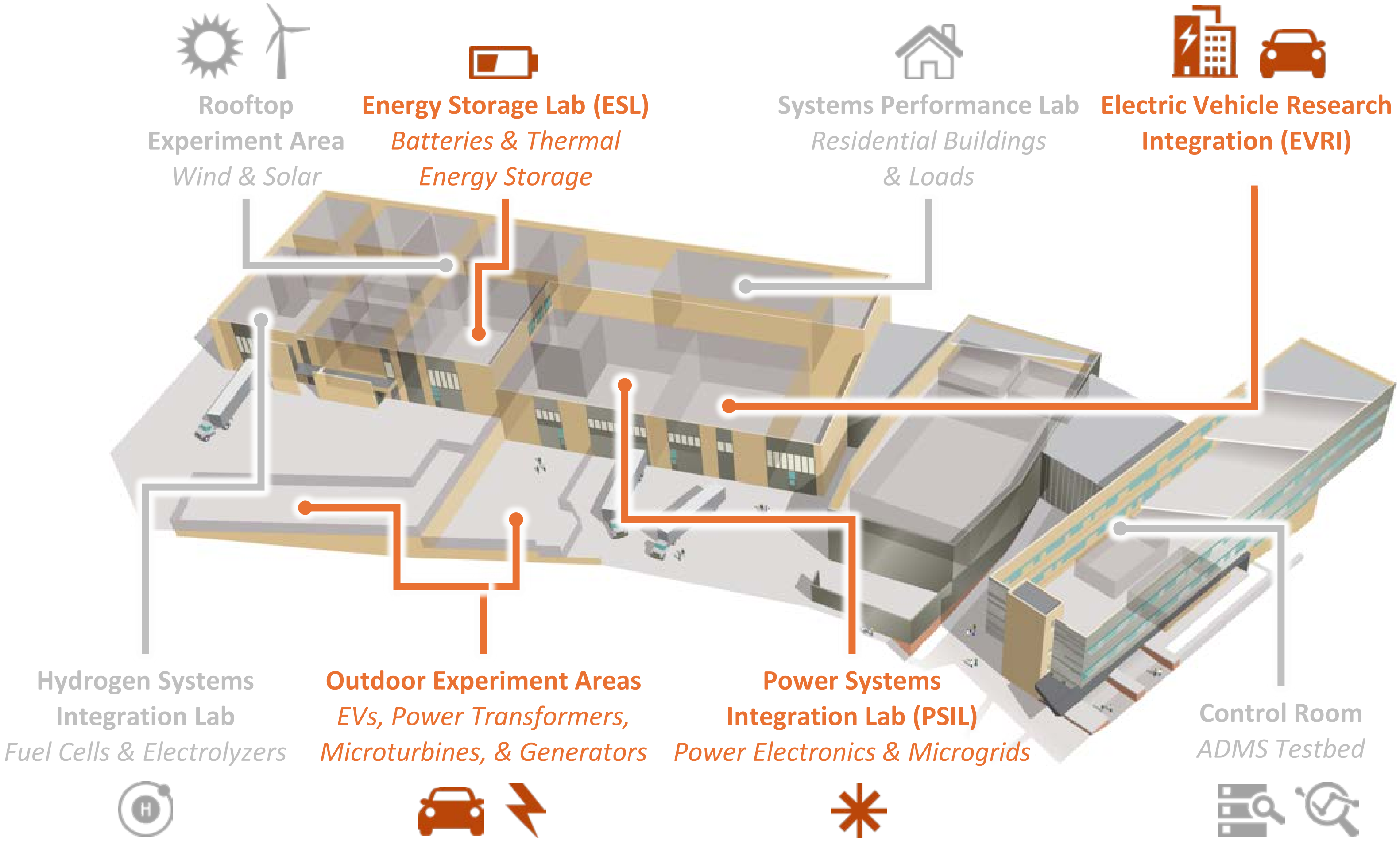
[1] P. Li *et al.*, "Reduced-Order Modeling and Comparative Dynamic Analysis of DC Voltage Control in DC Microgrids Under Different Droop Methods," *IEEE Transactions on Energy Conversion*, vol. 36, no. 4, pp. 3317–3333, 2021

eCHIP "DC Hub" Experimental Test Platform Overview

DC-distributed charging hub spanning multiple lab spaces

- **EVRI, ESL, PSIL, and Outdoor Test Areas**

Energy Systems Integration Facility (ESIF)



Droop Control Hardware Implementation

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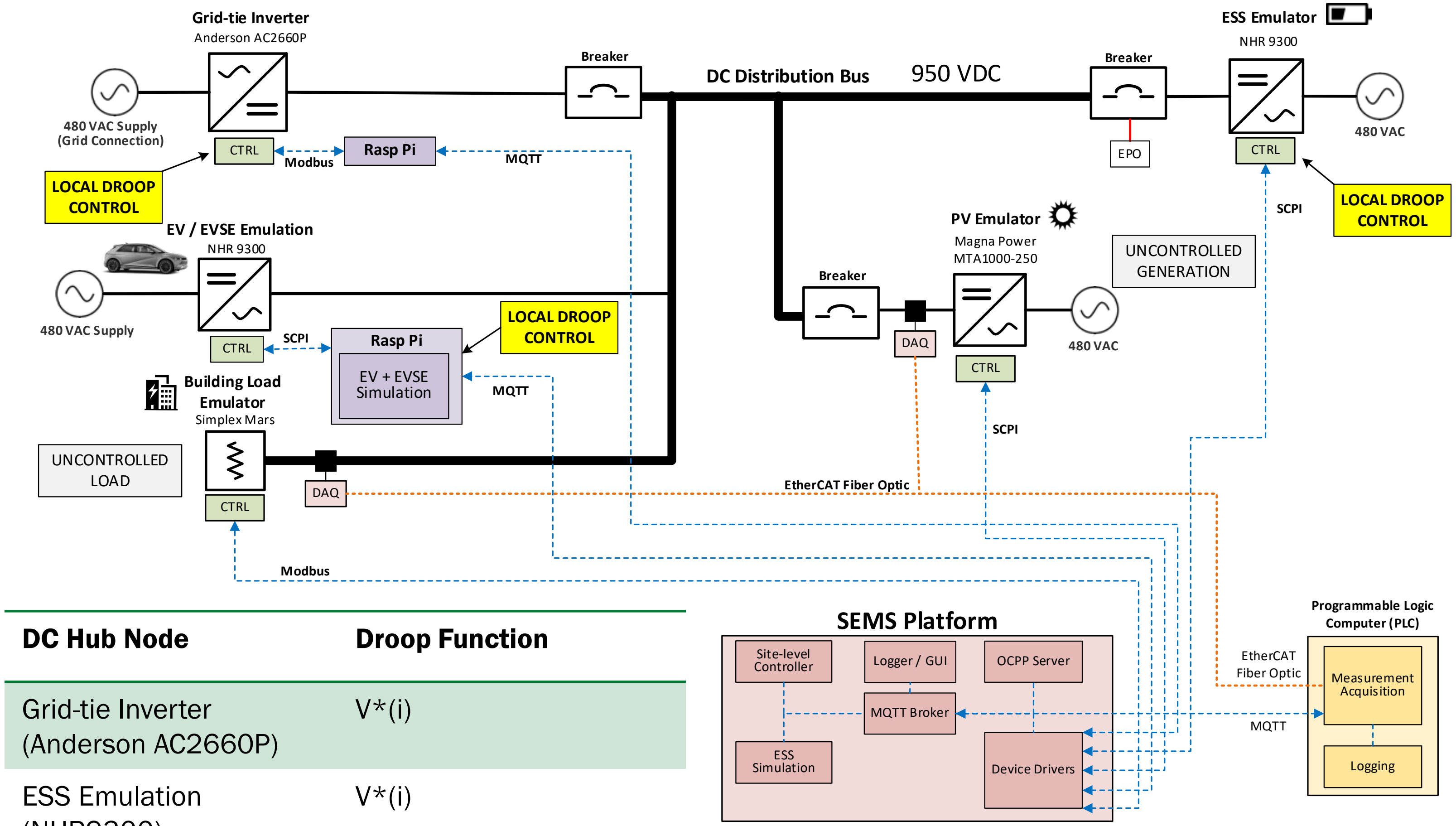


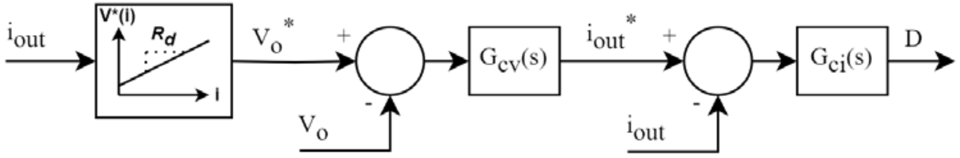
DC Hub Node	Droop Function
Grid-tie Inverter (Anderson AC2660P)	V*(i)
ESS Emulation (NHR9300)	V*(i)
EV / EVSE Emulation (NHR9300)	$P_{limit}(V)$
PV Emulation (Magna Power)	N/A (uncontrolled generation)
Building Load Emulation (Simplex Mars)	N/A (uncontrolled load)

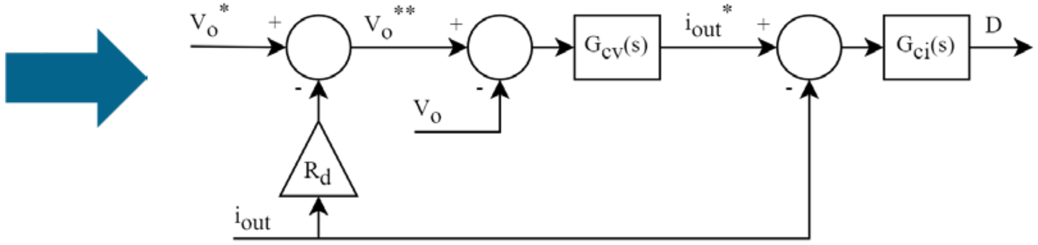
Clockwise from top left: Anderson AC2660P (GTI); NHR 9300 (EV/EVSE Emulation); Simplex Mars (Building Load); Magna Power MTA1000-250 (PV Emulation)

Droop Control Hardware Implementation

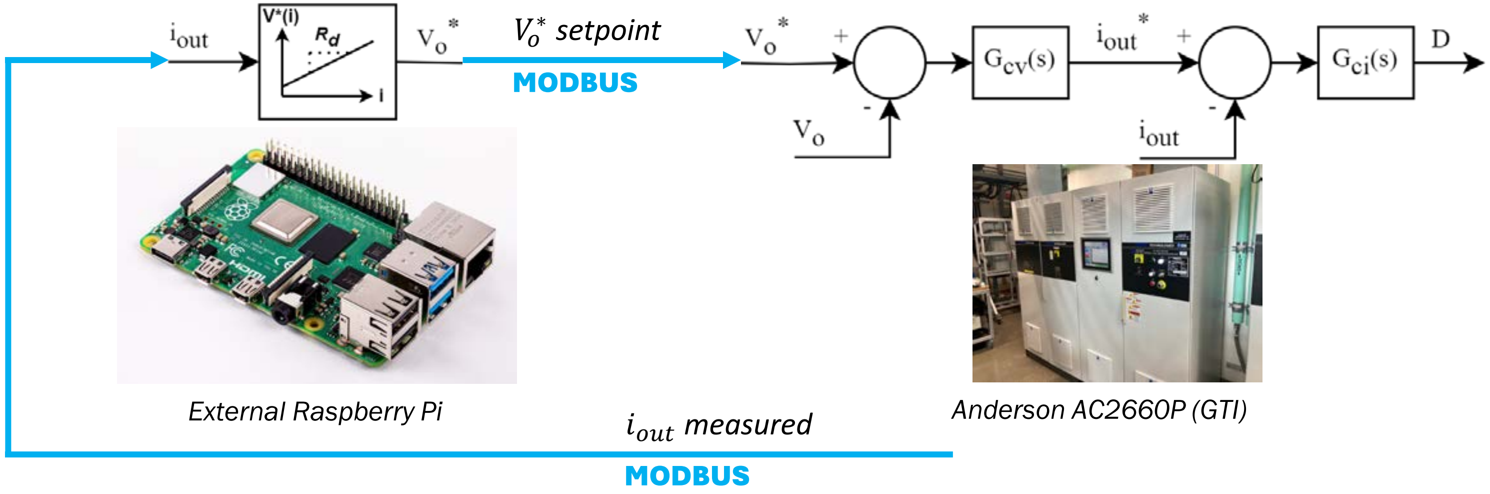
DC Hub Node	Droop Function	Droop Implementation
Grid-tie Inverter (Anderson AC2660P)	V*(i)	Option 1: Voltage control mode with output resistance emulation Option 2: External droop control implementation on raspberry Pi
ESS Emulation (NHR9300)	V*(i)	Voltage control mode with output resistance emulation
EV / EVSE Emulation (NHR9300)	$P_{limit}(V)$	External droop control implementation on Raspberry Pi

V*(i), Internal: Voltage control mode with output resistance emulation





V*(i), External: Raspberry Pi



External Raspberry Pi

Anderson AC2660P (GTI)

Droop Control vs Centralized Rules-based Controller – Experimental Setup

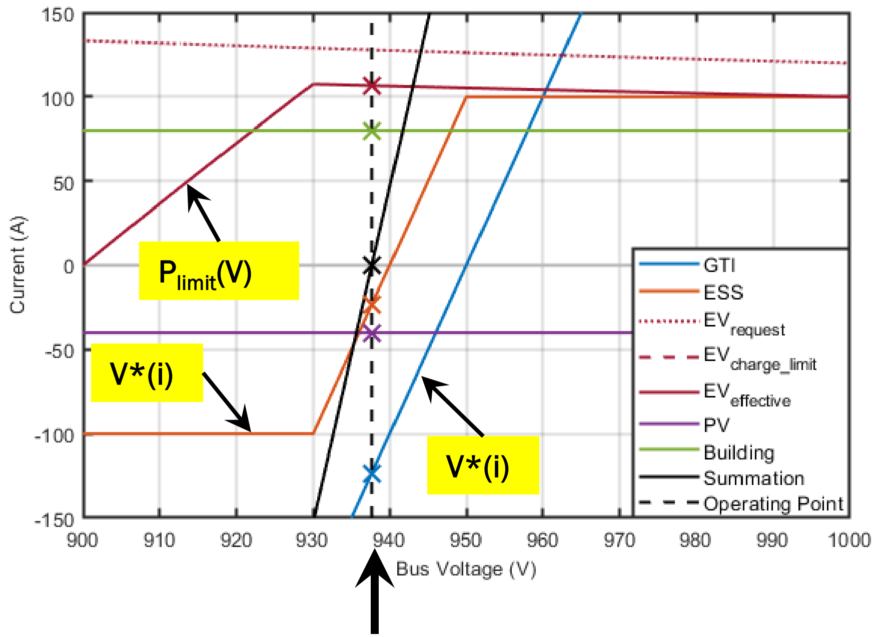
Common Test Case Parameters

DC Hub Node	Rated Power / Capacity
Grid-tie Inverter	660 kW
ESS Emulation	100 kW / 200 kWh
EV / EVSE Emulation	100 kW (EVSE limited) / 77.4 kWh (EV)
PV Emulation	40 kW
Building Load Emulation	80 kW

Centralized Rules-based Controller

- ESS power is dispatched as:
  $$P^*_{ESS} = -(P_{LOADS} - P_{GENERATION} - P_{THRESHOLD})$$
- Additional rules / conditions ensure the ESS SOC is maintained within its operational range.
- $P_{THRESHOLD}$ controls the bias point / offset of the ESS operation. When the net hub load (loads minus generation) exceeds $P_{THRESHOLD}$, then the ESS is discharging. Otherwise, it is charging.
  $$P_{THRESHOLD} = 100 \text{ kW}$$

Decentralized Droop-control Configuration



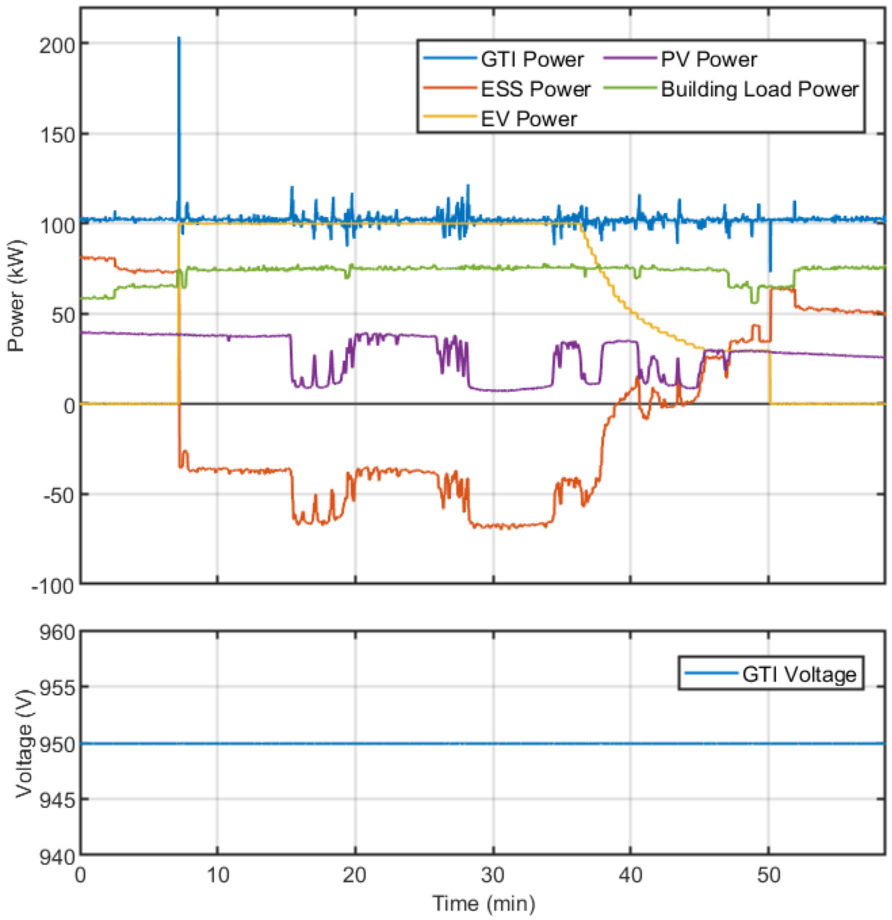
System operating point where Summation = 0 A

Example operating point shown:

DC Hub Node	Current (A)
Grid-tie Inverter	-123.3 A (power from grid)
ESS Emulation	-23.3 A (discharging)
EV / EVSE Emulation	106.6 A (120 kW requested, 106.6 A limit)
PV Emulation	-40 A
Building Load Emulation	80 A

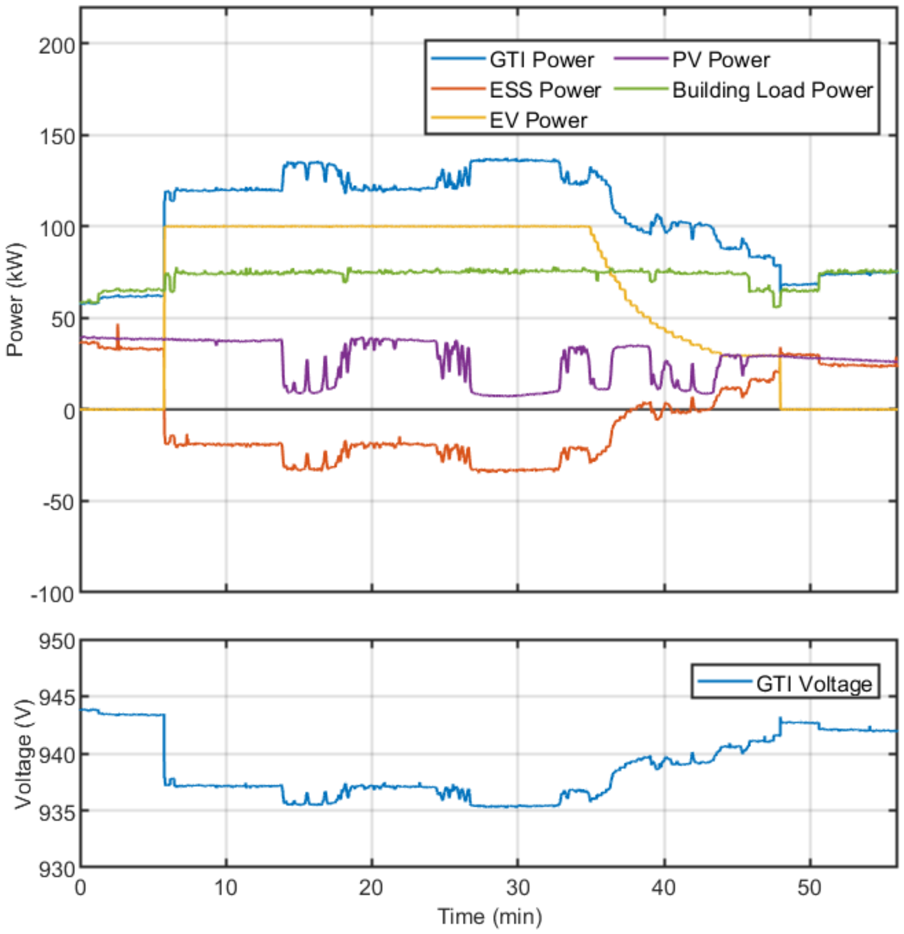
Droop Control vs Centralized Rules-based Controller – Results

Centralized Rules-based Control



DC Hub Node Powers and DC Bus Voltage.
Emulated EV Charging from 7 to 50 minutes.

Decentralized Droop Control



DC Hub Node Powers and DC Bus Voltage.
Emulated EV Charging from 5 to 48 minutes.

Islanded Operation using Droop Control – Experimental Setup

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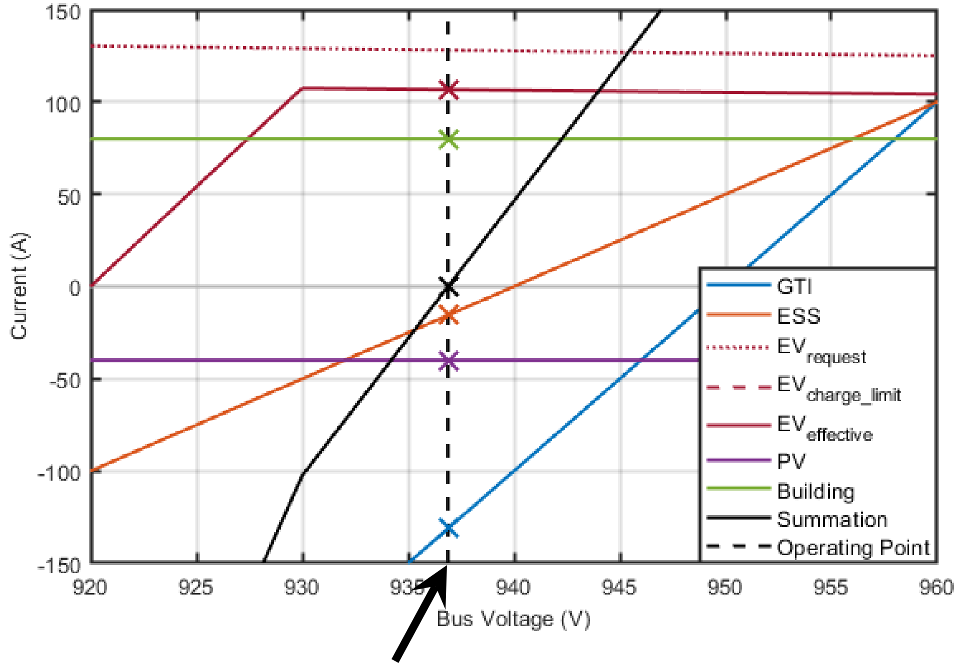
Nominal Operation (GTI connected)

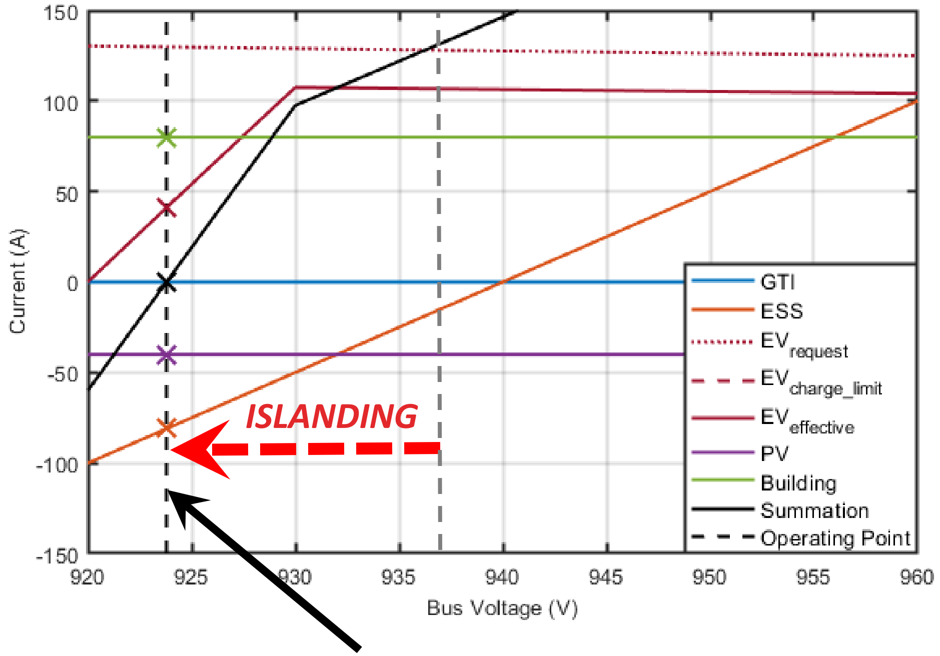


System operating point where Summation = 0 A

Example operating point shown:

DC Hub Node	Current (A)
Grid-tie Inverter	-131.2 A (power from grid)
ESS Emulation	-15.6 A (discharging)
EV / EVSE Emulation	106.7 A (120 kW requested, 106.7 A limit)
PV Emulation	-40 A
Building Load Emulation	80 A

Islanded Operation (GTI disconnected)



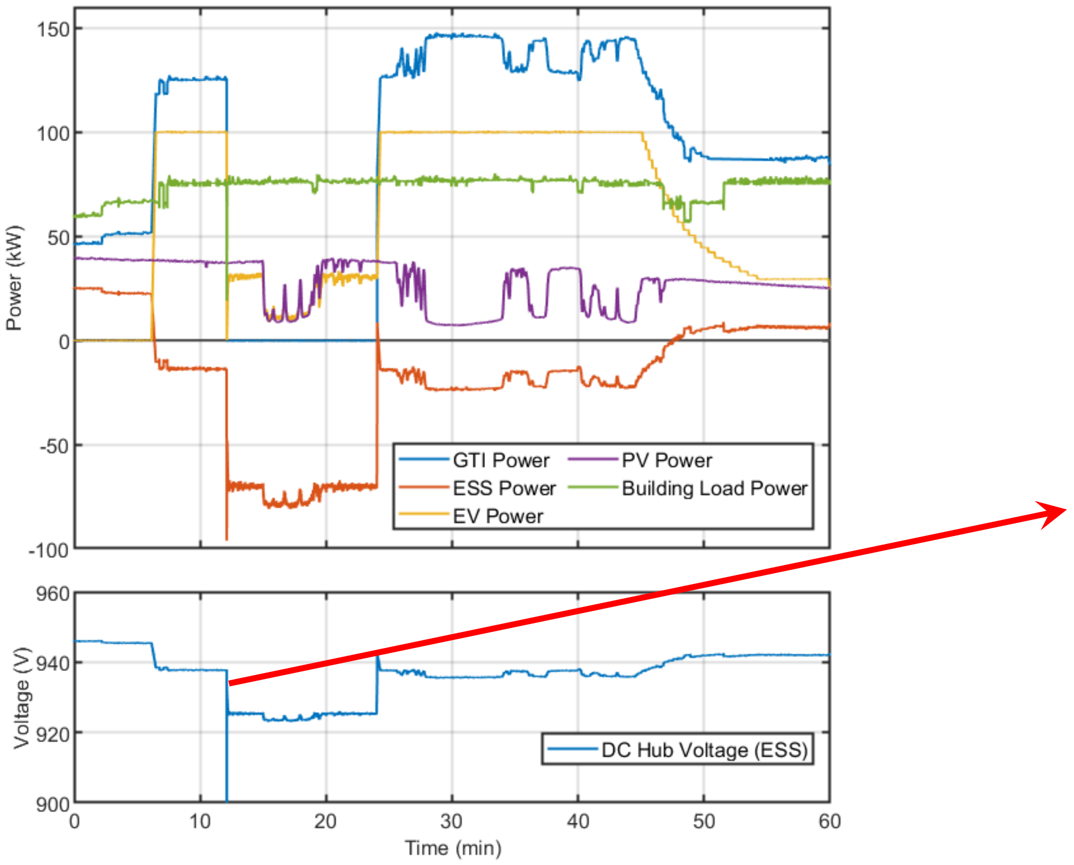
System operating point where Summation = 0 A

Example operating point shown:

DC Hub Node	Current (A)
Grid-tie Inverter	0 A (disconnected)
ESS Emulation	-81.0 A (discharging)
EV / EVSE Emulation	41.0 A (120 kW requested, 41.0 A limit)
PV Emulation	-40 A
Building Load Emulation	80 A

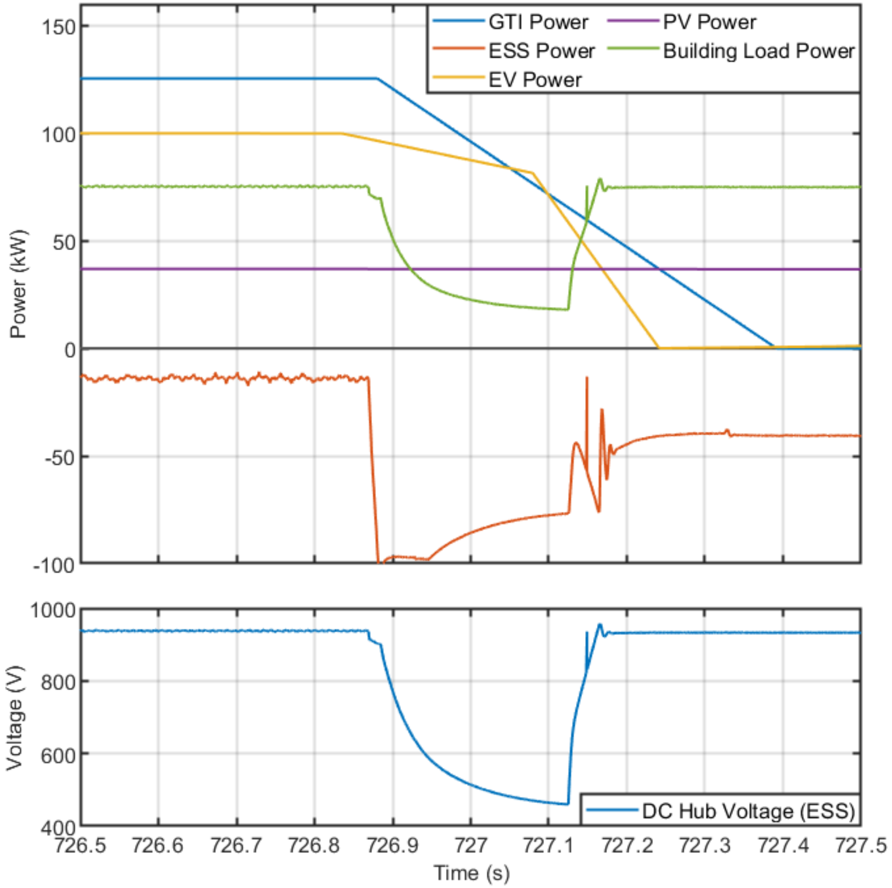
Islanded Operation using Droop Control - Results

Decentralized Droop Control with Islanding



DC Hub Node Powers and DC Bus Voltage.
Emulated EV Charging from 6 to 60 minutes.
Islanded from grid (GTI disconnected) from 12 to 24 minutes.

Loss of GTI Transient



DC Hub Node Powers and DC Bus Voltage.
Islanded from grid (GTI disconnected) at 726.87 seconds.

Exploring Piece-wise Linear Droop Curves – Experimental Setup

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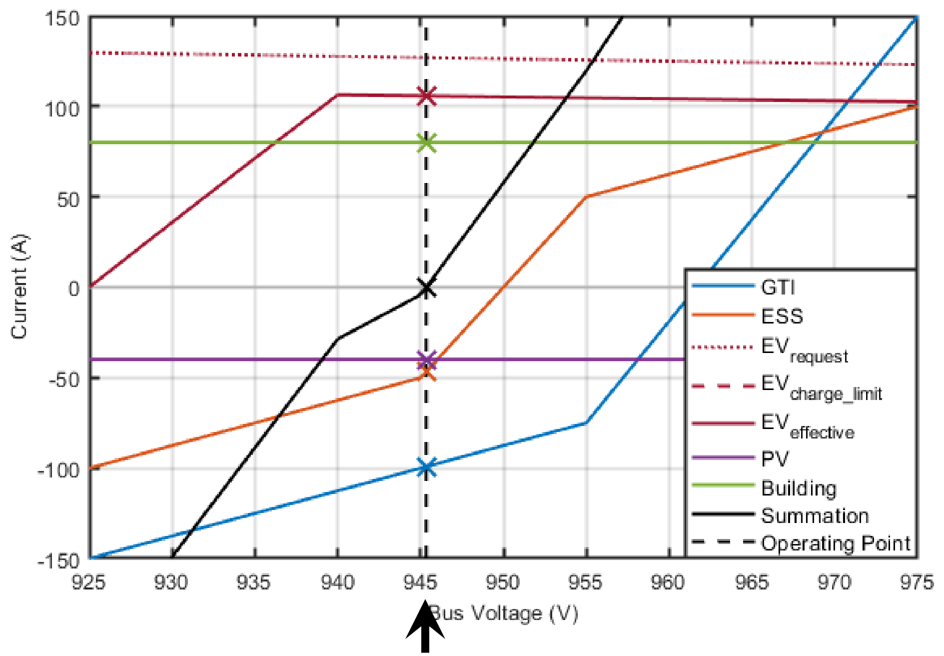
Nominal Operation (GTI connected)

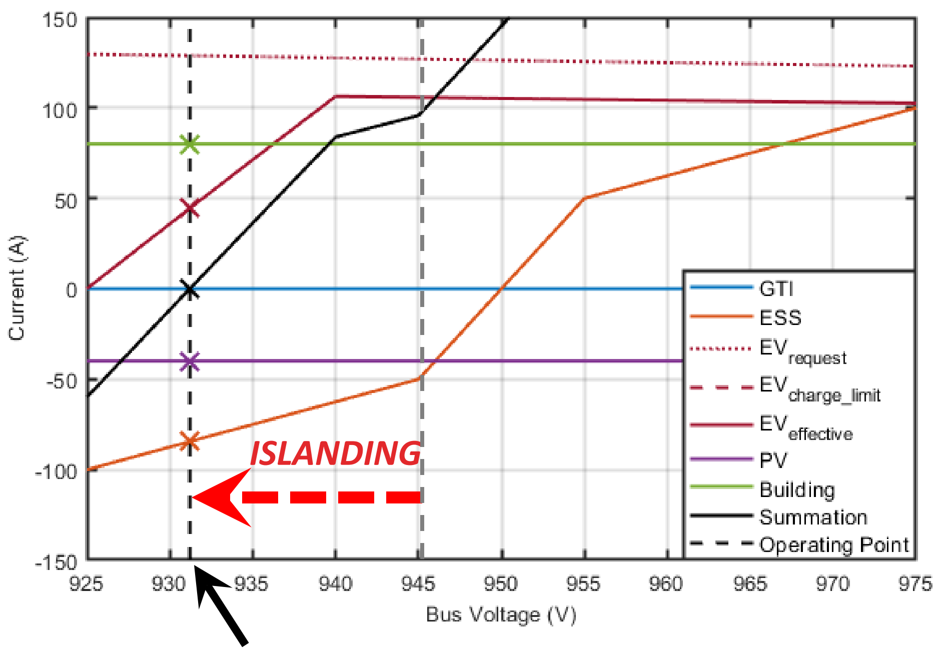


System operating point where Summation = 0 A

Example operating point shown:

DC Hub Node	Current (A)
Grid-tie Inverter	-99.1 A (power from grid)
ESS Emulation	-46.6 A (discharging)
EV / EVSE Emulation	105.8 A (120 kW requested, 105.8 A limit)
PV Emulation	-40 A
Building Load Emulation	80 A

Islanded Operation (GTI disconnected)



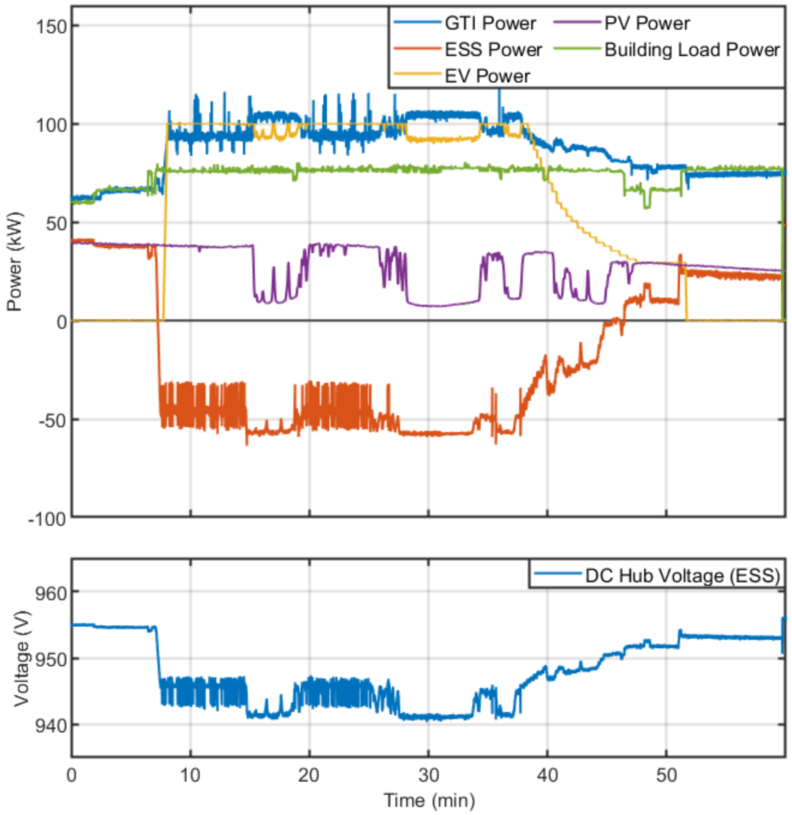
System operating point where Summation = 0 A

Example operating point shown:

DC Hub Node	Current (A)
Grid-tie Inverter	0 A (disconnected)
ESS Emulation	-84.5 A (discharging)
EV / EVSE Emulation	44.5 A (120 kW requested, 44.5 A limit)
PV Emulation	-40 A
Building Load Emulation	80 A

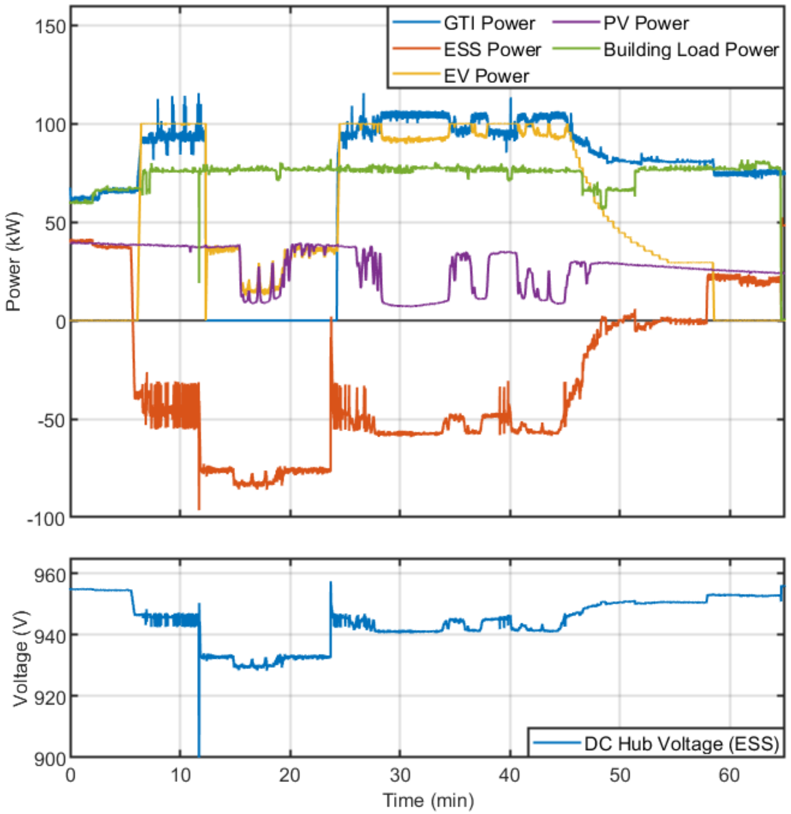
Exploring Piece-wise Linear Droop Curves - Results

Piece-wise Linear Droop: Nominal Operation



DC Hub Node Powers and DC Bus Voltage.
Emulated EV Charging from 7 to 52 minutes.

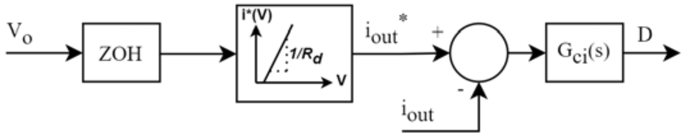
Piece-wise Linear Droop: Islanding Operation



DC Hub Node Powers and DC Bus Voltage.
Emulated EV Charging from 7 to 52 minutes
Islanded from grid (GTI disconnected) from 12 to 24 minutes.

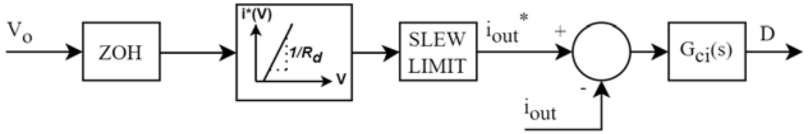
Stability Considerations

- Literature provides analysis for DC droop control systems. E.g. Impedance based stability analysis.
- In eCHIP HW implementation, we have observed some stability issues due to specific implementation constraints.
  - Adding droop control to nodes externally via Raspberry Pi introduces a zero-order-hold (ZOH) to the outermost control loop, due to the measurement sampling period and controller frequency.
  - In some situations, this causes a bounded oscillation in the droop system.
  - Two solutions:
    - Reduce external controller sample time and/or reduce the droop control slew rates (ensure oscillations bounded within an acceptable range).
    - Add low-pass filter to the external droop control loop to ensure stability.



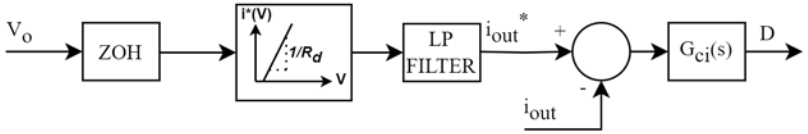
Depending on droop gains, ZOH of external droop controller can introduce oscillatory behavior with other droop controllers.

$$ZOH\ duration = T_s$$



Increasing the measurement / controller frequency can reduce the ZOH time, and adding a slew limit can limit oscillations to:

$$\Delta i_{out_{pk-pk}} = T_s \cdot i_{SLEW\_RATE}(A/s)$$



Low-pass filter can ensure stability and eliminate oscillations. E.g. design LP cutoff frequency as:

$$f_c < 10 \cdot \frac{1}{T_s}$$

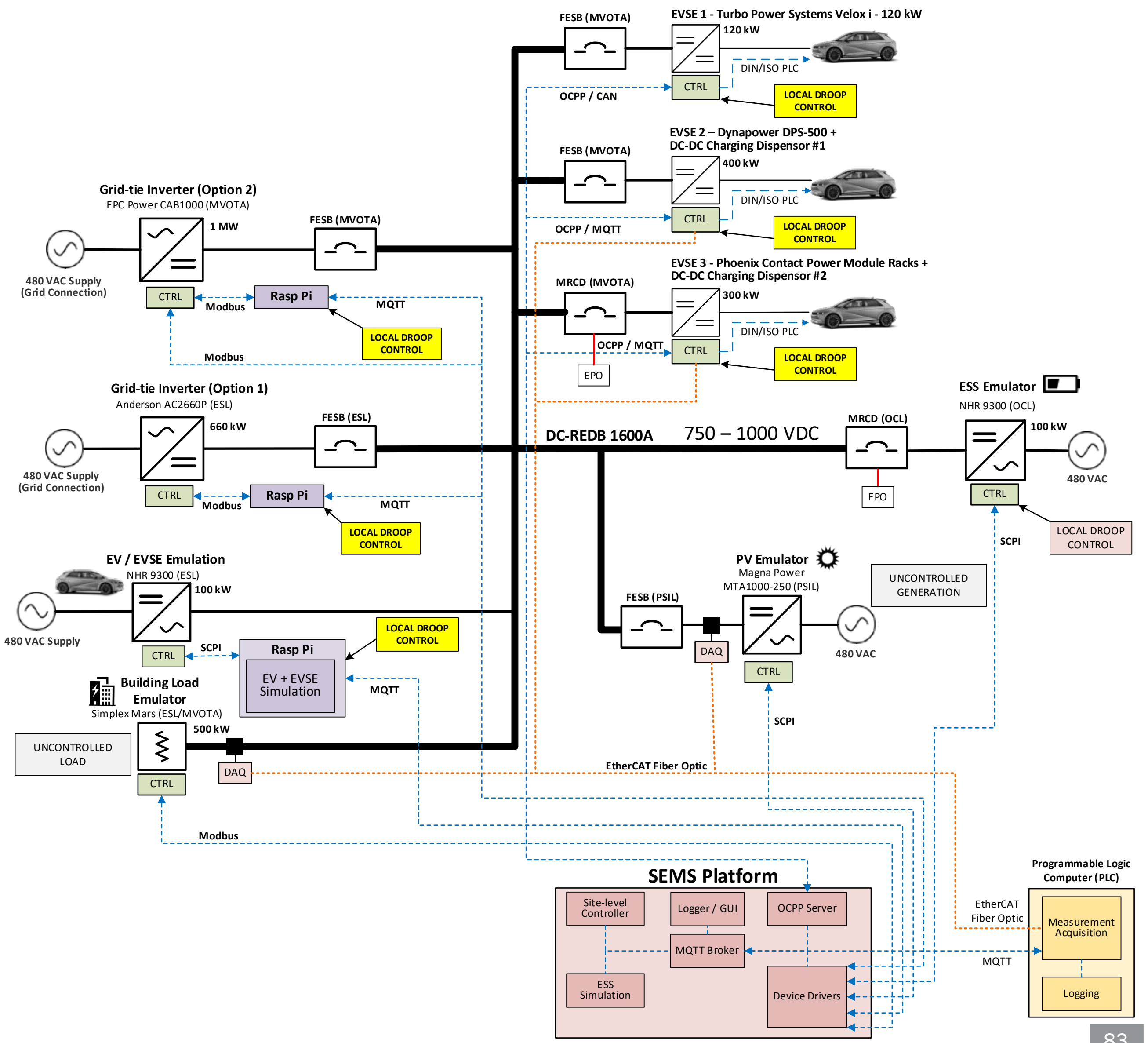
Future Work

eCHIP project will gain access to several DC-DC EVSEs, all of which will include a fully programmable droop-control mode.

DC-DC EVSE	Power (kW)	Input Voltage Range (VDC)	Droop Control Capable?
Turbo Power Systems Velox i	120	775 – 825	Yes
Custom NREL Build with Dynapower DPS-500 DC-DC	400	100 – 1000	Yes
Custom NREL Build with Phoenix Contact DC-DC Modules	300	650 – 825	Yes

- Combined with the existing test platform, these will enable more comprehensive droop-control testing and expanded use case demonstrations.

Demonstration of hybrid site control, realizing the combined benefits of decentralized droop control and an optimized centralized controller operating on the SEMS platform.



Conclusion and Next Steps

Conclusions and Review

- **Decentralized droop control offers advantages of improved site resiliency and security (compared to centralized controllers, since no communication between hub nodes is required)**
- **Droop control has excellent transient performance – hub nodes can respond rapidly to changes in bus voltage, and the bus voltage changes instantaneously with any load / generation changes.**
- **Droop control lends itself to islanded operation, since the hub naturally converges to a new operating point with no user intervention.**
- **Droop controls main weakness is reduced equipment utilization. This can be alleviated by careful droop curve design, but not as straightforward to achieve full utilization as in centralized controller.**

Next steps

- Experimental test platform expansion with several droop-enabled DC-DC EVSEs.
- Expanded droop-control use case demonstrations.
- Demonstration of hybrid site control, realizing the combined benefits of decentralized droop control and an optimized centralized controller operating on the SEMS platform.

Thank You!

Alastair Thurlbeck

Researcher | NREL CHARGE team

alastair.thurlbeck@nrel.gov

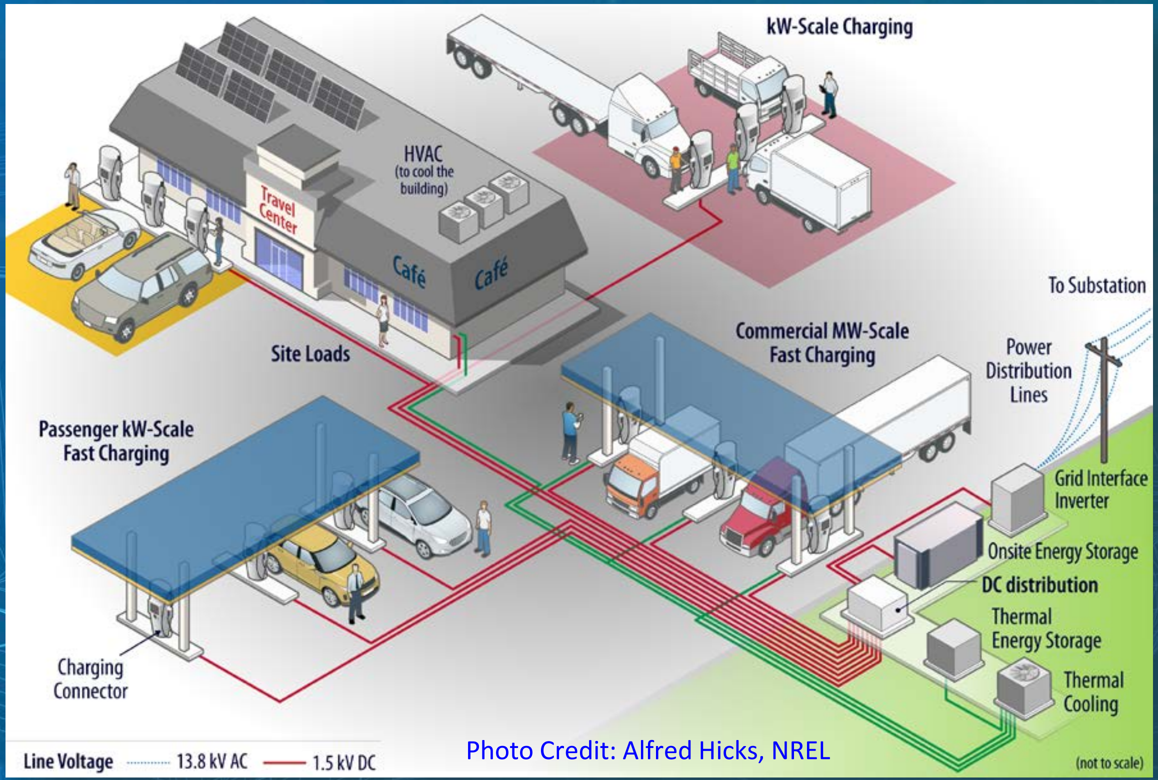


Photo Credit: Alfred Hicks, NREL

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