ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Design, Build and Test an Advanced Power Electronics Module That Enables Electric Vehicle Ultra-Fast Charging With Limited Grid Capacity

March 2026 | CEC-500-2026-008

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Agreement Number: EPC-21-014

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ACKNOWLEDGEMENTS

The author thanks the following individuals for helping execute and support this project:

David Jacques	Kris Chebul	Kevin Marundee	Michael Totah
Larry Klinger	Daniel Maluendas	Vahe Gulagian	Eric Sande
James Kennedy	BC Broussard	Dan Morgan	Woody Gibson
Sheryl Leduc	Zander Mrlik	Erik Stafl	Rishabh Jain
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency; renewable energy and advanced clean generation; energy-related environmental protection; transportation; and energy transmission and distribution.

In 2011, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned electric utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs to promote greater reliability, affordability, and safety for California electric ratepayers. EPIC investments advance these values by:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale projects), and finally with a clean electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Design, Build and Test an Advanced Power Electronics Module That Enables Electric Vehicle Ulta-Fast Charging With Limited Grid Capacity is the final report for EPC-21-014 conducted by Intertie Incorporated. The information from this project contributes to the CEC Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

California's main barrier to electrifying transportation is grid capacity: utilities cannot expand transmission and distribution infrastructure quickly and/or cost-effectively enough to meet customer demand. High-power charging for on-the-go electric vehicles (EV) (for example, passenger EVs, fleet vehicles, electric tractors, and electric drayage trucks) increasingly requires grid upgrades to accommodate the power requirements of EV fast charging stations, resulting in long and expensive delays.

To address this issue, the project designed, built, and tested an advanced power electronics module (PEM) that directly integrates charging with distributed energy resources and advanced power management technologies to facilitate direct current (DC) device integration. The project demonstrated how a modular, interoperable technology employed in a novel DC architecture can enable the installation and operation of DC fast charging stations using existing grid capacity without requiring costly upgrades.

In the project, a prototype PEM was integrated with high-voltage onsite solar, energy storage, and the grid (via a small bidirectional alternating current (AC)/DC converter connected to a building panel). The PEM strategically decoupled charging from the AC grid and harnessed the aggregate power deliverability of DC-coupled distributed energy resources. It provides an end-to-end power conversion solution sourcing power from a microgrid to deliver the power and voltage requirements of DC-fed EV charging stations. The resulting integrated solution successfully supplied 150 kilowatts at 950 volts to a commercially available DC fast charger without upgrading any utility or site electric infrastructure.

The new DC power conversion equipment, which is connected to a modular and interoperable DC architecture to provide grid-friendly EV charging, enables the timely deployment of DC fast charging at grid-constrained sites.

Keywords: DC fast charging stations, advanced power electronics module, PEM, high-power charging, DC device integration, expanding grid capacity

Please use the following citation for this report:

Mrlik, Richard and Zander Mrlik. 2026. *Design, Build and Test an Advanced Power Electronics Module That Enables Electric Vehicle Ultra-Fast Charging With Limited Grid Capacity.* California Energy Commission. Publication Number: CEC-500-2026-008.

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EXECUTIVE SUMMARY

Background

Transportation is the largest source of greenhouse gas emissions in California. To achieve carbon neutrality by 2045, the state must replace 14 billion gallons of annual gasoline consumption with zero-emission alternatives. Since each gallon of gasoline creates 20 pounds of carbon dioxide, this transition is crucial for the environment.

While battery-powered electric vehicles (EV) are the primary solution, they create a new challenge: all the energy previously supplied by gasoline must now flow through electric wires. This requires California's utilities to significantly expand an already constrained grid by 2045. Early EV adoption was successful because the grid could handle the initial demands of early EV drivers, who mostly relied on lower-power charging stations. Widespread adoption requires fast charging stations that can approach gas station convenience and fueling speeds. A 2023 JD Power study (JD Power 2023) noted that satisfaction significantly increased with charging speeds of 150 kilowatts (kW), which means fast chargers should provide at least 10 miles of driving range per minute.

The electric grid serving easily accessible retail locations was not designed to meet the power requirements of fast charging. Current fast charging stations connect directly to the grid using alternating current (AC) power and require the grid to handle the maximum possible power demand if all chargers were used simultaneously. This typically forces utilities to upgrade their entire infrastructure from power plants to local equipment. This can present a challenge for an electric grid that is expensive and time consuming to upgrade.

Project Purpose and Approach

To meet its climate goals, California needs technology and tools that mitigate the impact of transportation electrification on the grid, which runs on AC. EVs run on direct current (DC). Traditional fast chargers convert grid-supplied high-power AC to DC to charge EVs, which wastes grid resources. This is because the full charging power capacity is required to be reserved from the grid at all times, but grid power is needed for charging only a fraction of the time, leaving unused capacity idle most of the day.

This project introduced new hardware and a novel DC architecture that, together as a system, ease the burden of fast charging on the grid, while improving grid efficiency. Rather than drawing all power directly from the grid, this system selectively pulls limited AC power from the utility, using it to trickle-charge a DC microgrid that links a stationary battery, solar photovoltaics, and the new EV-charging hardware. The new EV-charging hardware is a power electronic module (PEM) that integrates fast chargers with the DC microgrid. The system reduces grid power needed for fast charging by ten times, while enabling a large solar array to most efficiently power EVs.

The project aimed to demonstrate a cost-effective, scalable way to give EV drivers 100 miles of range in 10 minutes, no matter the local grid capacity. This was achieved with the new PEM hardware, which enabled battery storage and solar photovoltaics to directly power EVs, independent of the grid. Directly connecting distributed energy resources (battery, solar, and small grid-tied inverter) to deliver high DC power is more cost-effective and energy-efficient because it requires fewer power conversions. Minimizing the size of grid connection also minimizes transformer losses, which, for typical charging load factors, adds 10 to 20 percent in energy losses. To facilitate scaling, the project prioritized interoperability, using commercially available hardware, with the system being flexible to enable fast charging for most EV brands and to integrate different solar and stationary battery storage brands.

A conventional AC charger would need 150 kW of grid power to deliver 10 miles of range per minute. Supplying this power from a gas station or a convenience store's panel would require 500 amps of spare capacity, which is rarely available. The project supplied 150 kW of charging power by combining the output of rooftop solar photovoltaics, battery storage, and an AC/DC converter connected to the building's panel with a 100-amp circuit. The combined DC power output was supplied to the proof-of-concept PEM prototype connected to Tritium's commercially available PKM150 fast charger.

A key challenge for fast charging systems that minimize reliance on grid power is to ensure there is sufficient energy to meet a site's charging demands. The project developed an intelligent energy management system (EMS) to ensure that the solar, storage, and limited grid resources could work together to meet the charging demand. AC-fed charging systems do not require intelligent EMS, since the grid provides 100 percent of power and on-demand energy.

Key Results

The project developed technology that combined hardware, firmware, and software in a PEM that supplied 150 kW of power to a charging station with only a 100-amp connection to the building panel. This is significant because electric panels of most locations that are convenient for fast charging typically have 100 amps of spare capacity, as was determined from a site assessment of 12 commercial properties that included convenience stores, gas stations, and quick service restaurants. This product/market fit assessment found that none of the sites could support a conventional 150-kW fast charger but all had 100 amps of spare capacity.

The system eliminated grid impacts by decoupling the charging process from the grid and by supplying 100 percent of the power required for charging from solar-plus-storage distributed energy resources (DERs). The project's DERs included 187 kilowatt-hours of battery storage, 80 kW of solar, and a 30-kW grid-tied bidirectional power converter; these were connected to the DC system referred to as the DC hub. Using this configuration, 20 charging sessions were successfully initiated and completed using Intertie's charging application on an iPhone. The following EVs were charged at their maximum charging power levels: Chevy Bolt, 55 kW; Tesla Model Y, 130 kW; Tesla Model X, 140 kW; and BMW I4, 150 kW.

To ensure that the system's DERs could supply the site's charging energy needs, the project developed an intelligent EMS, which combined an onsite controller, local and cloud software, and forecasting algorithms. The charging energy needs were determined from charging data at an existing, public, 50-kW fast charger located at the project site and operated by Intertie.

The project demonstrated that the EMS-controlled solar-plus-storage system was capable of supplying 100 percent of the charging energy for all of the testing.

Project cost data was tracked to compare DC-fed fast charging costs versus traditional AC-fed fast charging costs. For installations where a DC-fed charger is connected to a DC hub with existing DERs (such as in the project), the installed cost was found to be one-third of the installed cost of an AC-fed charger ($467/kW vs $1,122/kW). If the full cost of storage and the pro rata cost of DC-coupled solar are allocated to the charging project, the installed costs are similar ($1,092/kW vs $1,122/kW). For both cases, DC-fed fast charging operating costs are lower due to significantly lower demand charges and improved efficiency.

By supplementing the fast-charging use case with other revenues from existing DERs, the project demonstrated that DC-hub-boosted charging can lower electric fueling costs below those of gasoline or diesel, supporting organic growth throughout the state. With the primary objective of obviating the need for grid upgrades, the project provides a scalable template to rapidly deploy a network of super-fast EV chargers in California and validates an effective tool for the state to deploy in a timely manner to achieve its statutory climate goals.

Knowledge Transfer

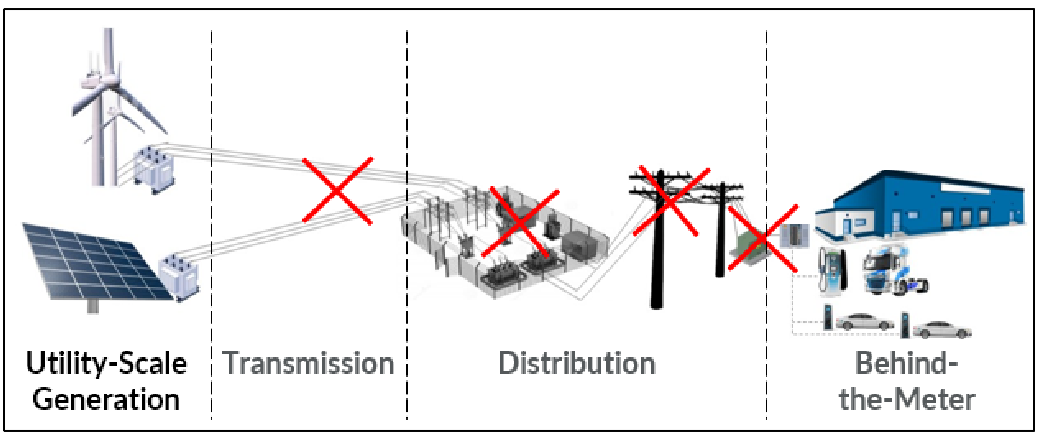
Intertie continues to share the results of this project with the industry, including utilities and potential customers, at workshops and through public reports, with the goal of accelerating the commercial adoption of the technology. The DC hub architecture advanced in the project is modular and has broader applications. As part of the DC hub architecture, DC-coupled solar photovoltaics was installed at a site with two commercial buildings in Fresno, California in 2024, applying lessons learned from the project. These buildings were completed but faced long delays awaiting utility upgrades for energization. In addition, their panels lacked the capacity to connect sufficient AC-coupled solar to meet the buildings' daily electrical energy needs. Drawing from lessons learned on DC power management, Intertie was able to triple the amount of solar connected by DC-coupling the solar. The site today is currently operating as an islanded microgrid whose primary energy source is solar photovoltaics.

CHAPTER 1: Introduction

Transportation is the largest source of greenhouse gas (GHG) emissions in California. To achieve the state's goals of carbon neutrality by 2045, decarbonizing transportation will be essential. As 99 percent of zero-emission vehicles are battery electric, transportation electrification is viewed as the obvious substitute for fossil fuels. California's early success with electric vehicle (EV) adoption was aided by available grid capacity that could support the power needs of early adopters. However, to achieve carbon neutrality, the majority of Californians must drive EVs. Broad-based EV adoption requires charging availability that rivals gas station convenience, which a 2023 JD Power study identified as comprising fast charging stations capable of supplying 150 miles of driving range in 15 minutes.

The main barrier to a convenient direct current fast charging (DCFC) network is grid capacity. Most DCFC projects in California require long, expensive grid upgrades.[1] A clear trend in EV markets is faster charging, which will require even more power and markedly stress an already constrained grid.[2] While the root cause is increased power demand, the core issue is that most DCFC are alternating current (AC)-fed. The grid must be sized to handle the maximum, simultaneous demand of all AC-fed fast chargers under National Electric Code (NEC) and utility standards, thus requiring upgrades to transmission, distribution, and customer facilities, as illustrated in Figure 1. California's grid cannot handle the projected fast charging demand using AC-fed technology. The project shows how direct current (DC)-fed fast chargers could allow California to expand its charging network without expensive grid upgrades. DCFCs obviate grid upgrades, providing California with a viable tool to deploy a convenient fast charging network.

Figure 1: Grid Upgrades Needed From Generation to Power Future Ultra-fast Chargers



Source: Intertie Incorporated

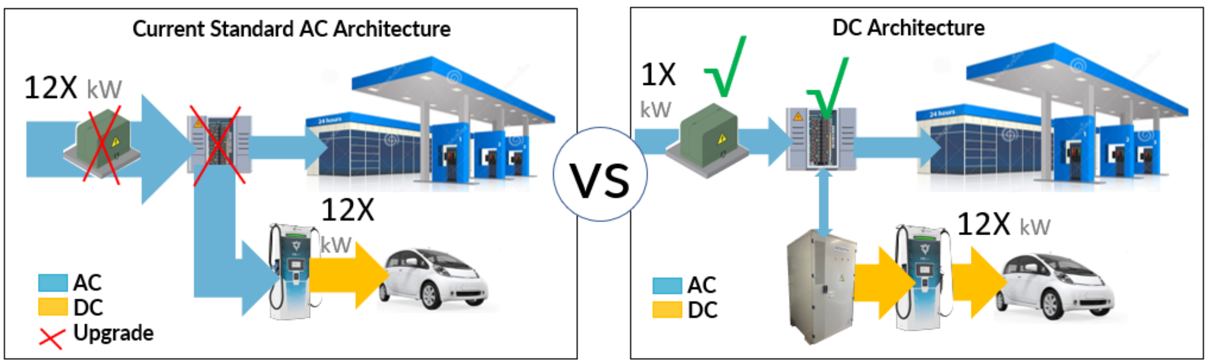
[1] DCFC costs in California corridors ranged from $122,000 to $440,000 for 50-kilowatt (kW) charge stations (Gamage et al. 2023).

[2] The new DCFC charges at least 3 times faster than previous models, with a minimum NEVI station power rating (150 kW).

Technical Need

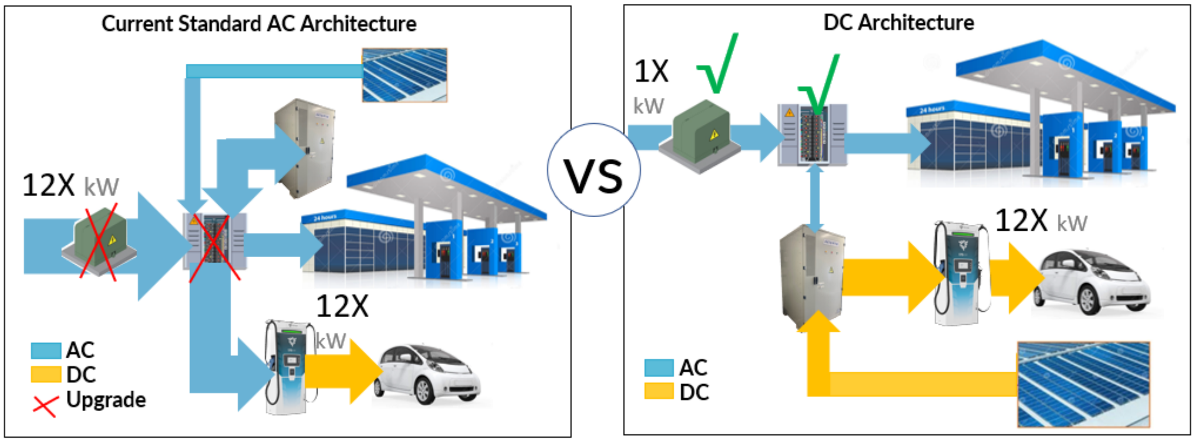
The best sites for fast charging are existing convenience stores, gas stations, and quick service restaurants, strategically selected for their traffic volume and visibility. Their electric infrastructure was not designed for high-power AC-fed charging, which dominates the EV charging market today. Most AC-fed chargers are all-in-one units (specifically, they connect to the AC grid, convert AC to DC, and supply DC power to EVs). Figure 2 and Figure 3 compare the grid capacity required by an AC-fed charger and DC-fed charging, with and without solar and storage, respectively. AC-fed chargers draw 100 percent of their power from the grid, while the DC-fed charger shown uses 1/12 the grid capacity — the battery supplies the balance. The DC architecture reduces grid impact by first trickle-charging a battery from the grid and then discharging high-power DC to a dispenser and the EV.

Figure 2: Comparison of Standard AC and DC Architectures for Charging



Source: Intertie Incorporated

Figure 3: AC and DC Architectures for Charging With Battery and Solar Added

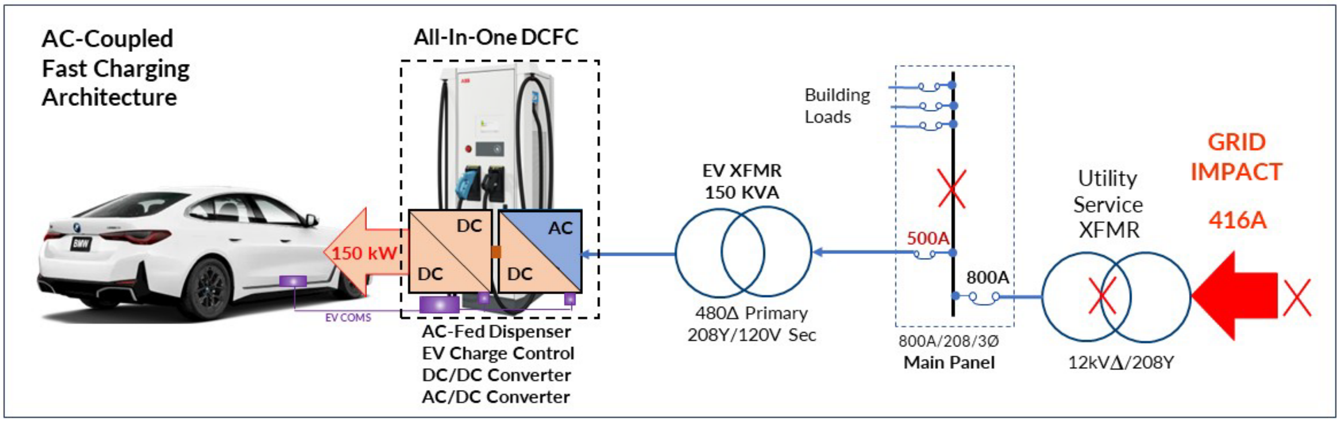


Source: Intertie Incorporated

While providing some demand charge relief, AC architectures have several disadvantages compared to DC architectures: i) the customer's electric panel must be upgraded; ii) larger power converters and transformers are required; iii) the utility may still require an upgrade; and iv) less solar can be added. The DC architecture offers a simpler, more efficient method to deliver DC power from batteries and solar for fast charging.

A schematic detailing the electrical equipment and power conversions required by an AC-fed charger is shown in Figure 4. To connect a 150-kilowatt (kW) AC-fed fast charger, a 150-kilovolt-ampere (kVA) transformer and a 500-amp circuit breaker are required. The circuit breaker takes up 62.5 percent of the largest electrical panel (800-amp) capacity that Intertie Incorporated (Intertie) found in the 12 commercial retail sites the project researched. The electric infrastructure at all commercial retail sites researched would have needed to be upgraded if one AC-fed 150-kW charger were installed.

Figure 4: AC-fed All-in-one Fast Charging Architecture



Source: Intertie Incorporated

In the above schematic, the electrical panel and utility transformer would require upgrades to accommodate the DCFC. At many sites, the utility distribution feeders would also need to be upgraded. Based on Intertie's recent microgrid installation at two commercial sites located in Fresno, such electric service upgrades would take one to two years. Based on Pacific Gas and Electric Company's (PG&E's) median circuit upgrade costs of $1,875/kW, the upgrade would cost $281,250, with a portion paid by the customer and the remainder paid by utility ratepayers.[3]

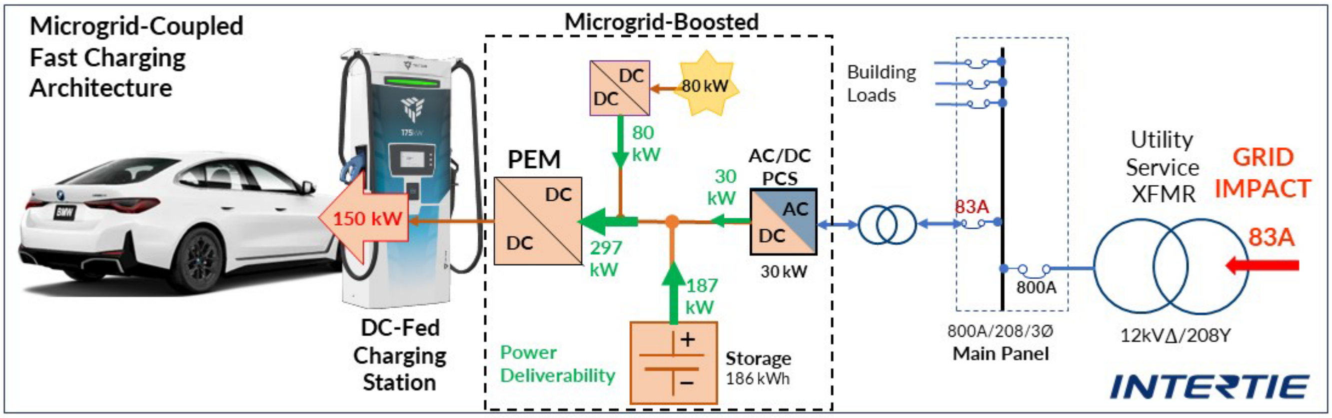
The EV charging industry needs new technology that minimizes the impact of fast charging on the grid. The technology should decouple the charging process from the AC grid, maximize DC power delivery of DC-coupled distributed energy resources (DERs), and selectively draw power from the grid via a smart, energy management system (EMS)-managed AC/DC converter. Figure 5 provides an electrical schematic of the project's DC hub architecture, which leverages the DC power delivery of a battery energy storage system (BESS), DC-coupled solar, and an EMS-managed AC/DC converter to meet the 150-kW DCFC load. Their combined charge power capacity is 297 kilowatts of DC power (kW_{DC}), through a grid connection of 30 kilowatts of AC (kW_{AC}), requiring only 83 amps (A) from the site's electrical panel.

As shown in Figure 5, the DC hub architecture reduces the DCFC's impact on the main panel and grid by 5 times, which the existing electric panel can easily accommodate. Note that the system actually reduced the impact on the grid by 10 times. The key technology for this

[3] From Pacific Gas & Electric Company's (PG&E)'s Distribution Deferral Opportunity Report (DDOR) 2021c for planned distribution grid investments - supplementary section 10)

architecture is the power electronic module (PEM), which connects a DC-fed charging station to the DC hub — a platform that lets DC power from DERs flow directly to fast chargers.

Figure 5: DC-fed Battery-boosted Fast Charging Architecture



Source: Intertie Incorporated

Capital Cost Advantage

Table 1 compares the capital cost (CAPEX) of a 150-kW charging station using the DC-coupled approach developed in this project versus a standard AC-fed 150-kW fast charging station. As shown in the first column, adding a DC-fed charger to an existing solar-plus-storage project (the Retrofit) is the lowest-CAPEX option for adding a fast charger. The second column itemizes the CAPEX of a stand-alone 150-kW DC-fed charging station, where 100 percent of solar and storage costs are assigned to the fast charger, and assumes that the microgrid provides no other benefit to the site host. Table 1 also shows that the cost of a single 150-kW AC-fed charging station can vary widely, depending on the utility upgrade cost, with PG&E circuit upgrade costs ranging from $250/kW at the low end to a median of $1,875/kW. At expected median costs, installing a conventional AC-fed charger is 2.5 times more expensive than a DC-fed system.

Table 1: Comparison of Single Fast Charger Project Cost

	1 x DCFC Project Cost			
	DC-Fed via PEM		Standard AC-Fed	
Cost Item	Retrofit[1]	Standalone[2]	Low[3]	Median[4]
Charging Equipment	$60,000	$60,000	$80,000	$80,000
Site Equipment & Installation	$10,000	$103,825	$50,000	$50,000
Utility Upgrade	$0	$0	$38,250	$281,250
CAPEX	$70,000	$163,825	$168,250	$411,250
All-In Cost per Fast Charger	*$70,000*	*$163,825*	*$168,250*	*$411,250*

[1] Retrofit: Marginal cost of adding charger to existing solar plus storage

[2] Standalone: Allocate 100% of solar plus storage costs to DCFC project cost

[3] Low: Lowest PG&E circuit upgrade cost of $255/kW

[4] Median: Median PG&E circuit upgrade cost of $1875/kW

Source: Intertie Incorporated

Table 2 compares the CAPEX for a project with 6 x 150-kW fast chargers that uses the DC-coupled approach developed in this project versus standard AC-fed fast charging. The same scenarios as in Table 1 were evaluated: retrofit and stand-alone for DC-fed, the range of PG&E upgrade costs for AC-fed. The more chargers that are installed, the greater the CAPEX savings of DC-fed systems.

Table 2: Comparison of Project Cost With Six Fast Chargers

	6 x DCFC Project Cost			
	DC-Fed via PEM		Standard AC-Fed	
Cost Item	Retrofit[1]	Standalone[2]	Low[3]	Median[4]
Charging Equipment	$250,000	$250,000	$345,000	$345,000
Site Equipment & Installation	$214,000	$343,000	$180,000	$180,000
Utility Upgrade	$0	$0	$229,500	$1,687,500
CAPEX	$464,000	$593,000	$754,500	$2,212,500
All-In Cost per Fast Charger	*$77,333*	*$98,833*	*$125,750*	*$368,750*

Source: Intertie Incorporated

Operating Cost Advantage

In addition to lower capital costs, DC-fed fast charging offers significant operating cost savings compared to AC-fed. Operating cost savings come from: i) reduced charging power demand; ii) improved efficiency; and iii) increased local solar self-consumption. Using the applicable

PG&E rate schedule based on load characteristics, Table 3 shows that AC-fed charging (without storage) results in demand charges that are 12 times higher. California has temporarily provided demand charge relief for fast charging, which shifts costs to other consumers. Improved efficiency and increased solar self-consumption further reduce operating costs.

Table 3: Comparison of Demand Charges (6 DCFC Stations)

B-19 Demand Charge Item	B-19 $/kW	Charging Station Type	
		AC-Fed	DC-Fed
Peak Demand, kW_{AC}		900	75
Maximum Peak Demand (Summer):	$26.34	$94,824	$7,902
Maximum Part-Peak Demand (Summer):	$21.11	$75,996	$6,333
Maximum Demand (Summer):	$44.00	$158,400	$13,200
Maximum Demand (Winter):	$44.00	$316,800	$26,400
Total Cost of Demand Charges		$646,020	$53,835

Source: Intertie Incorporated

Project Objective

The project aimed to create and test technology that lets existing sites like gas stations quickly add fast chargers that provide 10 miles of range per minute without upgrading the grid. Most high-traffic retail sites were chosen because they are visible and convenient, but they usually don't have enough grid capacity to add even one AC-fed fast charger without long delays and expensive upgrades. Since EVs run on DC, the project fed the fast charger from a DC hub that combined DC power from battery storage, solar, and a small grid-tied AC-DC converter that was small enough to connect to nearly any commercial site. The enabling technology developed in the project was a DC/DC converter, referred to as the PEM, capable of supplying 150 kW of power to a fast charger while connected to the DC hub. The project demonstrated how the PEM connected to the DC microgrid reduces AC grid power requirements by at least 10 times for fast charging, compared to conventional AC-fed DCFC.

The main challenge with limited grid capacity is coordinating DERs to provide enough energy for charging. To address this challenge, a control system with forecasting and predictive algorithms was needed to ensure there was always sufficient energy within the system. The project designed, installed, and configured an EMS controller and EMS cloud to manage energy supply and to optimize DC-coupled solar plus storage to satisfy the site's existing 220-kilowatt-hours (kWh) daily fast charging needs. The bulk of the energy was supplied via the 80-kW DC-coupled solar rooftop photovoltaics system.

The high-level objective of the project was to advance a scalable fast charging solution that could help California to achieve its climate goals in a timely manner. With the PEM and other DC power management technologies, Intertie is advancing a DC architecture platform that connects more solar and EV charging to the same grid. To scale, the PEM and integrated DERs must be:

- **Cost Effective:** At a minimum, provide lower life-cycle cost versus AC-coupled fast charging, and ultimately provide lower transportation fuel costs than fossil fuels.
- **Robust:** Meet 100 percent of the electrical power and energy requirements of a site's forecasted charging requirements.
- **Modular:** Be capable of integrating with different sizes and types of commercially available DERs as part of a DC-coupled microgrid that can execute multiple use cases. The project's PEM powers one 150-kW DCFC and connects 187 kWh of battery storage, 80 kW of DC-coupled solar, and a 30-kW AC/DC power converter. Using the same DC architecture, Intertie plans to upgrade the PEM technology to provide 1 megawatt (MW) of DCFC and harness 4 times the DER capacity.
- **Interoperable:** The PEM should enable plug-and-play interoperability with commercially available chargers from different manufacturers. In the project, the PEM interfaced with Tritium's PKM150, a commercially available 150-kW DCFC. The charger communication was handled via industry-standard Open Charge Point Protocol (OCPP) communications.
- **Intelligent:** Controlled by an EMS that opportunistically sources grid power, with most charging power supplied by energy storage and DC-coupled solar.

Sustainable Advantages of DC Distribution

Many clean energy technologies — such as solar, wind, battery storage, and EVs — operate natively on DC. DC distribution offers several sustainable advantages: it reduces energy conversion losses, improves power quality, simplifies control, and increases reliability. DC systems have no skin effect losses,[4] fewer power conversion steps, and higher-voltage, lower-current operation, resulting in lower overall losses than AC. DC systems improve power quality because all current delivers real power, with no reactive power to cause voltage swings, losses, or phase issues as in AC systems. DC systems are more reliable than AC, with fewer failure points, no synchronization issues, and simpler controls.

The PEM and DC power management technologies developed in this project enable DC architecture to maximize DC power flows and optimize the inherent advantages of DC distribution. The DC coupling of solar and storage in the project allowed two to three times more solar to be connected by avoiding NEC limitations on the allowable AC solar capacity that can connect to a building's panel (specifically, the '120 percent rule'). The PEM connected to the project's DC microgrid reduces the grid impact of fast charging by 10 times. By advancing DC coupling for behind-the-meter solar and ultra-fast charging, the project demonstrated how this advanced microgrid technology can greatly benefit Californians.

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[4] An AC skin effect concentrates current near the conductor surface, raising resistance and losses, unlike DC, which uses the full cross-section.

In summary, the project:

- Enables small to medium-sized commercial retail buildings and other ideal fueling locations to host ultra-fast charging while minimizing grid impacts.
- Enables the deployment of a fast-charging network by overcoming grid constraints in convenient locations, unlocking widespread EV adoption.
- Overcomes grid constraints to provide high-power charging for medium- and heavy-duty electric vehicles (EVs), which will immediately improve air quality in disadvantaged communities adjacent to highway corridors.
- Maximizes the deployment and utilization of distributed solar energy.
- Improves distribution efficiency through smart EMS controls that increase the site's load factor, allowing more energy to flow through the same grid capacity and reducing distribution costs for ratepayers.

CHAPTER 2: Project Approach

Project Research and Technology Objectives

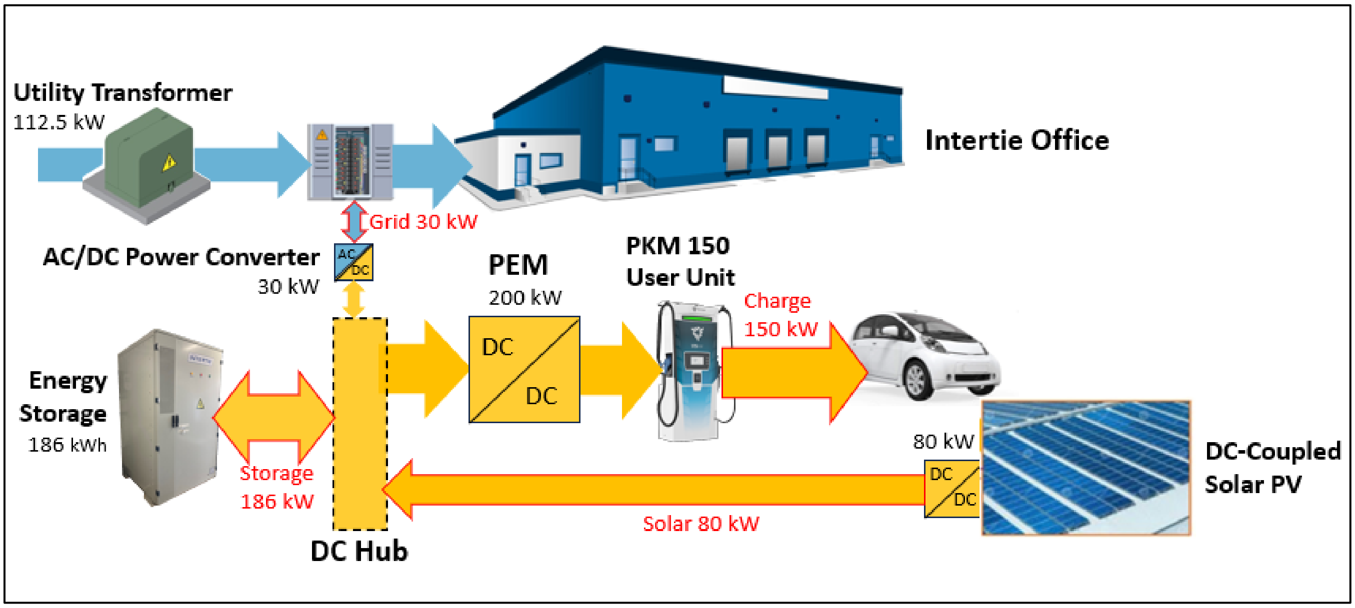
AC-fed fast chargers currently dominate the market and require significant grid capacity. The best locations for EV fast charging stations typically do not have adequate grid capacity to host AC-fed fast chargers. Grid constraints impede the deployment of fast chargers and will prevent California's efforts to electrify transportation—the biggest contributor to greenhouse gas emissions—in a timely manner.

The project’s main technical objective was to show that low-grid-impact, ultra-fast charging could be achieved by advancing DC-power management technology that delivers high-power levels to EVs using limited AC-grid resources. The research objective was to design and test a modular PEM that routed the aggregate DC power from battery storage, DC-coupled solar, and a small grid-tied bidirectional converter to a fast charger. While Intertie’s PEM establishes a foundational system, the DC distribution requires isolated charging DC/DC head-end units, a unique and important feature of Tritium’s PKM150 user unit.

The main project goal was to build and demonstrate a ‘proof of concept’ PEM prototype that could supply power to a DC-fed fast charging station and initiate several EV charging sessions using a commercially available charge station management system (CSMS) charging application. The project sought to demonstrate that the PEM could deliver 150 kW to a Tritium PKM150 user unit, supplied by a DC microgrid with 187 kWh of battery energy storage, 80 kW of solar, and a 30-kW bidirectional AC/DC converter, connected to the building electric panel via a 100A connection (shown by the electric system in Figure 6). The PEM is a software-enabled hardware technology that combines hardware, firmware, and software that were developed to meet the following technical objectives:

1. **Hardware:** An integrated system with interface circuitry, DC/DC converter, and embedded controls with 200-kW power capacity. To operate safely, the PEM hardware system must also contain pre-charge circuitry, contactor control, protective fusing, disconnects, and a dedicated controller.
2. **Firmware:** It must autonomously control its interaction with the microgrid at its input and the DC-fed charger at its output when managing the DC/DC conversion process. Firmware requires almost instantaneous feedback control to enable power conversion to respond to changing power demand at the output at a constant 950 volts (V) and to respond to varying voltages at its input interface with the microgrid.
3. **Software:** The PEM must be integrated into the charging process in which the charging station is controlled, using CSMS software that communicates via standard OCPP protocol. To satisfy the energy requirements of the anticipated charging demand with limited grid capacity, the EMS must optimize energy delivered from various sources (grid, solar, and energy storage) to reliably meet charging needs.

Figure 6: Project's DC-fed Battery-boosted Fast Charging Architecture With PEM



Source: Intertie Incorporated

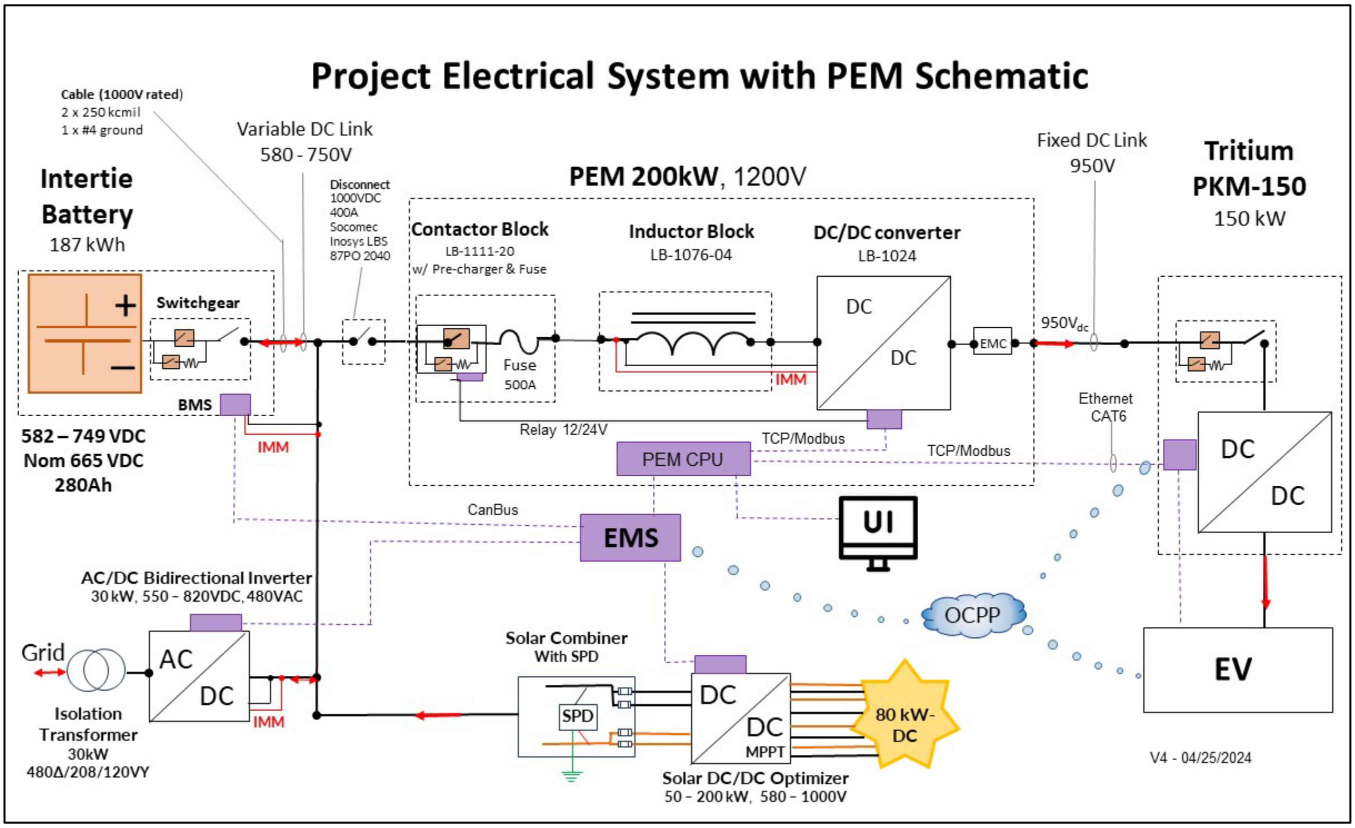
Demonstration Site

The research and demonstration site depicted in Figure 6 is located at 475 Coloma Street in Sausalito, California. The site is a commercial building where Intertie's power electronics lab is located. The site features rooftop solar, which Intertie connected via a DC optimizer (specifically, DC-coupled solar) to a BESS in Intertie's lab, where a Tritium PKM150 user unit was also installed.

Figure 7 provides a detailed electrical system diagram of the project microgrid, PEM, and connection to the DC-fed charger. The functional blocks of the PEM and how the PEM integrates the DC-fed charger with the microgrid are also shown. While the PEM, microgrid configuration, and hardware are specific to the project, a key advantage of the DC system architecture is its modularity, as the EMS and control algorithms are flexible to accommodate a wide range of DERs, sizes, and configurations.

Originally, the team planned to demonstrate boosted fast charging capability from the battery storage only. Intertie raised its target to provide microgrid boosting by adding DC-coupled solar to the battery power deliverability. Due to a lack of DC compatible products, a DC panel was designed and fabricated to provide protection and distribution for the DC-connected devices. The project team's approach was to develop the PEM, DC panel, and DC-fed charging station as a system with modular 'plug and play' functionality that also supplied fast charging more efficiently, reliably, and at a lower cost than conventional AC-fed charging.

Figure 7: Project Microgrid System and Schematic of PEM Integration



Source: Intertie Incorporated

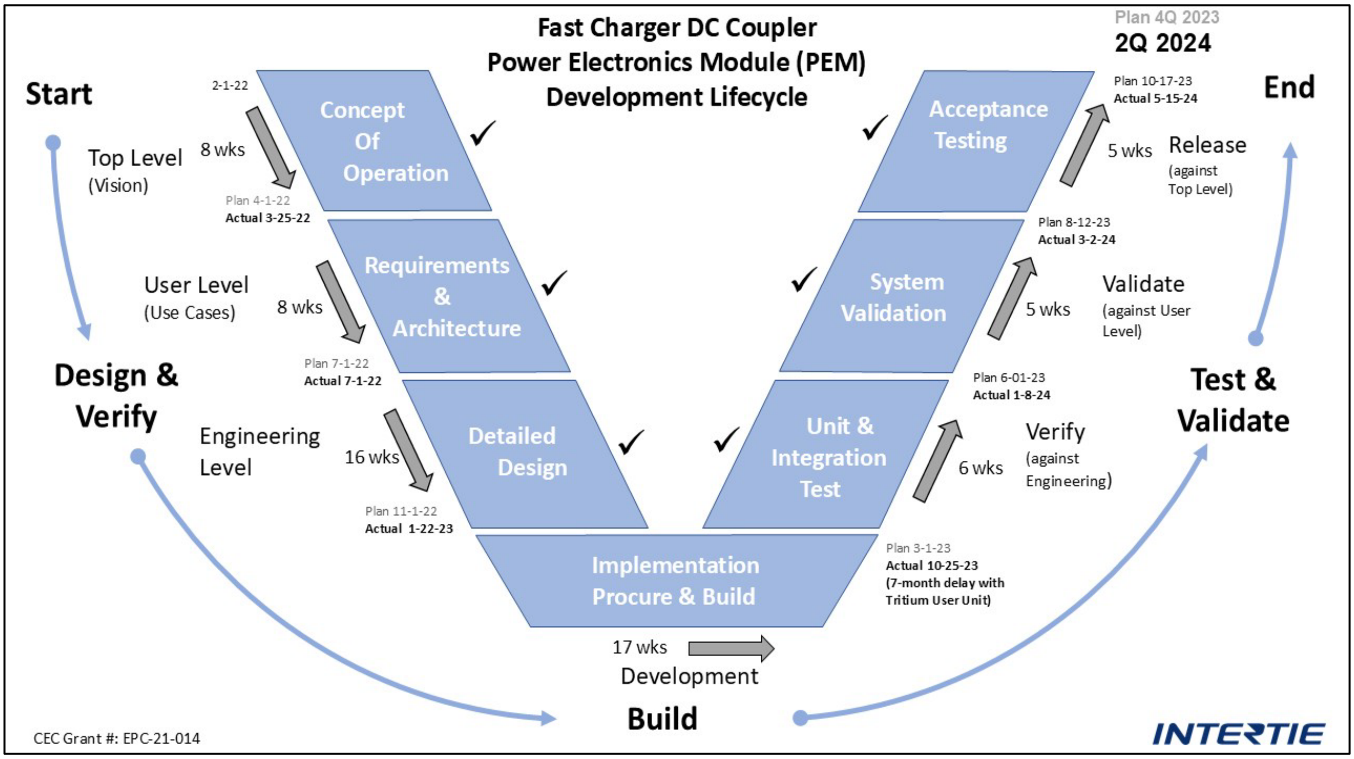
Project Approach

The project adopted a systems engineering approach for planning and implementing the design, build, testing, and operation of the PEM in a real-world environment. An overview of the product development lifecycle has been laid out in V-Model format in Figure 8 below. The V-model shows the linear progression of each development phase, from initial concept to acceptance testing. The V-Model provides a convenient tool for planning, scheduling, and tracking each phase. Figure 8 also shows the initial scheduled plan against the actual completion dates of each phase.

V-Model Plan: Schedule and Actual

The product/market fit was established by studying grid capacity in convenient EV charging locations and surveying what charging speeds on-the-go EV drivers wanted. The project team developed a concept of operation document that helped define requirements of both the PEM and the DC architecture it connected to. Once the requirements were specified, the project team completed a more detailed design followed by the procurement of components and the actual build process. Once the project team completed the PEM prototype, its power output, input and output interfaces, operating modes, and PEM control system were tested and validated. The acceptance testing required that the PEM could be powered by the microgrid and delivered to a DC-fed charger, with the charging session initiated and completed using a standard charging application from a smart phone.

Figure 8: PEM Project Product Development Plan



Source: Intertie Incorporated

Product/Market Fit: The project team completed site visits to assess electric infrastructure at 12 commercial properties, including convenience stores, gas stations, and quick service restaurants. The team found that the existing electric panel and utility service capacity at these convenient locations was 600A to 800A/208V/3Ø and that none of the sites had the capacity to add an ultra-fast charger.

Concept of Operation: To achieve convenience parity with gasoline refueling, the minimum EV charging requirement for on-the-go EV refueling was determined to be 150 miles of charge in 15 minutes, or 10 miles of charge per minute.

User Requirement: The minimum charging power requirement to deliver 10 miles per minute for an EV (with an efficiency rating of 4 miles per kWh) is 150 kW. Based on the site research detailed above, all locations had available 100A/208V/3Ø, which set the capacity of the grid-tied bidirectional power converter to be 30 kW.

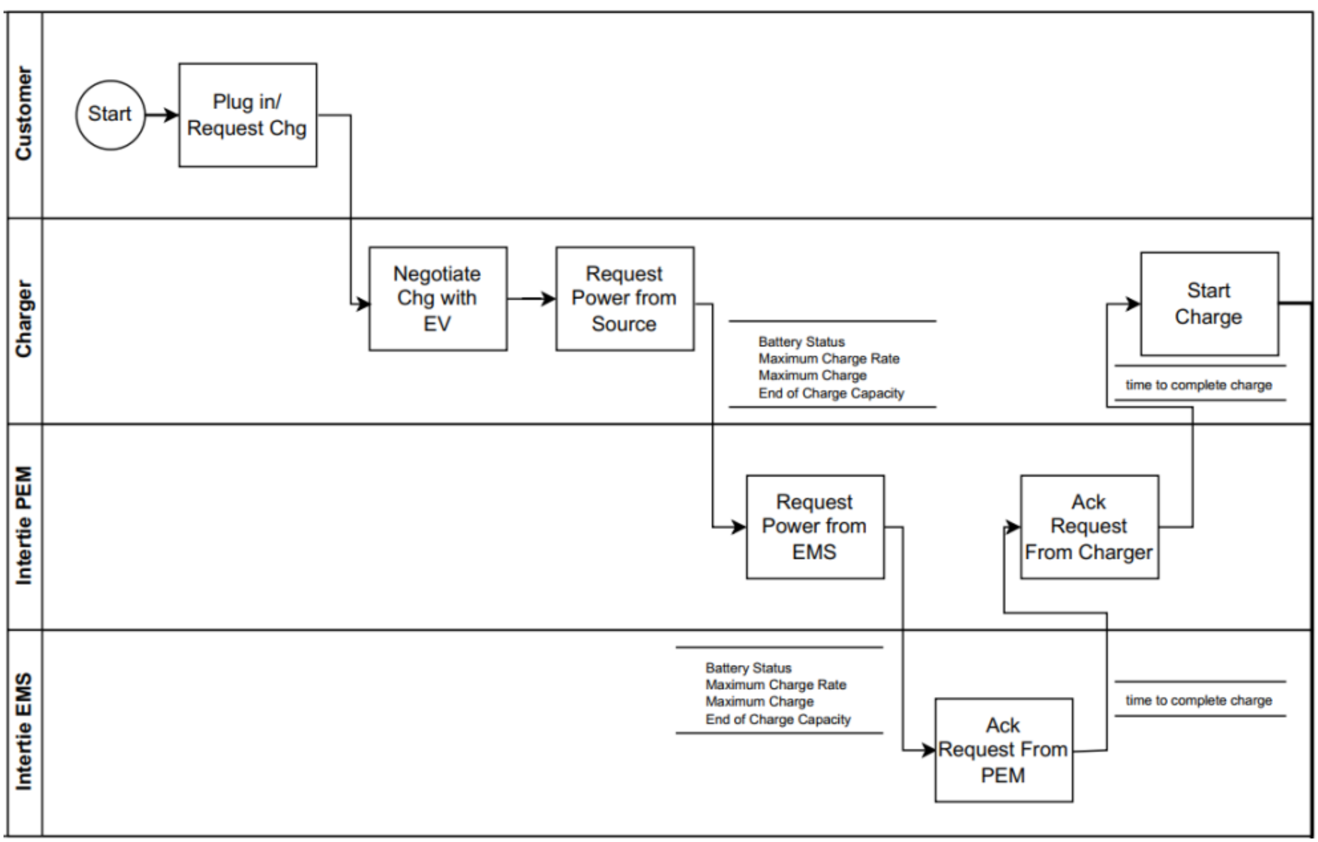
Detailed Design: The project team conducted extensive outreach to component and subsystem suppliers and firmware/software contractors to confirm that the PEM could be built and meet the specifications defined by the user requirements. Tritium's PKM150 was selected because it provided an isolated 150 kW charging DC/DC head-end unit. The PKM150 requires the PEM to supply power levels between 0 kW and 150 kW at 950 volts of DC (VDC) and stay within 940VDC to 960VDC. While sourcing power from a DC microgrid, the PEM is required to interface with variable DC voltage between 600VDC and 720VDC, which varies as a function of the battery's state-of-charge (SoC).

Hardware Build: The PEM prototype was assembled using commercially available components, including: a contactor block with pre-charger, an inductor block, a DC/DC converter, and a PEM control system. The PEM prototype was constructed on a mobile platform to facilitate testing. Component-level testing and end-of-line production testing were performed by respective manufacturers. Intertie's power electronics laboratory was reconfigured to accommodate high-power DC flows. The PEM was also connected to the building's existing microgrid, which Intertie modified to enable the PEM's operation in an actual operating environment.

Testing and Validation: The system validation test plan was completed by testing individual software and firmware components (for example, the PEM controller, PEM User Interface, and EMS Controller). The PEM firmware focuses on the PEM central processing unit (CPU) and its interactions with the DC-DC converter system. The project team wrote software to manage the dynamic, coordinated interactions of the EV driver, EV charging station, PEM, and EMS, as shown in Figure 9.

Acceptance and Release: Acceptance testing of the PEM required validation that an EV driver can charge from a PKM150 connected to the PEM that is sourcing power and energy from a microgrid. The project team developed EMS and PEM software using activity diagrams that map dynamic and coordinated interactions of all stakeholders for known use cases. Figure 9 shows the base case where there is sufficient energy to supply a set of charging requests.

Figure 9: Dynamic, Coordinated Stakeholder Interactions for PEM-Powered Charging Session



Source: Intertie Incorporated

Project Teaming Strategy

Power Electronics: System specifications were determined collaboratively, while the development and/or provisioning of the two major power electronics pieces was performed by Intertie and Tritium, as follows:

- Intertie led the work on the PEM system DC to DC converter.
- Tritium provided the isolated charging DC/DC head-end unit (PKM150 user unit).

Testing: Three levels of testing were included in the project:

- Component level testing and end-of-line production testing were performed by the respective manufacturers.
- Unit and system testing was conducted at Intertie laboratory with actual vehicles.
- Demonstration site testing was managed by Intertie.

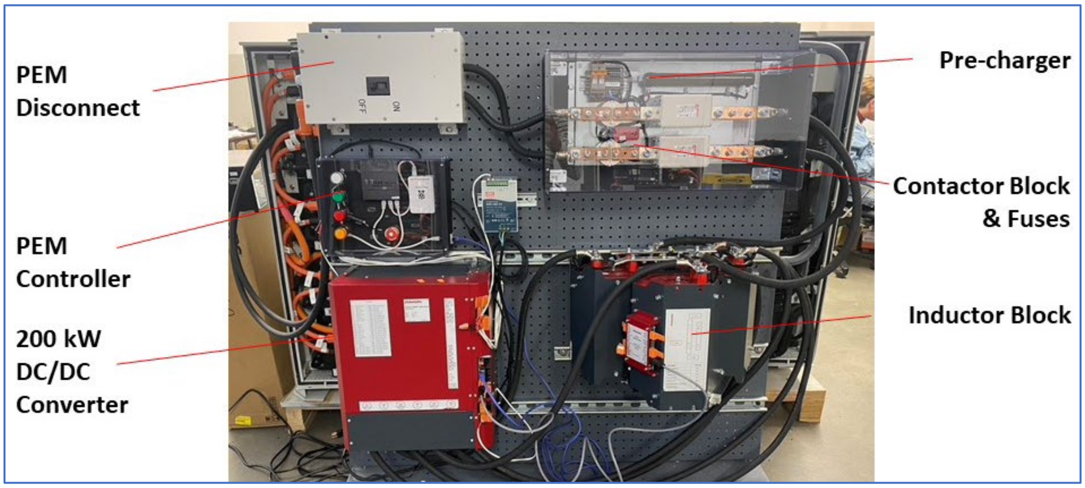
Technology Transfer: The California Mobility Center (CMC) is one of California's leading accelerator organizations for fueling and charging infrastructure industries, having worked on dozens of clean energy research and development projects. The CMC partnered with Intertie to provide the project with technology transfer support, including identification of technology transfer activities, as required by the solicitation.

Electrical Engineering: VGG Systems, a licensed professional electrical engineer, supported the design and modifications made to Intertie's power laboratory.

Key Project Milestones

1. Product/market fit confirmed through field research that electric panel and service capacities at convenient locations (for example, convenience stores, gas stations, and quick service restaurants) are insufficient for fast charging and almost all would require upgrades for a single 150-kW AC-fed charger.
2. The project team designed and built the PEM prototype using commercially available components, including a contactor block with pre-charger, an inductor block, a DC/DC converter, and a PEM control system (shown in Figure 10). The prototype unit is a 200-kW, non-isolated, bidirectional converter with 98 percent conversion efficiency. The high side has a voltage range of 60VDC to 1200VDC, thus satisfying the 950VDC input requirement of the PKM150. The low side ranges from 0 kW to 1150 kW, covering the entire microgrid DC bus voltage range.

Figure 10: PEM Prototype Built on Mobile Platform



Source: Intertie Incorporated

3. The project team designed, built, and programmed the PEM control system and user interface. A controller and firmware were developed to control the DC/DC converter, monitor and control contactors, interface with the DC charger head end, and make the data available to other components in the system such as Intertie's external EMS.

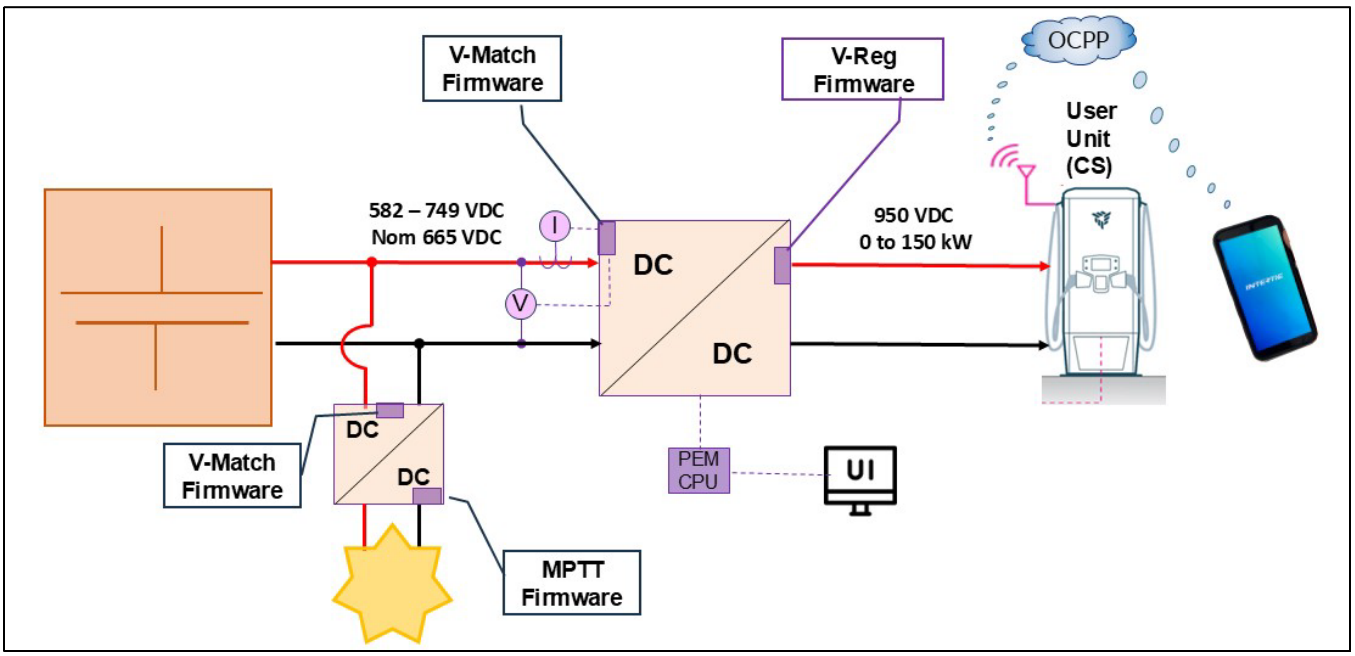
   A screen shot of the project's user interface (UI) is shown in Figure 11. The interface proved to be a quick and effective tool that allowed technicians to enter commands for startup, commissioning, troubleshooting, and testing. These commands included starting and stopping a charge, identifying faults, resetting the DC-DC converter should any faults occur, and other commands needed for operating and testing. Because this is a prototype system, the UI only needed to be rudimentary, as shown.

Figure 11: PEM Basic UI

Source: Intertie Incorporated

4. **Autonomous Operation:** A critical milestone was developing the PEM's embedded firmware to program control algorithms, which allowed the PEM to operate autonomously without the external PEM or EMS controller. Control algorithms in the DC/DC converter embedded firmware enable instantaneous response to current and voltage at the input (V-match) and power demand at the output (V-reg). The algorithms provide appropriate feedback control based on measured voltage and current, as shown in Figure 12. By operating autonomously, the PEM automatically responds to the charger changing power demand while adapting to varying microgrid bus voltages.
5. **Microgrid Power Boost:** The project team successfully implemented and synchronized voltage match firmware in the solar DC-optimizer, PEM, and bidirectional power converter to aggregate power delivered from storage, solar, and the grid to the PEM, as shown in Figure 12.

Figure 12: Microgrid DC-powered Fast Charging Controlled via OCPP Enabled by Autonomous PEM Operation Using Smart Firmware

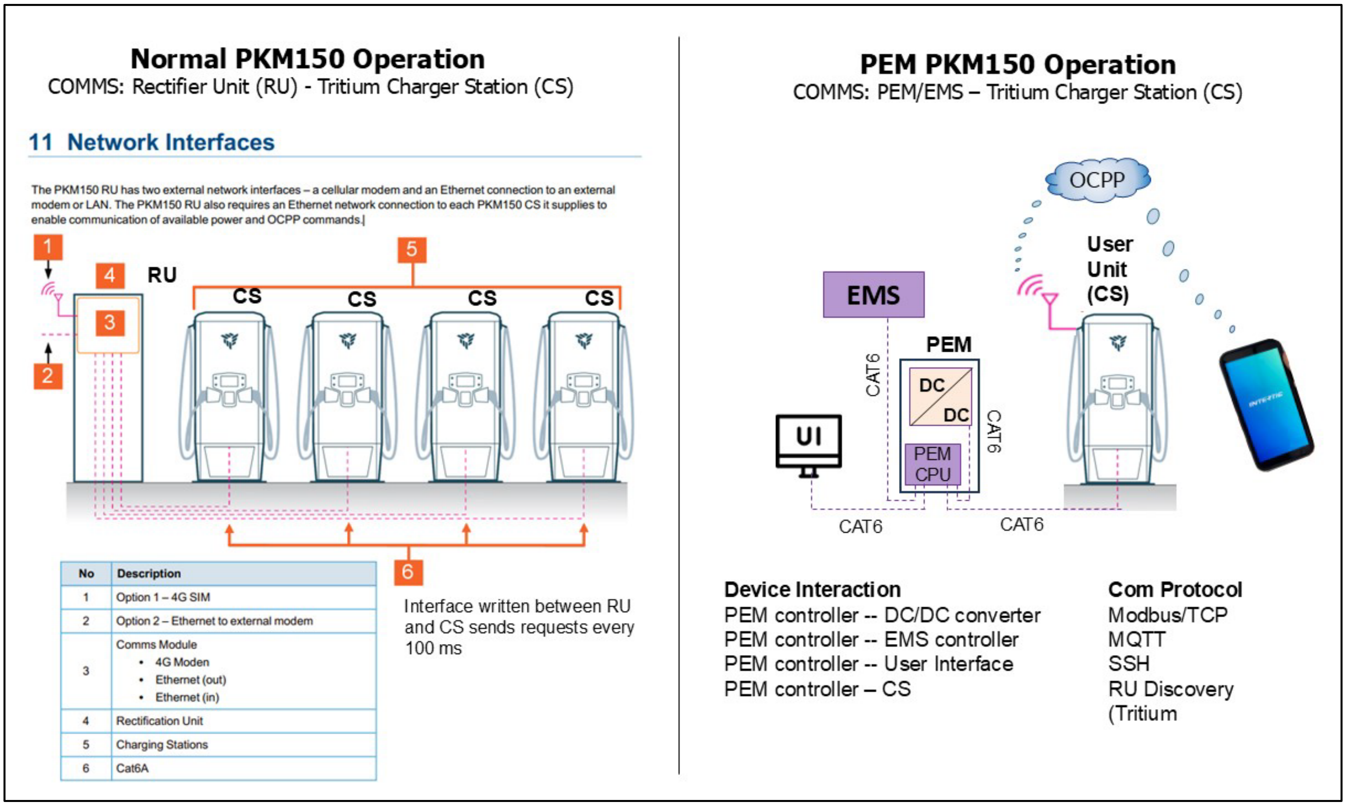


Source: Intertie Incorporated

6. **Interoperability:** The project demonstrated that the PEM could operate Tritium's PKM150 by starting and stopping charging sessions with a charging application via OCPP. While the PEM's embedded firmware provided seamless power control (Key Milestone 1), Tritium's PKM150 charging station was designed to communicate with Tritium's rectifier unit (RU) with proprietary communication protocols. To overcome this obstacle, the project team had to "trick" Tritium's charger station into thinking it was being controlled by Tritium's RU rather than the PEM, as shown in Figure 13. Successfully communicating with Tritium's charging station without the RU was an important step to achieving interoperability. This required Tritium's willingness for an external system to control its DC-fed head end charging station. One of the project's

reach goals was for the PEM to operate with charging stations from multiple manufacturers. While designed for interoperability, this goal would have required a significant amount of cooperation and coordination with multiple original equipment manufacturers (OEMs).

Figure 13: Tritium PKM150 Charger Station Communication – Standard Versus PEM



Source: Tritium PKM Operations Manual

CHAPTER 3: Results

The project developed DC-DC power conversion technology that powered a commercially available ultra-fast charger using no additional grid capacity at the demonstration site. The technology combined hardware, firmware, and software in a PEM that was designed, built, and operated to provide 150 kW of power to a charging station. The PEM eliminated grid impacts by decoupling the charging process from the grid and connecting directly to the DC side of a BESS microgrid. The project's microgrid featured 187 kWh of battery storage, 80 kW of solar photovoltaics, and a 30-kW grid-tied AC/DC bidirectional power converter. The firmware embedded in the PEM contained control algorithms that reliably managed the charging stations' power requirements and delivered power from the microgrid to the charger. Intelligent EMS software ensured that the microgrid-powered PEM could supply charging needs with a very small grid connection. The DC-coupled solar and storage microgrid supplied 100 percent of the charging energy during testing and could supply 100 percent of the energy for fast charging at the site, based on current demand.

By supplementing the charging use case with other revenue use cases from the microgrid, the project demonstrated that microgrid-boosted charging can lower EV fueling costs below those of gasoline or diesel. Demand charge savings is the most impactful use case, followed by solar self-consumption and energy arbitrage. Energy arbitrage, or the ability to selectively charge the battery system during low electric energy cost periods, is another revenue use case. The system can also be configured to provide grid services and deliver energy and power to alleviate grid congestion. Finally, during outages, the system can continue to supply charging, limited by the amount of energy stored and the recharging provided by the local solar.

The DC-hub architecture advanced under the project has already been deployed in two commercial projects in Fresno, California in 2024. These projects needed to overcome inadequate switchboard capacity and long delays for utility upgrades. While the projects successfully demonstrated that DC hubs can add more fast charging and solar, the project faced several hurdles to implementation, including regulatory barriers, lack of DC hardware, supplier viability, and OEM cooperation.

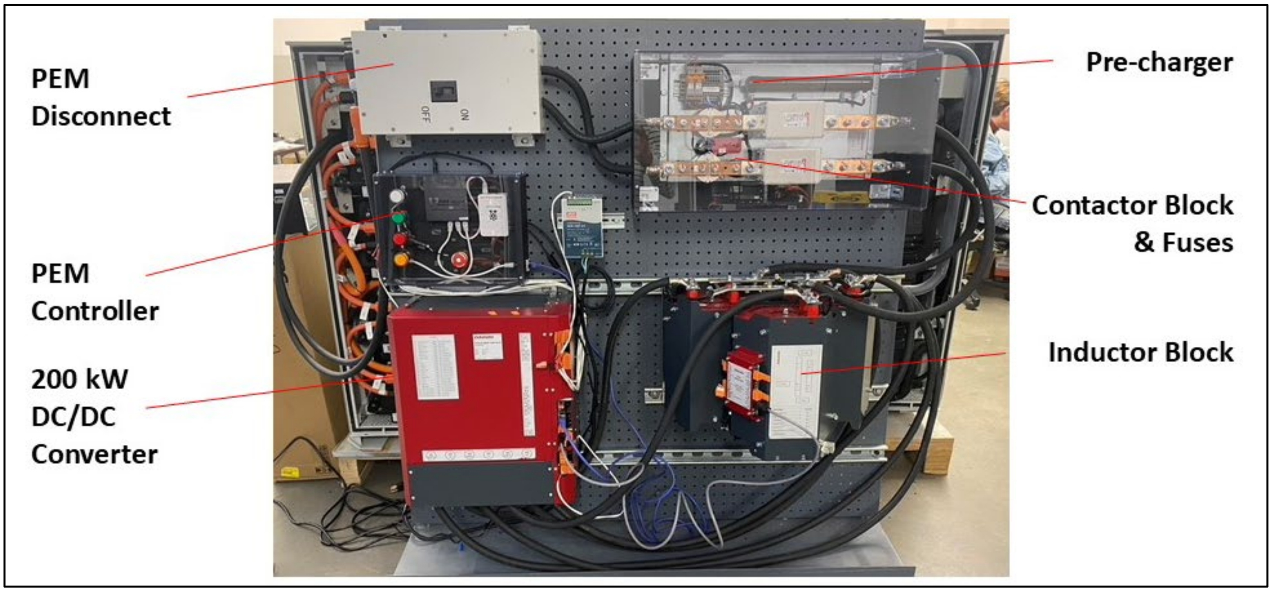
Design, Build, and Demonstrate That the PEM Technology Can Supply up to 150 kW of Power to Tritium's PKM150 User Unit

Design and Build

The project's primary deliverable was to design and assemble a PEM prototype capable of powering a commercially available ultra-fast DC charger directly from a microgrid DC bus. The DCFC selected for the project was Tritium's PKM150 because it provides isolation from the power source, which enables the PEM to safely interface with multiple charging stations, satisfying the program criteria of scalability and interoperability. The PKM150 requires a 950VDC constant voltage input.

A PEM prototype was designed and assembled using commercially available components, constructed on a mobile platform to facilitate testing inside the laboratory. As shown in Figure 14, the PEM prototype had a DC disconnect, pre-charge circuitry, a contactor block, fuses, a 200-kW DC/DC converter, an inductor block, a PEM controller, and metering. The PEM prototype was located inside Intertie's test facility and was connected to the building's microgrid, which Intertie modified to enable the PEM's operation in an actual operating environment.

Figure 14: PEM Prototype

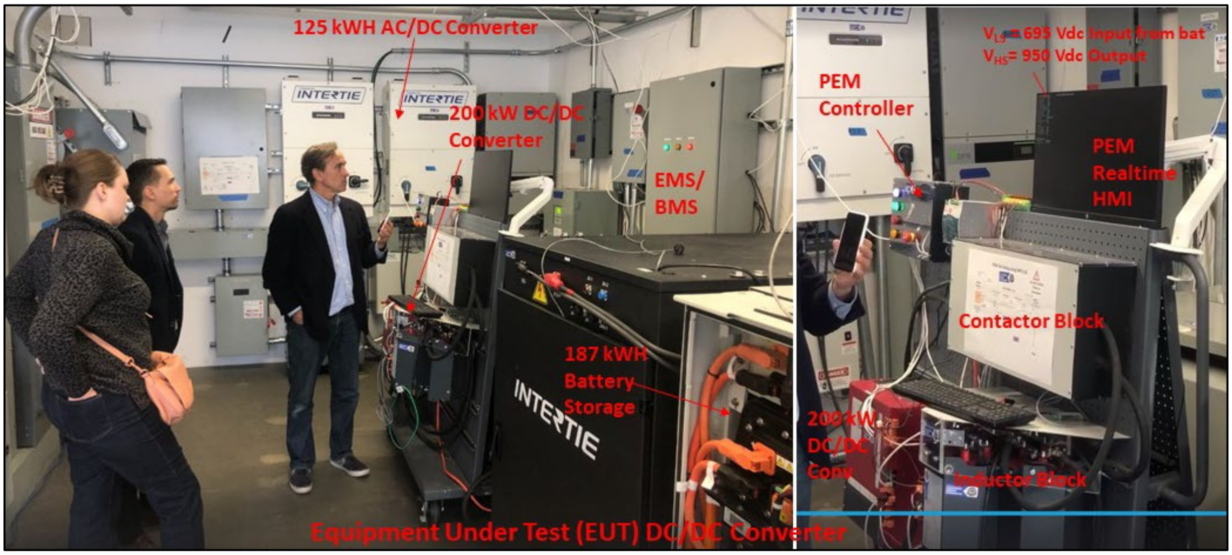


Source: Intertie Incorporated

Testing

Because the commercial availability of the Tritium PKM150 user unit was uncertain through the duration of the project, the test setup was modified by using a 125-kW bidirectional converter to simulate the charger operation. The test setup design is shown in the single line diagram in Appendix A. The PEM was connected to a 187-kWh battery storage system at its input and to the 125-kW bidirectional AC/DC power conversion system (PCS) at its output. The PCS was programmed to draw a constant 950 volts, identical to the Tritium PKM150 charging station. The initial test was conducted during a California Energy Commission (CEC) site visit, as shown in Figure 15. Intertie conducted additional testing after the CEC site visit.

Figure 15: PEM Prototype Testing in Lab Using Simulated Charging During CEC Site Visit

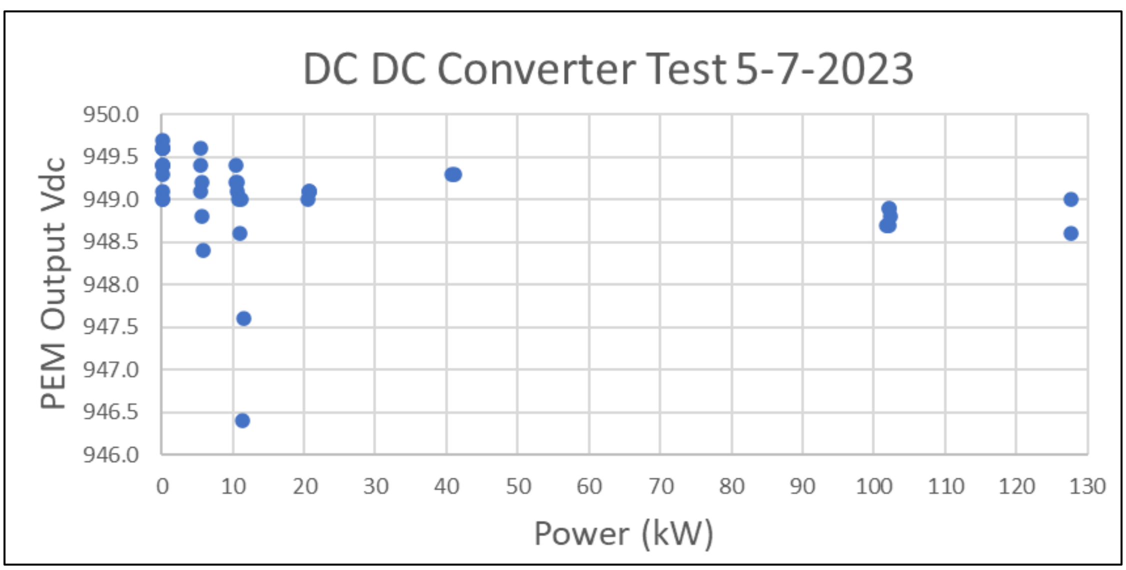


Source: Intertie Incorporated

Results

The results of the PEM's DC/DC conversion during the CEC visit are shown in Figure 16. The test was initially run at low power rates, then quickly ramped up to above 100 kW, then ramped down. The maximum voltage deviation was only 0.37 percent and the PEM remained well within Tritium's charger station voltage range of 940 VDC to 960 VDC.

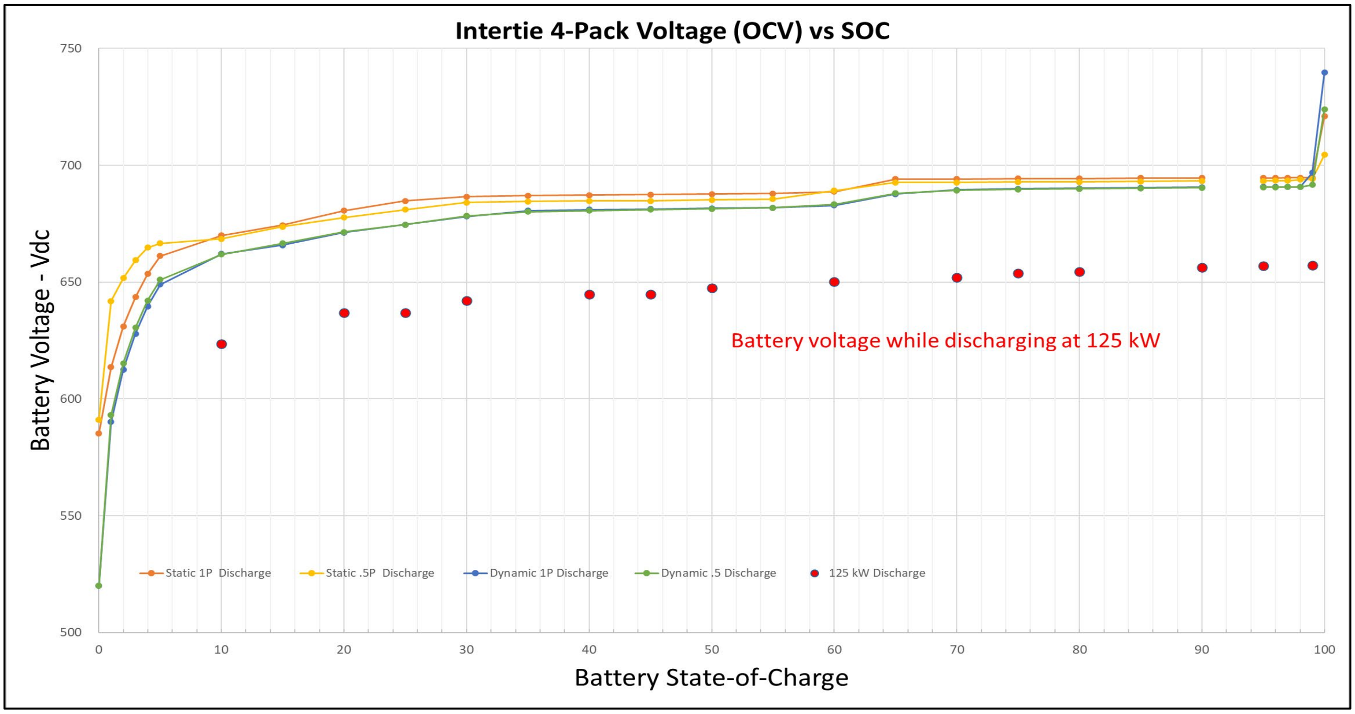
Figure 16: PEM Output Voltage (VDC) Versus Power (kW) in Test Conducted May 7, 2023



Source: Intertie Incorporated

The PEM output was connected to the PCS and the PEM input was connected to a 187-kWh battery system. The PCS was operated at 25-kW, 50-kW, 75-kW, 100-kW, and 125-kW power inputs. The graph in Figure 17 shows the input voltage to the PEM over a full cycle test at 125 kW.

Figure 17: PEM Input Voltage While Battery Is Discharging at 125 kW (V Versus SoC)



Source: Intertie Incorporated

Milestones

- The PEM prototype was designed and fabricated for $25,000 bill-of-material, a 200-kW power block at 12.5 cents per watt (¢/W). At scale with integrated packaging, Intertie can reduce the cost to $15,000 for a 300-kW power block or 5 ¢/W. The 300-kW block is more cost-effective than the power rectifier that connects the PKM150 user units, which is sold by the electric vehicle supply equipment (EVSE) supplier Tritium.
- Using the PEM Interface, the PEM controller successfully configured the pre-charger, contactor operation, and DC/DC conversion for a range of microgrid-boosted power delivery.
- Due to an EVSE supplier delay, the project successfully simulated DCFC operation using an AC/DC power converter that adequately tested the PEM's DC/DC conversion capability.
- The DC/DC conversion process autonomously controlled interaction with the battery at its input using V-match firmware to match variable voltages from the battery and autonomously controlled its output, which required varying power levels and a constant 950 volts.

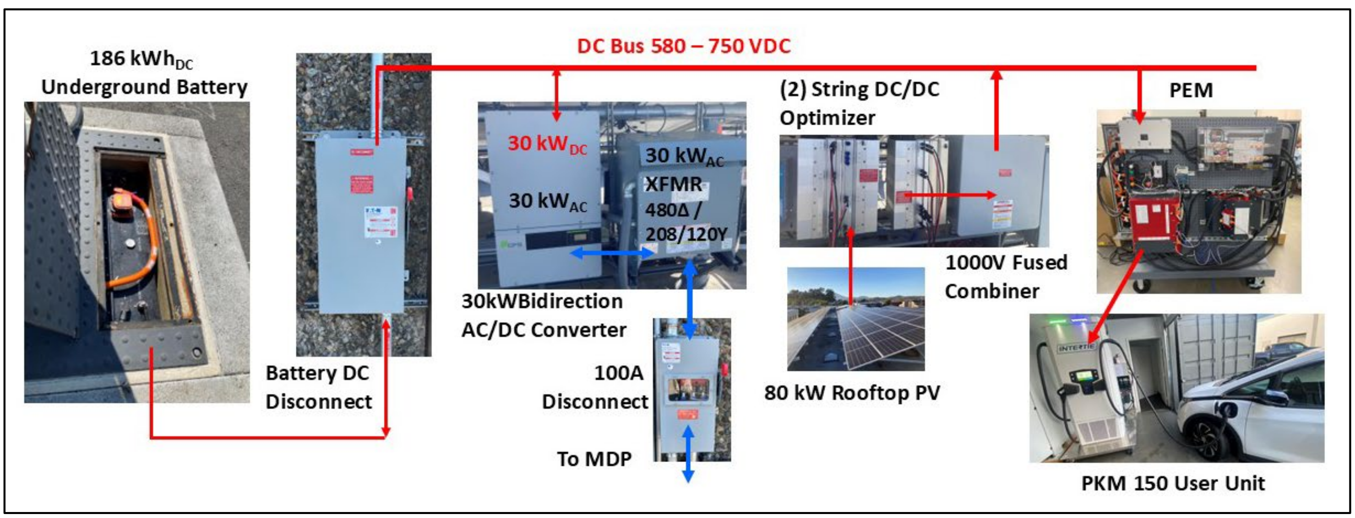
- The PEM firmware reliably controlled the system operation, without real-time PEM or EMS controller interaction, simplifying the control system and facilitating interaction with other DC devices.

Install and Operate the PEM-powered 150-kW Charging Station With PEM Connected to Solar Plus Storage

Another key project deliverable was to demonstrate that the PEM could power an ultra-fast charger powered by a microgrid in its intended environment, a commercial retail location with insufficient grid capacity to support AC-fed DCFC. The deliverable included the ability to manage charging sessions using EV charging applications on smart phone devices.

In the project, Tritium's PKM150 charging station was installed and connected to the PEM. The PEM interfaced with a microgrid connecting the following resources: a 187-kWh BESS, an 80-kW solar DC optimizer, 80-kW solar array, and a 30-kW bidirectional power converter grid-tied to the building panel via a 100A/208V/3Ø connection. The project's microgrid shown in Figure 18 is detailed in the single line diagram in Appendix B.

Figure 18: Bridgeway Microgrid Supplying 150 kW to DCFC via PEM Connected to a 100A circuit



Source: Intertie Incorporated

Twenty charging sessions were successfully initiated using Intertie's EV charging application (via OCPP) with the following EVs: 3x Chevy Bolts, 5 sessions each; 1 Tesla Model Y, 2 sessions; 1 Telsa Model X, 2 sessions; and 1 BMW I4, 1 session. The maximum charging power is limited by the EV. For the charging sessions, the maximum charging power achieved for the 4 vehicles was as follows:

Chevy Bolt:	55 kW
Tesla Model Y:	130 kW
Telsa Model X:	140 kW
BMW I4:	150 kW

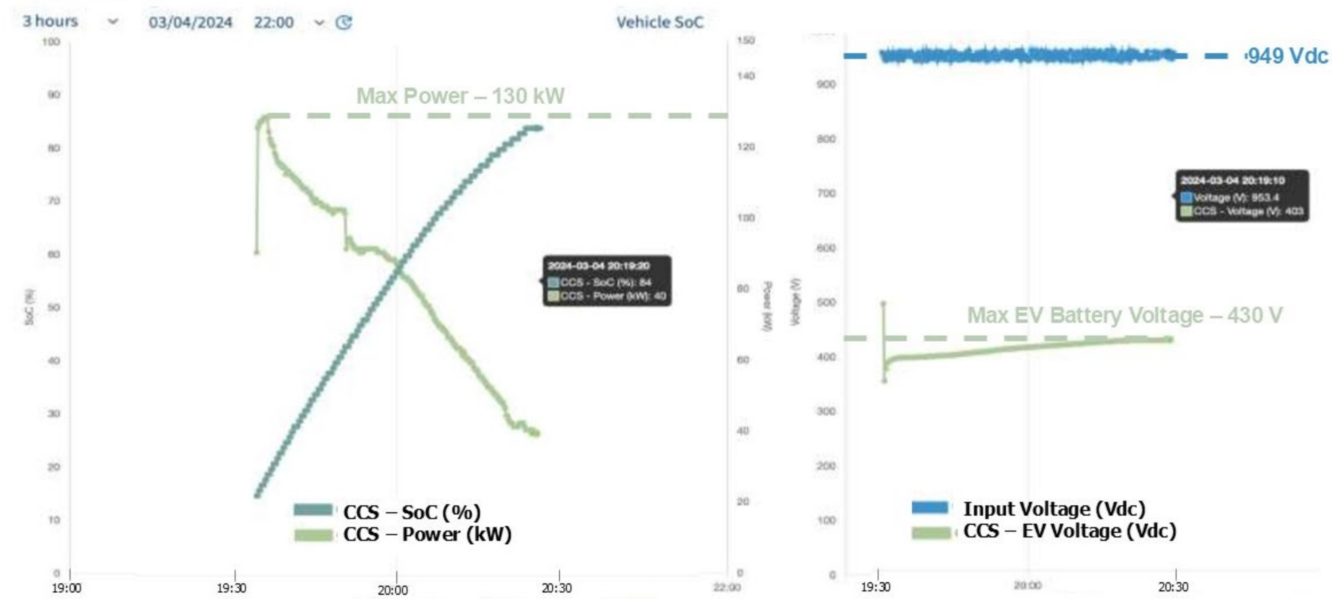
Charging Session With Tesla Model Y

Charger Station and EV Data

The charging session for the Tesla Model Y powered via the PEM-connected charging station is shown below. The data in Figure 19 was provided through Tritium's Pulse Platform, which provides data from the charging vehicle (in this case, the Tesla Model Y) and the Tritium PKM150 user unit. Of note, the PEM maintained a constant voltage of 949VDC over the range of power (25 kW to 130 kW) requested by the Telsa Model Y. One hundred percent of the power used in this charging session was supplied by the DC-coupled solar and the battery; no grid resources were required.

Figure 19: Data From Charger and EV — Tesla Model Y Charging Session Powered by PEM

Date Time	Serial Number	Connector ID	Delivered Energy (Kwh)	Minutes	SoC Start	SoC End
3/4/2024 11:40 to 12:19	72200185	2	56.7	39.13	15%	84%



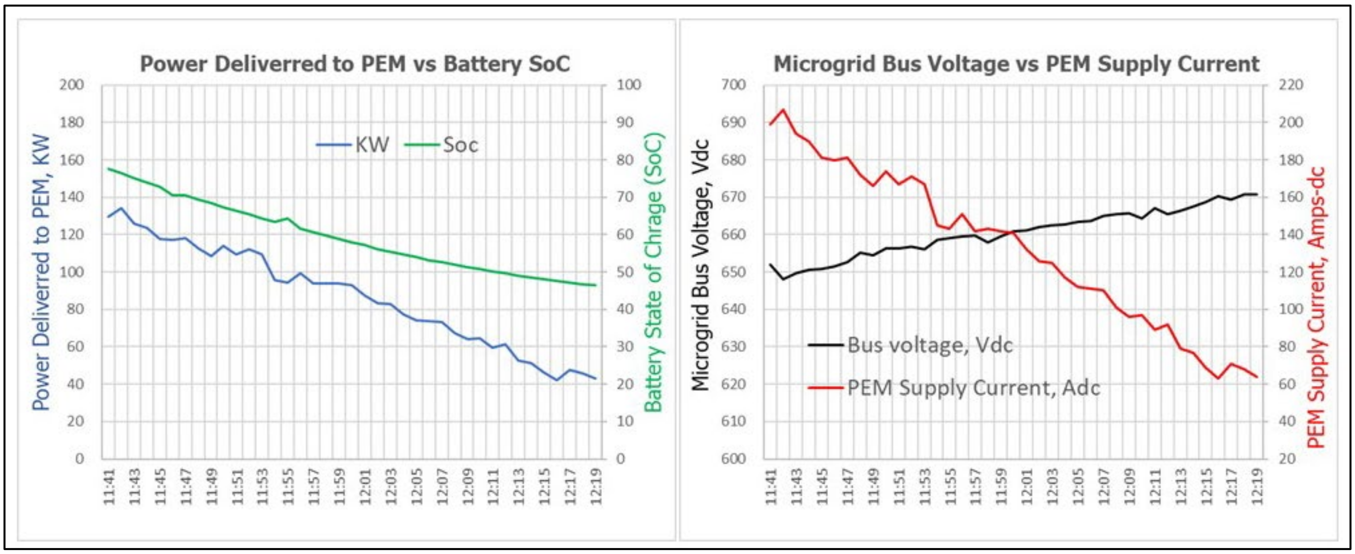
Source: Intertie Incorporated

The microgrid response from the Tesla Model Y charging session is shown in Figure 20. During this session, all of the power was supplied by the microgrid's BESS. Several observations were made from the microgrid operation, as follows:

- During the session, the battery delivered 58.1 kWhs ([77.6 percent — 46.4 percent SoC)] x 186.4 kWh) and the Tesla received 56.7 kWh, with 1.4 kWhs or 2.5 percent efficiency losses from the DC power flow from the microgrid battery discharge, PEM DC/DC conversion, and EV battery charging.
- After accounting for losses in the microgrid battery discharge and EV battery charging, the PEM DC/DC conversion had to operate at a higher efficiency than its 97.5 percent efficiency rating.

- Counterintuitively, the battery bus voltage increased while the SoC decreased because charge current was simultaneously decreasing in response to decreasing power commands from the Tesla Model Y.
- Obtaining accurate SoC calculations is essential for EMS planning to ensure that there is adequate energy in the system to meet forecasted charging demand. The battery management system has 2 SoC algorithms: 1) V versus SoC and 2) coulomb counting. Coulomb counting is required here.

Figure 20: Data From Microgrid — Tesla Model Y Charging Session Powered by PEM



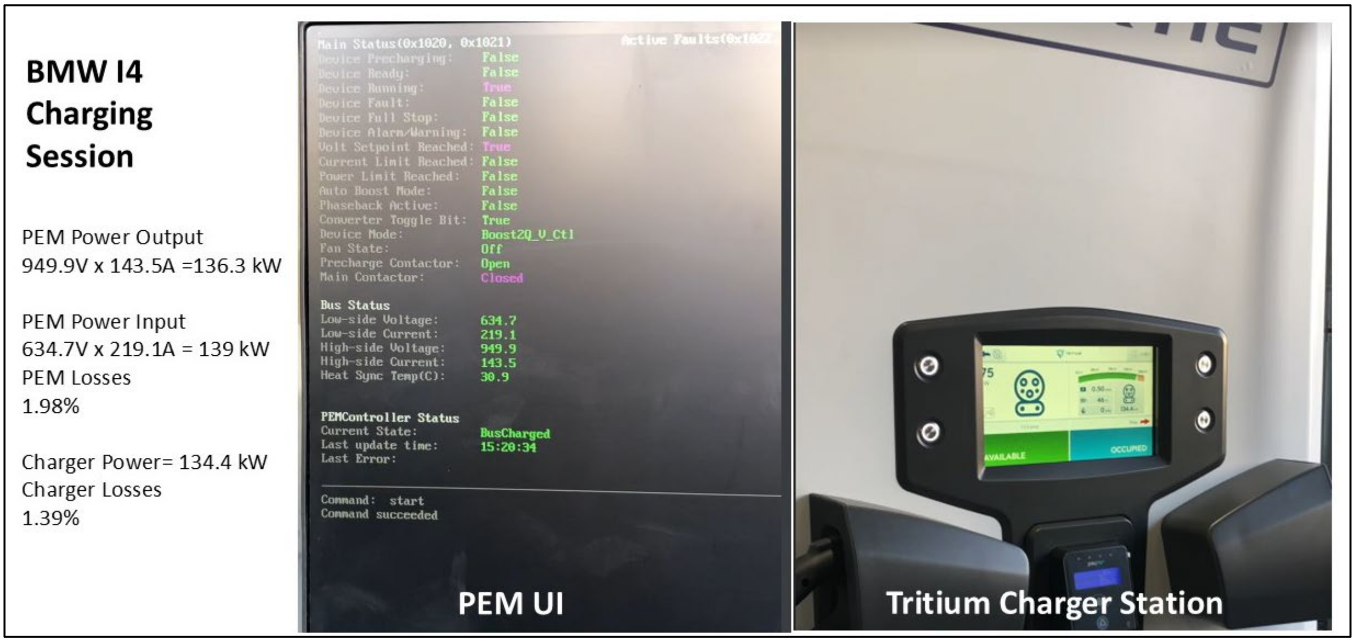
Source: Intertie Incorporated

Charging Session With BMW I4

The 150-kW target charging power was achieved only when charging a BMW I4 using the Tritium charging station powered by the PEM-enabled microgrid. A snapshot of one BMW I4 charging session with data from the PEM UI and the Tritium Pulse Platform is shown in Figure 21. The charging session here maxed out at 148 kW. During this session, power was supplied from the microgrid battery storage and DC-coupled solar — no power was supplied by the grid.

The PEM interface provided additional data to measure the efficiency of the PEM based on input and output data. The calculation is provided for the instance recorded in Figure 21, which shows the PEM was operating at 98.6 percent efficiency.

Figure 21: Data From PEM UI and Tritium — BMW I4 Charging Session Powered by PEM



Source: Intertie Incorporated

Milestones

The PEM successfully powered normal operating scenarios for charging EVs from distributed energy resources and achieved the maximum charging power target of 150 kW.

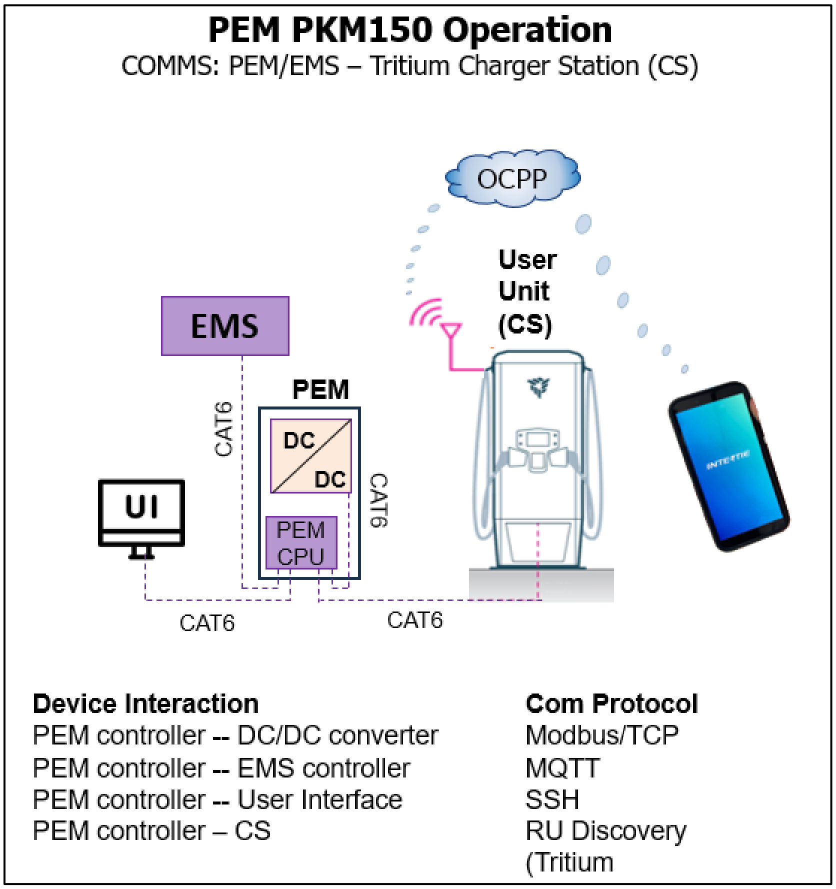
The PEM control system detected an isolation fault on the microgrid side caused by leakage current in the DC/DC optimizer, validating the PEM's safety features.

Managed Charging Load With the OCPP 1.6 Protocol

During the DC-DC testing, a charge request was received via a message from the PEM interface. In the final testing, the charge request was initiated using Intertie's mobile charging application, which arrives via an OCPP backend at the charger station and is communicated to the PEM controller and EMS controller via ethernet. OCPP is an open standard communication protocol for charge point operators. Control communication between the Intertie network and the Tritium PKM150 or other DC fast chargers is performed using OCPP 1.6.

Intertie needed to validate the Tritium PKM150 user unit first, by testing integration capabilities between the EMS controller, PEM controller, cloud network, and Tritium software over OCPP 1.6. Charging sessions were successfully started and stopped via OCPP communication. Using open standards (such as OCPP) to control charging sessions is a fundamental enabler of interoperability, which was one of the project's goals.

Figure 22: Charge Control Communication Using OCPP 1.6



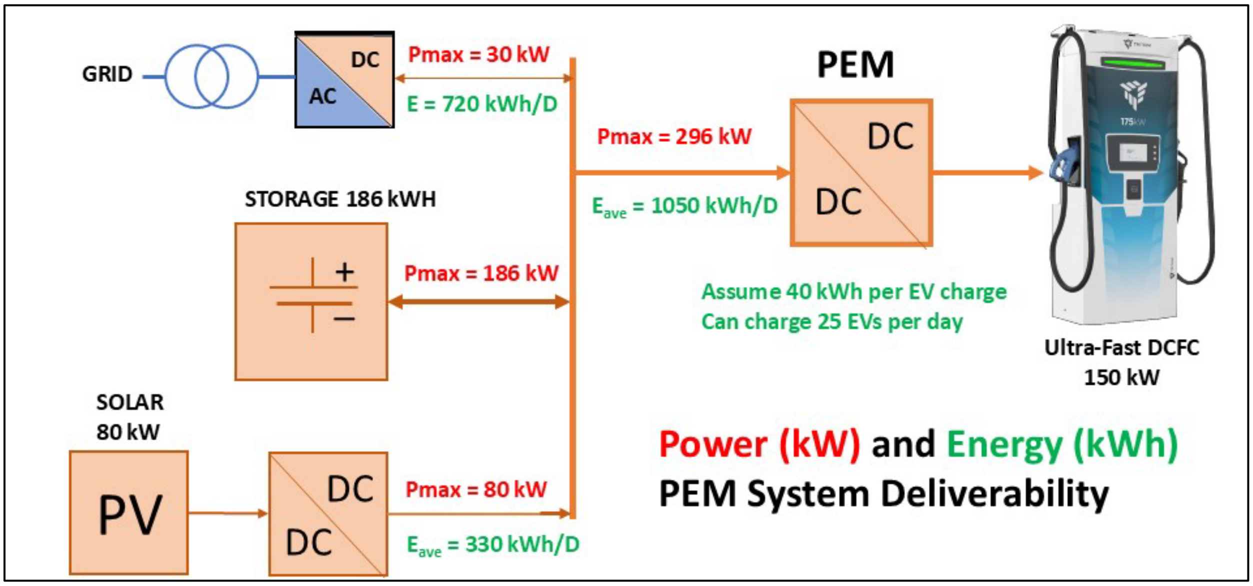
Source: Intertie Incorporated

Intelligent EMS Optimizes Microgrid Assets to Meet Energy Requirements of Anticipated Charging Demand With 100 Percent Solar

The system was designed to meet the power and energy requirements of ultra-fast charging demand at the site. One of the principal advantages of the DC-coupled design is the ability to aggregate power deliverability from the battery, solar, and the grid, which significantly reduces grid power requirements. The limited grid power requires intelligent energy management and device modularity so, if the energy requirements of the site's charging demand exceed the grid and local production, more resources can be added.

In Intertie's system architecture, its EMS site controller communicates with individual hardware components in real time and sends information to Intertie's EMS cloud platform. Energy management algorithms use solar and load forecasts to generate AI-based battery plans and dynamically allocate the system's energy deliverability based on connected resources and charging demand. For this project, the microgrid can deliver 296 kW_{DC} of power and 1,050 kWh per day of energy, as shown in Figure 23.

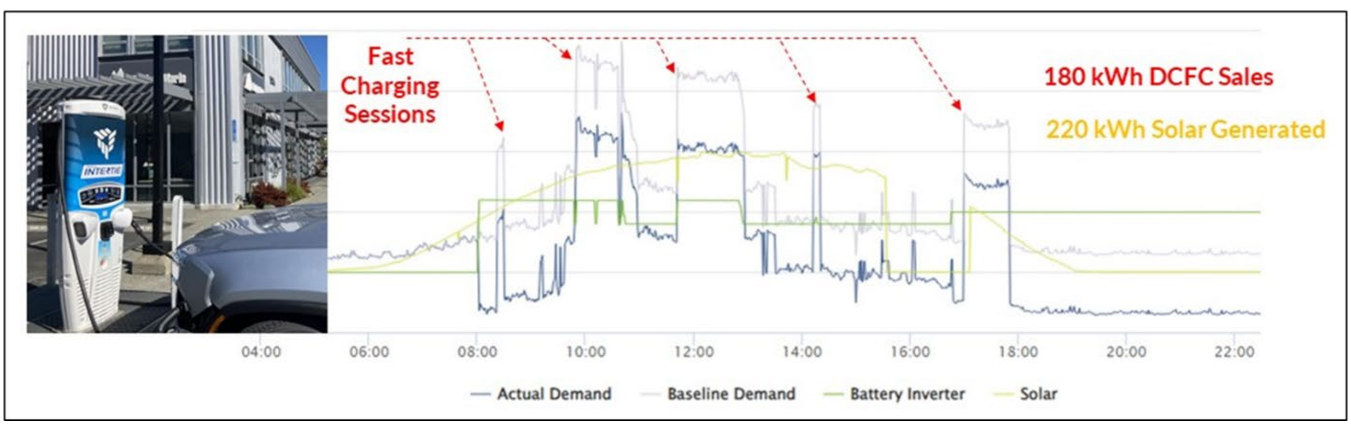
Figure 23: Project Power and Energy Deliverability



Source: Intertie Incorporated

The project site has a public 50-kW Tritium Veefil fast charger open, monitored by Intertie's EMS. Figure 24 shows a daily solar and load profile. On this day, 220 kWh of solar energy was produced; there were five fast charging sessions that consumed 180 kWh. The EMS supplied 100 percent of the site's fast charging needs with solar. The annual average solar generation at the site is 330 kWh per day. Due to a regulatory constraint with PG&E that prevents the battery inverter from importing from the grid (non-import selection) during very low solar production days, the site would not be able to satisfy the charging load. This is an artificial limitation imposed by the utility and can be overcome by intervening at the California Public Utilities Commission.

Figure 24: Site Fast Charging Demand, Aggregate Load, and Local Solar

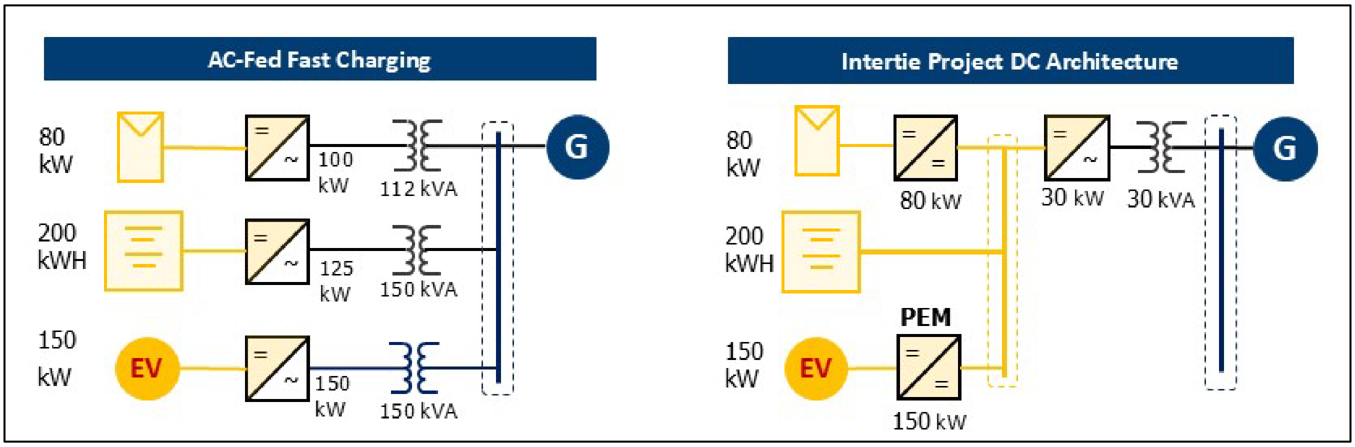


Source: Intertie Incorporated

PEM Enhances DC Architecture Competitive Advantages

Figure 25 shows how the grid, battery, and solar would provide 150 kW of fast charging for two configurations: 1) conventional AC-fed architecture and 2) the project's DC architecture. The site is assumed to have a 208V panel, typical for commercial retail buildings.

Figure 25: Project DC Architecture Versus Equivalent AC-fed Charging



Source: Intertie Incorporated

Table 4 compares relevant attributes of each configuration depicted in Figure 22 that would occur when providing microgrid-boosted fast charging at a commercial property. As shown, the PEM connected to the DC architecture has significant advantages versus a traditional AC-fed fast charger (typically an all-in-one unit).

Table 4: Attributes of DC Versus Equivalent AC Architectures for 150-kW Charging

Comparable Attribute	PEM in DC Hub Architecture	Current Leading AC-Fed Tech
Required Transformer Capacity	30 kVA	412 kVA
Amps Connected to Panel Bus (208/3Ø)	83 A	1040 A
Peak AC Demand	30 kW	150 kW
Losses		
Solar to Charger	4.0%	11.9%
Solar-BESS-Charger	4.0%	15.2%
Grid to Charger	8.3%	8.5%
Grid-BESS-Charger	8.3%	18.1%
PEM Enabled EV Charging Efficiency	93%	87%

Source: Intertie Incorporated

- The DC architecture requires 93 percent less transformer capacity, reducing project costs, the size of the installation footprint, and transformer core losses.
- It has less than 1/12 the impact on the electrical panel and grid. The project's electrical panel is 800A; per NEC code, the electrical panel — and likely the utility service — for an AC-fed configuration would need to be upgraded.
- The DC architecture has much higher efficiency than AC architecture. If the BESS is used (which will increasingly be used in California to maximize solar self-consumption with NEM3 tariffs providing significantly lower netback pricing), the system will generate more than 10 percent energy savings.
- Non-energy benefits:
    - DC architecture allows for easier integration of renewable energy, power, communications, and controls.
    - DC systems can seamlessly act as microgrids (islanded from the grid), which improves resilience.
    - DC microgrids are decoupled from the AC grid even when grid-tied, which makes devices on the DC microgrid less susceptible to frequency and voltage disturbances on the grid.

Project Technology Applied to Construction Projects

The DC power management technology advanced in the project was commercialized and installed in two new projects in the Fresno, California area to increase renewable energy. These commercial construction projects faced similar problems:

- PG&E was unable to upgrade electrical service for an extended time period.
- The building switchgear and electrical panel could not connect the solar capacity required by the building, per NEC 120 percent rule.

Drawing from lessons learned on DC power management from the project's DC-coupled microgrid system, Intertie designed, installed, and operated an islanded microgrid that DC-coupled 200 kW of solar, tripling the installed solar capacity. As shown in Figure 23, smart DC combiners with fusing and relay-controlled contactors were needed to ensure that the BESS wasn't overcharged by solar.

Figure 26: Smart DC Combiner Technology Deployed in Fresno Area Islanded Microgrid

Source: Intertie Incorporated

Summary of Technical Barriers and Challenges

Supplier viability: Two key suppliers of DC power management equipment went bankrupt during the project, requiring Intertie to find alternative vendors.

OEM cooperation: The biggest challenge in making the PEM interoperable with EVSE manufacturers is establishing their cooperation in allowing Intertie to integrate the PEM with DC-fed chargers. For this project, the interaction was limited to OCPP communication.

Lack of DC hardware: There are few options for vendors supplying equipment supporting DC architectures.

Regulatory barriers: Intertie faced significant friction with PG&E and its DC-coupled solar plus storage topology. Moreover, DC-coupled solar plus storage systems are not permitted to have DC loads connected, making interconnection problematic.

CHAPTER 4: Conclusion

For California to achieve its goal of carbon neutrality by 2045, 300 terawatt-hours (TWh) of electricity would need to replace the 13.6 billion gallons of gasoline and 2.06 trillion cubic feet of natural gas the state consumes annually. The grid must double or triple its capacity by then.[5] Given the breadth of grid constraints despite the relative early stages of the state's transition to net zero, the state cannot exclusively rely on utilities to expand the traditional power grid. To achieve its climate goals, the state needs to also broadly deploy distributed clean energy solutions that mitigate the impact of new electrification, expand onsite renewables, and increase the utilization of the existing grid.

In particular, decarbonizing transportation will be essential to achieve net zero goals, as it removes the state's largest source of GHG emissions. However, broad EV adoption necessitates vehicle-charging availability that rivals the convenience of gas stations, requiring an extensive network of high-power DCFC stations capable of supplying at least 10 miles per minute. By far, the biggest barrier to establishing such a network is grid capacity.

The project developed new technology and tools that mitigate the grid impact of transportation electrification, can expand distributed renewable generation beyond what the market provides today, and maximizes grid utilization. Using new power electronics technology and an advanced DC-hub architecture, the project minimized the impact of fast charging on the grid, providing a template showing how to timely deploy a convenient DCFC network across the state. The blueprint is to decouple the charging process from the AC grid, maximize DC power delivery of DC-coupled distributed energy resources, and selectively draw power from the grid via a smart, EMS-managed AC/DC converter. The new technology developed in the project combined hardware, firmware, and software in a PEM that powered a commercially available charging station from a DC microgrid. The PEM is a modular, plug-and-play device that can connect fast charging stations to other DC-coupled DERs, including solar and battery storage. Such DC architecture optimizes the inherent advantages of DC power distribution.

The project demonstrated the following benefits:

- The PEM supplied up to 150 kW of power to Tritium's PKM150 user unit using **no grid resources** and can be controlled using charging applications available on smart devices.
- A DC-coupled solar-plus-storage microgrid supplied 100 percent of the charging energy during testing and could have supplied 100 percent of the site's energy for fast charging based on current demand.

[5] Every year, California consumes 13.6 billion gallons of gasoline and 2.06 trillion cubic feet of natural gas. Assuming the weighted-average vehicle (cars, trucks) consumes 20 miles per gallon and the equivalent EV gets 2 miles/kWh, this electrification would require 136 TWh and 51 gigawatts (GW) of grid capacity. If we assume the natural gas consumption is replaced with the most efficient heat pump, this electrification would require 160 TWh and 55 GW. For reference, California's summer and winter peaks are 38 GW and 31 GW, respectively, and the state has the capacity to generate 55 GW.

- The project’s DC architecture connected double the amount of solar capacity compared to conventional solar AC inverters.
- The PEM seamlessly integrated a fast charger with a DC hub that combined power delivered from a battery, rooftop solar photovoltaics, and a small grid-tied AC/DC converter.
- While AC-fed fast charging can reduce its grid impact using local battery storage and solar with proper power control, DC architecture with the PEM delivers performance and efficiency benefits that AC architectures can’t match for high-power charging:
  - The DC architecture requires 93 percent less transformer capacity, reducing project costs, the size of the installation footprint, and transformer core losses.
  - It has less than 1/12 the impact on the electrical panel and grid, obviating an upgrade to the electrical panel and utility service.
  - It has much higher efficiency, saving more than 10 percent in energy use.
  - It is easier to integrate and control, improving reliability.

Ratepayer Benefits

The PEM is a technology that provides three major benefits for California ratepayers:

1. It reduces utility grid upgrades needed for traditional AC fast charging, avoiding additional costs being added to the rate base, thus helping prevent future rate increases.
2. It improves a site’s load factor, enabling more energy to flow through the same grid capacity and spreading distribution costs over more kWh, which lowers distribution rates for all customers.
3. It lowers the capital cost of deploying fast charging, ultimately reducing the cost of charging for all Californians.

Challenges

The project had its fair share of challenges. While the multi-disciplinary engineering execution was challenging, external challenges proved to be more problematic, as they were unexpected and beyond the team’s control.

Supplier Viability

Challenge: Two key suppliers of DC power management equipment went bankrupt during the project, requiring Intertie to find alternative vendors.

Lesson learned: Remain adaptable to market changes and limitations; continue prioritizing modularity and interoperability.

OEM Cooperation

Challenge: The biggest challenge in making the PEM interoperable with EVSE manufacturers is establishing their cooperation in allowing Intertie to integrate the PEM with DC-fed chargers. For this project, the OEM limited Intertie's interaction to OCPP communication.

Lesson learned: Develop successful projects that establish Intertie as a reputable player in the EV charging industry, particularly for fast charging technologies, and can lead to partnerships with EVSE manufacturers.

Lack of DC Hardware

Challenge: There are systematic barriers hindering the advancement of DC architectures, particularly in the 1000V and 1500V class that is needed for microgrids. There are few options for vendors supplying equipment supporting DC architectures.

Lesson learned: Have the engineering and development capability to design and build purpose-built products.

Regulatory Barriers

Challenge: Intertie faced significant friction with PG&E and its DC-coupled solar-plus-storage topology. Moreover, DC-coupled solar plus storage systems are not permitted to have DC loads connected, making interconnection problematic.

Lesson learned: Engage with utilities, regulators, and lawmakers to remove barriers to the development and deployment of DC technologies.

Recommendations and Next Steps

1. Begin a proceeding at the California Public Utilities Commission to remove regulatory barriers to implementing DC loads in battery storage systems, which currently block interconnections. The proceeding should also enable import and export to the grid from microgrids.
2. Develop an expandable, rack-mounted PEM unit with integrated power electronics to facilitate site installation, lower costs, and accelerate scalability.
3. Upgrade PEM technology to be able to supply power to multiple DCFCs being used simultaneously (more than 1 MW) without impacting the grid.
4. Develop partnering strategies to expand customer base and enable integration with multiple charger station OEMs.
5. Secure the manufacturing facility to begin scaling production.

List of Terms/Glossary

Term	Definition
A	ampere or amps
AC	alternating current
BESS	battery energy storage system
CAPEX	capital cost
CEC	California Energy Commission
CMC	California Mobility Center
CPUC	California Public Utilities Commission
CPU	central processing unit
CSMS	charge station management system
DC	direct current
DCFC	direct current fast charger/charging
DER	distributed energy resource
EMS	energy management system
EV	electric vehicle
EVSE	electric vehicle supply equipment
GHG	greenhouse gas
GW	gigawatt
KVA	kilovolt-ampere
kW	kilowatt
kWH	kilowatt-hour
MW	megawatt
NEC	National Electric Code
OEM	original equipment manufacturer
OCPP	Open Charge Point Protocol
PCS	power conversion system
PEM	power electronics module
PG&E	Pacific Gas & Electric Company
Ø	phase
RU	rectifier unit
SoC	state-of-charge
TWh	terawatt-hour
UI	user interface

Term	Definition
V	volts
VDC	volts of DC

References

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Project Deliverables

While most of the key technical tasks as identified in the Agreement and Scope of Work are provided in this report, other Project Deliverables include the following list of products and/or reports.

1. System Engineering and Design Final Report
2. Basic PEM System Construction Final Report
3. DC-DC Conversion Final Test Plan
4. DC-DC Conversion Validation Final Report
5. System Validation Final Test Plan
6. System Validation Final Report with Appendices

These project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.

Additionally, technical tasks identified in the Statement of Work include:

a. Electrical single line diagrams of the power laboratory that was modified to perform the high-power testing.
b. Electrical single line diagram of the project microgrid that was used to test the PEM in real world operation.