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ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Smart Power Integrated Node (SPIN)

Vehicle-to-Grid Integration with Local Distributed Energy Resources Enabling Zero Net Energy, Resiliency, and Distribution Grid Services

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PREFACE

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

In 2012, 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 California Energy Commission and the state's three largest investor-owned 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 Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- 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), and finally with clean, conventional electricity supply
- Supporting low-emission vehicles and transportation
- Providing economic development
- Using ratepayer funds efficiently

Smart Power Integrated Node (SPIN) - DC Vehicle-to-Grid Integration with Local DER Enabling Zero Net Energy, Resiliency, and Distribution Grid Services is the final report for the Open Vehicle to Building/Microgrid Integration Enabling ZNE and Improved Distribution Grid Services Project (EPC-16-054) conducted by the Electric Power Research Institute (EPRI). Information from this project contributes to the Energy Research and Development Division's EPIC Program.

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

ABSTRACT

California’s transportation electrification policy goals require rapid and widespread deployment of plug-in electric vehicles (PEVs) and charging infrastructure. Technologies to manage charging and discharging of PEVs can help increase use of renewable electricity, improve site resilience, and provide distribution system benefits. This requires both hardware and software advances on the vehicle and charger using methods that are scalable, safe, and compliant with applicable codes and standards. This project developed and demonstrated the Smart Power Integrated Node (SPIN) to meet these needs and increase customer and electric system benefits from PEV adoption.

The SPIN system allows customers to simultaneously balance and optimize multiple connected distributed energy resources such as solar photovoltaic, battery energy storage, and bidirectional PEVs. Through the application of open standards-based interfaces, the project achieved the goals of interoperability, cybersecurity, and compliance with California Public Utilities Commission Rule 21 smart inverter interconnection requirements. The project demonstrated the SPIN system as one of the first vehicle-to-grid capable direct current chargers based on the combined charging system standard. Building upon previous work sponsored by the US Department of Energy, this project also evaluated the impact of bidirectional power flow on vehicle battery degradation.

This project built, integrated, and demonstrated the capabilities of the design-intent SPIN system with Fiat City PEV and a production 2020 Chevrolet Bolt. Testing validated the ability of the SPIN system to support islanded loads (referred to as vehicle-to-building). The battery testing revealed the significant potential to use the PEV battery for electric services with limited but quantifiable degradation from bidirectional charging. The project modeled potential customer value across a variety of scenarios of grid services, ranging from approximately $450/year to $1,000/year per PEV. The report concludes with discussing technology transfer plans for continued product development, certification, and commercialization.

Keywords: Vehicle-to-Grid (V2G), Vehicle-to-Building (V2B), Distributed Energy Resources (DER), Microgrid, Distributed Energy Resource Management System (DERMS), Zero Net Energy (ZNE), Solar, Energy Storage, Plug-in Electric Vehicle (PEV)

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Introduction

California implemented numerous policies to reduce greenhouse gas emissions and increase use of renewable resources in the electric sector while transitioning the transportation sector to zero-emission technologies such as plug-in electric vehicles (PEVs). Today, California leads the nation with more than 1 million PEVs, more than 1.12 million solar photovoltaic (PV) home installations, and 250,000 homes that can store electricity generation (behind the meter storage). According to one estimate, about 125 megawatts (MW) of residential storage has been installed in California alone.

At the same time, there was growing customer, utility, and policy attention focused on increasing the resilience of the electricity system in a changing climate. Worsening drought and wildfires resulted in public safety power shutoffs that left millions of Californians without electricity. The recent heatwave in the summer of 2020 prompted the state's first rolling blackout in more than a decade. Combined, these trends drove strong interest in understanding how PEVs, solar PV, and behind-the-meter storage can help simultaneously decarbonize California's electricity and transportation systems while increasing customer and electric system resilience.

Today, residential behind-the-meter storage is almost entirely provided by small-scale (approximately 7–15 kilowatt-hours) lithium-ion batteries that have a high cost (approximately $1,000–$1,200 per kilowatt-hour. High costs can make behind-the-meter storage challenging to justify economically without incentives. Programs like the Self Generation Incentive Program are designed to help overcome this barrier.

A potentially lower cost strategy is to use the battery inside a PEV to provide functionality comparable to stationary storage. Powering loads through facility circuits — referred to as vehicle-to-building (V2B) or vehicle-to-home (V2H) — could provide similar resilience and environmental benefits without the cost of purchasing a dedicated storage system. A PEV could provide enough storage to power a home for many hours without significant impact to battery degradation when managed following manufacturer's recommendations. For homes with solar PV or other distributed generation installed, PEV charging and discharging could be coordinated with local generation to provide backup for even longer durations spanning several days. The potential of PEV batteries for electricity services will grow as battery durability improves and battery pack sizes become larger — many PEV models have a battery pack that exceeds 100 kilowatt hours (kWh). When operated during infrequent outages, a PEV could potentially store enough energy to power a building for several hours or longer if the building has solar PV installed. In addition to having on-site generation benefits, installing and coordinating charging the battery with other distributed energy resources (DER) can provide benefits to distribution system operators by helping to reduce renewable curtailment, supporting local loads, or exporting electricity during times of peak demand or steep ramp rates.

Unfortunately, most PEVs and chargers today are designed only to receive electricity from the grid and deliver it to the vehicle, as opposed to operating by sending and receiving energy to and from the vehicle and the grid (bidirectionally). Realizing the resilience, economic, and environmental benefits of bidirectional charging integrated with other DER requires developing hardware and software to cost-effectively coordinate local loads, DER operation, and PEV charging and discharging. Commercializing bidirectional charging technologies will require low-cost solutions and applying open standards and communication protocols — many are still in development but evolving rapidly — that enable operating across different makes and models of vehicles and chargers. Additionally, automotive original equipment manufacturers (OEM) and battery suppliers need data to evaluate the extent of which discharging the battery for vehicle-to-building applications contributes to battery degradation or raises warranty considerations.

Project Purpose

This project developed and tested the Electric Power Research Institute's Smart Power Integrated Node (SPIN) system, which combines a bidirectional PEV charger with a DER management system capable of meeting all Rule 21 smart inverter requirements. Rule 21 describes the interconnection, operating, and metering requirements for generation facilities (including energy from batteries) to be connected to a utility's distribution system. By integrating solar PV, a bidirectional PEV charger, and optional stationary storage with a single piece of equipment, SPIN eliminates redundant components (for example, multiple inverters changing direct current to alternating current), reducing hardware and installation cost. The SPIN system allows customers to use their PEV battery energy to power homes or buildings without purchasing a stationary storage system.

The project team advanced the technology readiness of the SPIN system by developing software; conducting laboratory testing of communications, charging, and discharging functionality; and measuring battery degradation associated with bidirectional operation to inform automotive OEM product development plans.

Project Approach

The team developed and tested hardware and software across multiple sites, which validated the production-intent SPIN prototype with commercially available PEVs. The project approach followed these activities:

- Defined communication system for the SPIN system to operate when connected to the grid and participating in grid services and when disconnected from the grid and supporting backup loads.
- Defined, developed, and implemented software for multiple vehicle-grid-integration (VGI) use cases, including maximizing renewable use, minimizing grid impacts, and enabling PEV quick charging using onsite solar and stationary battery storage.
- Conducted testing of power electronic components and the integrated SPIN system.
- Quantified the impact of bidirectional operation on PEV battery degradation by conducting accelerated testing in a controlled laboratory environment.
- Evaluated customer and ratepayer benefits associated with widespread adoption of bidirectional chargers such as the SPIN system using the Distributed Energy Resource Value Estimation Tool.
- Shared project results and information with the industry to move the SPIN prototype through product development toward certification and commercialization.

This project engaged a broad team of subject matter experts including: EPRI, Stellantis, Flex Power Control, Rhombus Energy Solutions, Kitu Systems, Gridscape Solutions, Oak Ridge National Laboratory, and National Renewable Energy Laboratory. A technical advisory committee was formed at the beginning of the project and met three times through project completion. The technical advisory committee included the California Independent System Operator; University of California, Los Angeles; automotive OEMs including Honda, Toyota, Ford, Nissan, Audi, and Stellantis; third-party service providers including Kitu Systems and Nuvve; the California investor-owned utilities; and Sacramento Municipal Utility District.

Leveraging several related awards from the Department of Energy, the team tested and validated the performance of the SPIN system in two phases. In the first phase, Flex Power Control worked with engineers at the Oak Ridge National Laboratory National Transportation Research Center to develop and test the proof-of-concept power electronic conversion components and controls. Based on this testing, the team integrated the controls software with the design-intent prototype in mid-2020. The team defined specific use cases for the SPIN system and developed software for use case implementation and testing system performance. The second phase was integration and testing with both modified and commercially available PEVs.

Accelerated testing of potential PEV battery degradation associated with bidirectional operation occurred at the National Renewable Energy Laboratory Energy System Integration Facility. Stellantis provided two identical 17 kWh LG Chem battery packs of the type used in the Pacifica plug-in hybrid minivan. The team developed representative charging and discharging profiles for driving (approximately 11.7 kWh daily) and vehicle-to-building operation (an additional 5 kWh daily) and cycled one battery for driving only and one for driving and vehicle-to-building services. Both batteries were cycled approximately three times per day for more than 12 months, collecting data representative of nearly four years of daily operation.

Project Results

The SPIN system efficiency in charging and discharging mode was between 85 and 97 percent depending on the power level. An outage was simulated to verify the SPIN system could provide backup power from the PEV battery and transition between grid-tied (or "grid following" mode in which the SPIN system is connected to the grid and controlled by grid assets) and islanded operation (or "grid forming" mode in which the SPIN system is disconnected from the grid and is the main power provider to the building). The system was able to deliver 2 to 5 kW from energy supplies emulating a PEV battery to variable loads.

The SPIN system was tested with a Fiat 500 PEV supplied by Stellantis to validate basic charging functionality. The team only had access to the Fiat for a limited time, so testing continued with production 2020 Chevy Bolt PEVs. The SPIN system charged the Chevy Bolts using the combined charging system connector at up to 10 kW (for a short duration and up to 3 kW for continuous testing) and discharged the vehicles at up to 2 kW (which was software-limited to ensure no adverse impacts to battery health).

While there is measurable degradation in battery capacity from vehicle-to-building operation, testing results indicated significant cumulative energy throughput (or total energy stored and delivered) available for grid services over the lifetime of the battery. Compared to the driving-only battery test pack, the vehicle-to-building battery test pack supplied around 44 percent more energy daily and had 60 percent greater throughput. The vehicle-to-building test pack experienced 2.3 percent annual degradation (reaching 89.7 percent of original capacity at the end of testing) compared to 1.8 percent for the driving-only test pack (95.3 percent at end of testing).

The project team also analyzed the potential resilience, economic, and environmental benefits of bidirectional charging technologies, such as the SPIN system, for several use cases. The Distributed Energy Resource Value Estimation Tool was used to evaluate scenarios including premise-level resiliency (residential or small commercial building scale), distribution level peak shaving, and system-wide peak reduction or mitigation of curtailment. The analysis assumed a PEV the size of a Chevy Bolt could provide 10 kW and 20 kWh (about 33 percent of the nameplate capacity) for grid services and 10 kW and 40 kWh of backup energy during outages. The results showed the SPIN system has lower capital costs of approximately $21,000 compared to a commercially available 40 kWh stationary battery storage system, can enable between $450 and $1,200 per PEV per year in energy bill savings through distribution and system wide energy services, and can reduce greenhouse gas emissions by about 125 pounds per PEV by reducing renewable curtailment.

Technology/Knowledge Transfer

Three technical advisory committee (TAC) meetings were hosted by EPRI. Interactions with the project TAC — including representatives from automotive OEMs, utilities, the California Independent System Operator (Calfornia ISO), standards setting bodies, equipment manufacturers, and third-party service providers — helped direct project activities.

This project raised stakeholder awareness of the SPIN system and bidirectional charging technologies broadly with key stakeholders including automotive OEMs, utilities, and DER solutions providers. The project team presented to utility advisors (including Southern California Edison (SCE), Sacramento Municipal Utility District, Los Angeles Department of Water & Power, Pacific Gas & Electric Company, Xcel Energy, Korea Electric Power Company, Tokyo Electric Power Company, EPB Chattanooga, and Hawaiian Electric Company) to solicit feedback, ensure alignment with industry requirements, and assess compliance with existing technical standards. Additionally, the team shared project results at multiple Department of Energy Annual Merit Review meetings, EPRI biannual advisory council meetings, seminars at three universities (University of California, Los Angeles, Stanford University, and Lehigh University), DISTRIBUTECH 2020, and the inaugural EPRI Electrification Conference as well as the 2022 EPRI Electrification conference.

Building from this project, EPRI is working with multiple utilities to streamline grid interconnection requirements for bidirectional chargers. The technical details from this project were shared with standards development organizations and are informing standards revisions to incorporate reverse power flow in direct current (DC) charging communications between the PEV and charger. This will enable adoption by the OEMs and the equipment makers to deploy this technology at scale. Because DC bidirectional chargers do not require on-vehicle hardware, some of the legacy PEVs currently deployed, such as Chevy Bolt, could become bidirectional capable with only a software update.

Flex Power Control continues to test, improve, and advance the SPIN system toward certification and commercialization. Currently the intention is to develop two product variations (specifications in Appendix A) – one simplified version named SPIN-EVO focused on providing backup power from PEVs during outages, and the second version named SPIN-MPX that functions as the complete design-intent system integrating solar, local storage, and bidirectional charger as tested in this project. The next steps include testing the prototype in a utility grid environment, collecting operational data, and evaluating pathways to obtain certification from a nationally recognized testing laboratory. Flex Power Control identified potential manufacturing partners and has plans to do capital raising to support certification and listing.

The initial target market for the SPIN system was residential installations in California that have or plan to install rooftop solar. The mid- to long-term market plan is to expand product offerings for medium commercial buildings such as office buildings. At least three automotive OEMs are in active discussions with Flex Power Control as well as California investor-owned utilities, which are considering the SPIN system in their product listings and upcoming pilots.

Benefits to California

The SPIN system combines multiple functionalities to help simultaneously integrate intermittent renewable generation, reduce grid impacts from PEV charging, and provide resiliency for customers without the costly behind-the-meter stationary storage. The SPIN system can reduce customer costs by replacing the following components with one single unit:

- Behind-the-meter stationary storage, which costs approximately $15,000 fully installed for 10 kWh capacity and requires a dedicated inverter resulting in additional conversion losses.
- PV inverter, which costs approximately $1,750 and is not able to provide customer resilience by supporting islanded loads during an outage.
- Networked controllable alternating current PEV charger, which costs approximately $750 to $1,000 and charges vehicles at a lower rate than the SPIN system is capable of.

Combined, the direct customer cost of these pieces of equipment is approximately $28,000, compared to the target volume production cost of the SPIN system of around $7,000 including installation. Thus, the SPIN system could potentially save California adopters approximately $21,000 per unit while providing access to energy storage on-board PEVs capable of providing longer durations of backup power. Furthermore, the SPIN system can provide bill savings for customers while simultaneously providing benefits to the electric system through local peak reduction or even system-level demand response. These operational benefits combined with lower upfront costs present a compelling economic case for scaling up deployment of the SPIN system and other bidirectional charging technologies.

Chapter 1: Introduction

Background

California has implemented numerous policies designed to reduce greenhouse gas emissions and increase deployment of renewable resources in the electric sector while transitioning the transportation sector to zero-emission technologies such as plug-in electric vehicles (PEVs).[1,2] Today, California leads the nation with more than one million PEVs, more than 1.12 million homes with solar photovoltaic (PV) installations, and 250,000 homes with behind-the-meter (BTM) storage.[3,4] A total of 125 megawatts (MW) of residential storage was deployed in California by 2019, according to the latest data.[5]

There has also been growing customer, utility, and policy attention focused on increasing the resilience of the electricity system in the face of a changing climate. A worsening drought and multiple wildfires resulted in public power safety shutoffs (PSPS) that left millions of Californians without electricity.[6] The recent heatwave in the summer of 2020 prompted the state's first rolling blackouts in more than a decade. In response, several new programs focused on increasing resilience were implemented.[7] These trends drove strong interest in understanding how PEVs, PV, and BTM storage can help simultaneously decarbonize California's electricity and transportation systems while increasing customer and electric system resilience.

Today BTM storage is almost entirely provided by small-scale (approximately 7–15 kilowatt hours) lithium-ion batteries that have a high cost (approximately $1,100 per kilowatt-hour) both in terms of fully installed direct capital expense and levelized costs.[8] Even with the federal income tax credit, this cost is about $900 per kilowatt hour. Today, a commercially available 5

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[1] Renewables Portfolio Standard Program. CPUC. https://www.cpuc.ca.gov/rps/.

[2] California Governor Executive Order N-79-20. 2020. https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf.

[3] EPRI analysis based on third-party registration data, as of July 2020.

[4] Statistics and Charts: NEM Solar PV, California Distributed Generation Statistics. 2021. California Distributed Generation Statistics. https://www.californiadgstats.ca.gov/charts/.

[5] Battery Storage in the United States: An Update on Market Trends. 2021. DOE EIA. https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage_2021.pdf.

[6] Utility Public Safety Power Shutoff Plans (de-energization). 2021. CPUC. https://www.cpuc.ca.gov/psps.

[7] Governor Newsom Launches $75 Million Program for State and Local Governments to Mitigate Impacts of Power Shutoffs. 2019. Office of Governor Gavin Newsom. https://www.gov.ca.gov/2019/10/25/governor-newsom-launches-75-million-program-for-state-and-local-governments-to-mitigate-impacts-of-power-shutoffs/.

[8] Cost of Residential Energy Storage in California. EnergySage. https://www.energysage.com/local-data/energy-storage-cost/ca/.

kilowatt (kW), 2–3 hours of residential storage system costs approximately $15,000 fully installed.[9]

A potentially lower cost strategy is to use the battery inside a PEV to provide functionality comparable to stationary storage. Powering loads through facility circuits — referred to as vehicle-to-building (V2B) or vehicle-to-home (V2H) — could provide similar resilience and environmental benefits without the cost of purchasing a dedicated storage system. A PEV could provide enough storage to power a home for many hours without significant impact to battery degradation when managed following manufacturer's recommendations. For homes with solar PV or other distributed generation installed, PEV charging, and discharging could be coordinated with local generation to provide backup for even longer durations spanning several days. The potential of PEV batteries for electricity services will grow as battery durability improves and battery pack sizes become larger — many PEV models have a battery pack that exceeds 100 kilowatt hours (kWh). Daily mobility needs and associated energy requirements remain relatively unchanged (approximately 15–20 kWh).[10]

Beyond site resilience benefits, deploying and coordinating bidirectional chargers with other types of distributed energy resources (DERs) could provide distribution system benefits by reducing curtailment and DER back feeding, or by discharging to local loads or grid during system ramps and peaks. This could also provide environmental and economic benefits due to increased use of renewables while offsetting fossil fuels. Replacing a midsize fossil fueled vehicle (25 miles per gallon fuel economy) with a PEV charged entirely from renewable resources reduces greenhouse gas emissions by 11,400 pounds (lb) per year. Fuel savings from switching to an electric vehicle could exceed $1,000 per year.[11]

Most PEVs today use alternating current (AC) on-board and direct current (DC) off-board chargers that are designed to receive energy from the grid, as opposed to both sending energy to and receiving energy from the grid. Capturing the resilience, economic, and environmental benefits of bidirectional charging coordinated with DER requires development of hardware and software that cost-effectively manages local loads, DERs, and PEV charging and discharging. Achieving scale and interoperability requires implementation of standards and communication protocols that continue to evolve rapidly. Furthermore, automotive original equipment manufacturers (OEM) and battery manufacturers require data to evaluate whether bidirectional charging degrades the PEV battery or raises warranty concerns. Specific challenges to scaling bidirectional charging that this project helped address include:

- High costs for hardware and installation for discrete PV, storage, and PEV charging equipment. Figure 1

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[9] Marsh, Jacob. 2021. "[The Tesla Powerwall Home Battery Complete Review](https://news.energysage.com/tesla-powerwall-battery-complete-review/)." EnergySage. https://news.energysage.com/tesla-powerwall-battery-complete-review/.

[10] Assuming about 50 miles of driving round-trip each day on average and PEV efficiency around 3 miles per kWh.

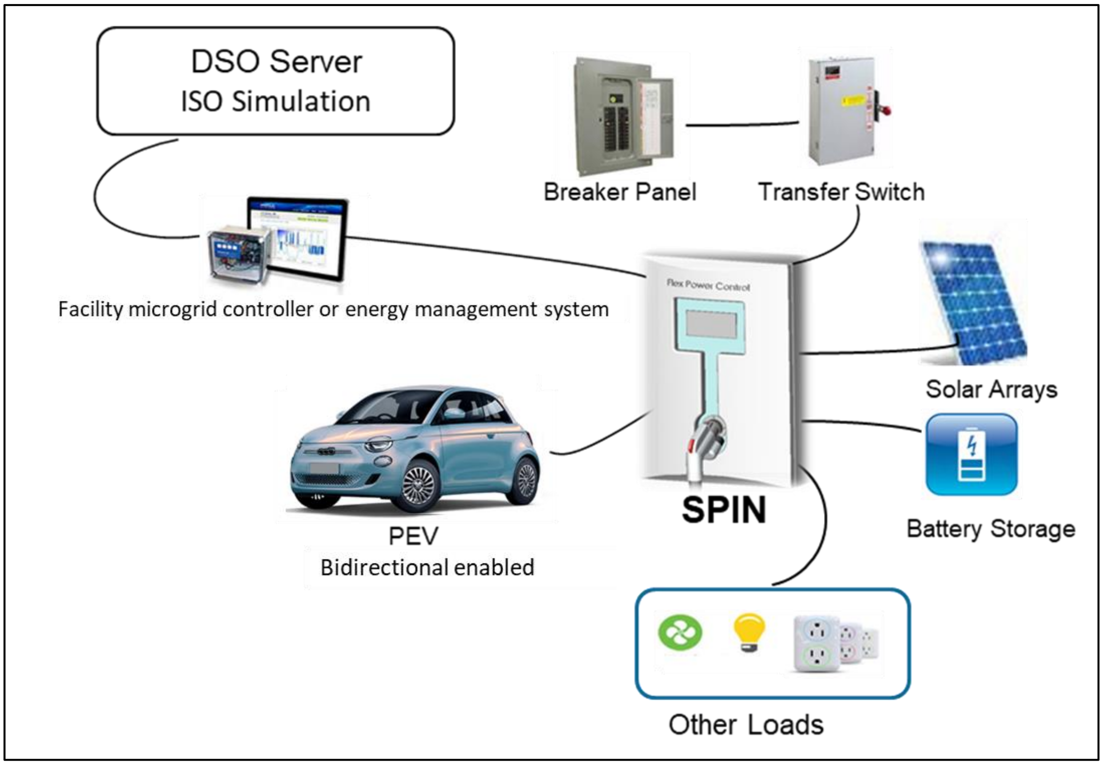
[11] Greenhouse gas savings calculations assume the following: 0.524 lb. CO2/kWh of electricity in California; 19.4 lb. CO2/gallon of gasoline; 12,000 miles/year driving; efficiency of 25 mpg for conventional vehicles and 3 miles/kWh for PEV. Cost calculations assume an average gasoline price of $4/gallon replaced by the average electricity rate of 20 c/kWh.

- Uncertainty on the part of automotive and battery OEMs regarding implementation and potential battery degradation associated with bidirectional charging.
- Lack of clarity and maturity of open standards that improve interoperability and facilitate seamless operation and safe interconnection of bidirectional PEVs.
- Lack of available products that allow bidirectional charging and optimization of local load and DERs either independent from or in support of the distribution system.

Project Purpose

This project developed and validated the Smart Power Integrated Node (SPIN) system to help address the scaling challenges listed. The SPIN system combines power conversion capabilities for solar PV, bidirectional PEV charging, residential energy monitoring, and optional stationary storage. The SPIN system, shown in Figure 1, runs local and cloud-based control algorithms to optimize connected energy assets in near real-time. The system can simultaneously maximize self-consumption of renewable energy through predictive analytics of weather forecasts and customer energy consumption profiles. In the presence of price or other signals from the grid, SPIN can modify the site demand profile to send or receive energy from the grid, with appropriate measurement and verification to meet renewable requirements as a generating resource.

Figure 1: SPIN Conceptual Diagram



Conceptual diagram of SPIN system and connected assets. The SPIN system coordinates PEV charging and discharging with other premise loads, local DERs such as solar PV and stationary storage, and a local energy management system if present.

Source: EPRI

The SPIN system is composed of the following key components:

- Two multi-port bidirectional converters and a DC power routing matrix of switches integrated as one DC-coupled system that can replace the stand-alone PV inverter and stationary storage inverter while providing a standard combined charging system (CCS) bidirectional PEV charger.
- Centralized control system monitoring the energy flow to the premise loads, bidirectional PEV charger, local PV, and optional stationary storage.
- Optimization algorithms to enable specific use cases including maximizing use of local generation, provision of backup power during outages, and integration with building or distribution management systems or potential third-party aggregators to maximize customer value.

The integration of multiple components within the SPIN system avoids redundant equipment, simplifies installation, and reduces hardware and installation costs. Because the SPIN system is a DC bidirectional charger, it can be interconnected as a smart inverter and comply with California Public Utilities Commission’s (CPUC) Rule 21 requirements once certified. This can further reduce costs through rapid design, permitting, and interconnection.

Building on previous awards from the US Department of Energy (DOE), the Electric Power Research Institute team developed software to implement specific bidirectional use cases and validated the performance of the SPIN system during laboratory testing with multiple PEVs. This project also conducted accelerated testing of PEV batteries under controlled conditions to evaluate the impact of bidirectional operation on battery degradation. This information can inform automotive OEMs as well as identify gaps in standards and testing protocols related to using PEVs for electric services. To evaluate the potential customer and ratepayer benefits of bidirectional charging technologies, this project developed several scenarios using the Distributed Energy Resources Value Estimation Tool based on projected PEV adoption and performance assumptions.[12]

Project Partners and Activities

Multiple teams worked across the country to get various parts of the integrated system ready for integration testing, as shown in Figure 2. The following organizations were involved in the execution of this project.

- *Electric Power Research Institute (EPRI)* acted as the prime contractor and led project management, defined system requirements, developed testing plans, conducted data analysis, and carried out technology transfer activities. Staff from the Knoxville, Tennessee, and Palo Alto, California, EPRI locations participated in this project.
- *Flex Power Control* conceptualized, designed, developed, and participated in system integration testing of the SPIN system.
- *Oak Ridge National Laboratory National Transportation Research Center* provided component and system integration testing of the proof-of-concept SPIN system in Knoxville, Tennessee.

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[12] EPRI. 2021. “Distributed Energy Resources Value Estimate Tool (DER-VET)”. https://www.der-vet.com/.

- *National Renewable Energy Laboratory Energy Systems Integration Facility* conducted accelerated battery degradation testing in Golden, CO.
- *Stellantis* (formerly Fiat-Chrysler Automobile Group) provided a PEV modified for CCS-based bidirectional operation for testing with the SPIN system, a pair of PEV battery packs for accelerated testing, and engineering staff and facilities located in Auburn Hills, Michigan.
- *Kitu Systems* provided the IEEE 2030.5 communications server used for smart inverter dispatch and is based in San Diego, California.
- *Gridscape Solutions* adapted their microgrid controller for microgrid integration functionality and is based in Fremont, California.
- *IoTecha* provided the on-vehicle open standards-based communications interface cards that implemented HomePlug Green PHY link between the charger and PEV. IoTecha, Inc. is based in Cranbury, New Jersey.

Figure 2: Geographic Footprint of SPIN Project Work

Project footprint for development and testing of the SPIN system funded by DOE and CEC.

Source: EPRI

To validate the SPIN system and inform automotive OEMs about potential battery degradation impacts, this project completed the following key activities:

- Define use cases and requirements for the SPIN system to operate in stand-alone mode or as part of a larger microgrid.
- Design the system architecture and communication interfaces as well as supporting software to enable bidirectional charging based on secure open standards.
- Develop and integrate the system first through a virtual testing followed by component-by-component verification and culminating in full system integration.

- Test and collect data with the integrated production-intent prototype to validate its performance in the use cases defined as well as evaluate battery degradation.
- Evaluate ratepayer benefits from the project as well as potential benefits from adoption of bidirectional charging technologies such as the SPIN system at scale.
- Transfer the technology through conferences, academic seminars, and targeted outreach to standards bodies, automotive OEMs, and utilities.

Chapter 2: Project Approach

This project progressed through several sequential stages as described in detail below. The objective was to develop and test an integrated SPIN system prototype that allowed flexible implementation while providing multiple potential benefits to the user. Project activities beginning with use case definition through subsystem development and integration are described in this chapter. The results of system testing, battery degradation evaluation, value assessment, and technology transfer activities are described in subsequent chapters.

Define Use Cases

The project team identified specific use cases for the SPIN system, whether operating in stand-alone mode managing all connected DERs or as a controllable bidirectional PEV charger within a larger microgrid managed by an external controller. Descriptions of seven use cases supported by the SPIN system are provided below. The use cases can be classified as site-focused, local distribution grid-supportive, and system-level services that align with potential customer value streams.

1. **DC charge PEV.** Upon plug-in, gathers driver and vehicle information such as battery state of charge and departure time when charge is needed, and schedules optimal charging based on estimated and real-time performance of local DERs. The project employed only open standards to enable interoperability.
2. **Minimize charging costs**. Gathers information such as utility tariff structure and solar generation forecasts to calculate and execute cost-optimized charging schedule based on estimated and real-time performance of local DERs.
3. **Maximize self-consumption**. Optimizes bidirectional charging, flexible loads, and optional stationary storage to maximize use of local renewable generation such as solar PV, reduce back feeding, and limit use of grid electricity.
4. **Plan charging and discharging day-ahead profile**. Uses data on historical daily energy use, weather patterns, and any day-ahead demand response event notifications to develop a forecasted optimal charging and discharging schedule.
5. **Mitigate system renewable curtailment.** Reconfigures charging and DERs to maximize consumption of electricity from the grid during times of high renewable generation.
6. **Discharge or curtail charging based on local grid conditions.** Based on power demand limits (threshold and duration) from local distribution system operator, optimizes PEV charging and discharging with other DERs to export or limit electricity consumption from the grid based on local (for example, transformer or feeder-level) conditions. In the case of grid-connected operation when the utility service is on, this use case allows power to flow across the meter. In case of the grid-isolated condition during an unplanned or a planned service interruption, this use case manages the back-up power to the connected local circuits.

7. **Discharge or curtail charging to limit system peaks or ramp rates**. Receives requests from the independent system operator or scheduling coordinator and optimizes PEV charging and discharging with other DERs to export or limit electricity consumption from the grid based on bulk system conditions.

Upon start-up, the SPIN controller first checks whether a PEV is connected and if it needs charging based on driver and vehicle information such as state of charge (SOC) and the time charge is needed. The driver or home-owner preferences can be provided to SPIN using the companion smartphone app. If the connected PEV does not require charge, the SPIN system checks if the facility or grid needs power export from the PEV and if the facility is grid-connected or experiencing a power outage. If grid-connected, the SPIN master controller is put into grid-following mode and the battery discharges to the lower SOC limit set by the user or automotive OEM. When not connected to the grid, the SPIN system switches to grid-forming mode and can discharge the PEV to power local facility loads.

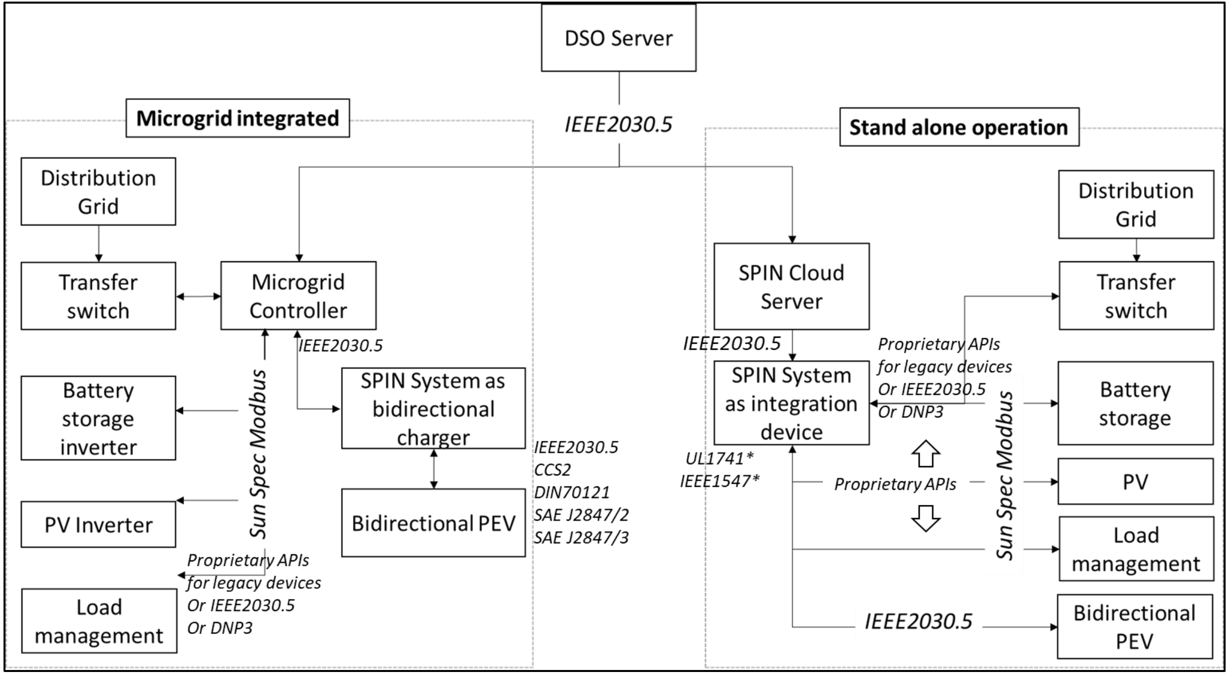
The system has a default selection of use cases, which includes maximizing self-consumption and minimizing backflow of the connected solar PV (if applicable), while grid-connected, and maximizing the outage support duration, during a service disruption. The customer has additional options to specify the preferences through the smartphone app. This can enable customers to reduce customer energy bills or provide backup power during outages if installed with a transfer switch. Future functionalities that are not implemented in this version of the SPIN system include messaging of set points to stabilize grid frequency or harmonic instabilities.

Design System Architecture

The project team developed a system architecture and specified communication pathways to enable implementation and testing of the aforementioned use cases with the SPIN system.

Figure 3 illustrates the flexible system architecture for operating either within a larger microgrid (left) or in stand-alone mode (right). Depending on implementation, the SPIN system is designed to interact with a variety of components including: the distribution system operator (DSO) sending price and other grid signals; a microgrid controller running a local energy management system (EMS); DERs such as solar PV, optional stationary storage, and flexible loads; and a bidirectional PEV.

Figure 3: SPIN System Architecture for Microgrid or Stand-Alone Operation



SPIN system architecture for operating as a bidirectional PEV charger managed within a microgrid (left) or in a stand-alone operation actively managing local DER and grid connection (right).

Source: EPRI

The external communication interface with the DSO is standardized using the IEEE 2030.5-2018 specification and the internal SPIN system software operates the same in both implementations, which are described below.

- **Microgrid operation.** One or more SPIN systems are deployed as bidirectional PEV chargers controlled by an external EMS running on the facility microgrid controller. The SPIN system only manages PEV charging and discharging based on driver schedule and mobility requirements (for example, minimum battery state of charge and time charge is needed) and in response to the microgrid EMS. Other DERs such as solar PV and stationary energy storage are managed by the facility microgrid controller, which receives electricity pricing and/or other grid signals from the DSO.
- **Stand-alone operation.** One or more SPIN systems are deployed at a facility and receive price and other grid signals directly from the DSO. The SPIN system operates as a bidirectional PEV charger as well as manages power flows between the grid, solar PV, and optional stationary energy storage. The SPIN system Analytics Cloud Server provides optimized cost and operational parameters based on available assets, driver preferences, and other potential constraints.

Provision of the identified use cases with the SPIN system architecture required adapting and implementing numerous standards including the smart inverter functions per IEEE 2030.5, Common Smart Inverter Profile CSIP, Society of Automotive Engineers (SAE) J2847/3 and J2847/2 for DC Charging Communications, and DIN SPEC 70121 for bidirectional DC charging (which provides the foundation for IEC/ISO 15118-2, IEC/ISO 15118-20, and SAE J2847/2). The primary changes to the protocols included modified signaling sequence while transitioning from charging to discharging mode, in addition to changes in the supervisory code that kept track of the utility power to decide whether the SPIN system was in the grid-following, or grid-forming (during an outage) mode, in conjunction with implementing the bidirectionality of vehicle to electric vehicle supply equipment (EVSE) charging current request to enable an off-board charging system implementing DC CCS to become reverse power flow capable. The testing of the SPIN system as part of a larger microgrid was completed through simulation using EMS and grid signaling emulators.

The CCS connector is the most prevalent plug standard and can DC charge up to 450 kW. In the US, the DIN 70121 protocol is the foundation for communication between the vehicle and charger in CCS-based DC charging systems. DIN 70121 serves as the basis for SAE J2847/2 (the US standard for DC charging communications) and IEC/ISO 15118-2 (the EU standard for DC charging communications). In its present form, DIN 70121 only enables unidirectional power flow (charging the PEV from the grid). However, by changing the number format in DIN 70121 to allow positive and negative values for the current commanded by the vehicle from the charger, the power flow can be made bidirectional enabling discharge with a negative current request. This suggests that any CCS-equipped PEV can be made capable of bidirectional charging with a relatively simple software update.

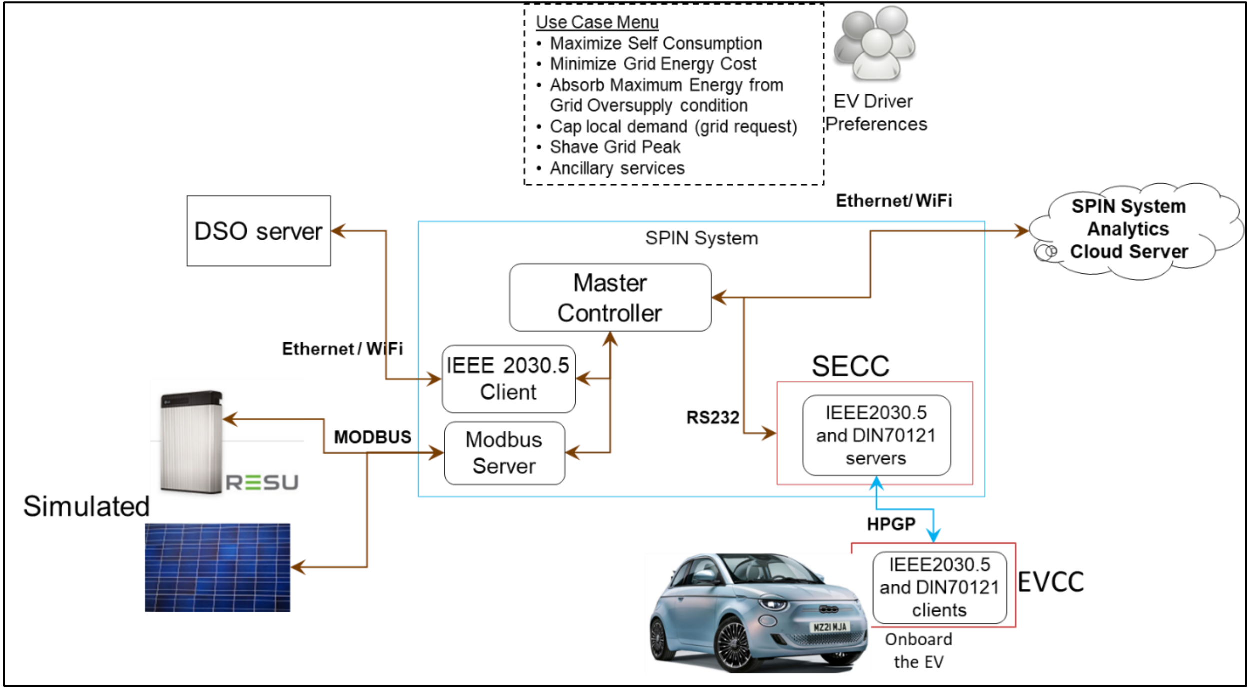
Develop and Integrate Subsystems

Much of the remaining discussion is focused on testing and validation of the SPIN system in stand-alone operation. The project team iteratively developed and tested several subsystems to ensure proper signaling and power flow between the SPIN system and bidirectional PEV. As shown in Figure 4, key subsystems include the following:

- SPIN master controller that communicates over Wi-Fi or ethernet with an external cloud server and runs local software to control the power conversion and routing based on driver preferences, DSO signals, and internal conditions. The SPIN master controller also combines the existing state of the DERs and demand, grid signals, and customer preferences to determine the PEV charging and discharging, in addition to local energy storage (if present) charge/discharge commands. The grid and the customer preferences are typically stored in the SPIN cloud.
- Modbus server for messaging between the SPIN master controller and other connected DER.
- IEEE 2030.5 client to receive grid signals from the DSO, aggregator, or facility EMS while meeting Rule 21 smart inverter requirements and IEEE 2030.5 server to signal to the bidirectional PEV.
- Supply equipment communication controller (SECC) that runs charging process management software, specifically DIN 70121 as tested or potentially ISO 15118 in the future. The SECC communicates with the PEV over HomePlug Green PHY (HPGP) — a type of powerline communications — and the Controller Area Network (CAN) bus on the PEV. The SECC also implements the IEEE 2030.5 server that communicates with the electric vehicle communications controller-based client, in addition to DIN 70121 server.
- Electric vehicle communications controller (EVCC), which resides on the vehicle and was provided by IoTecha. The EVCC includes the IEEE 2030.5 client for translating grid signals received from the SPIN system and carries the software for translating messages between HPGP and controller area network. Stellantis implemented both IEEE 2030.5 client and the

revised DIN 70121 protocol client on the EVCC and verified functionality using a unidirectional CCS charger.

Figure 4: **Key Subsystems for the SPIN System in Stand-Alone Operation**



The SPIN system communications architecture includes internet-based protocol from DSO server all the way to the PEV, with the master controller managing customer preferences, grid preferences, and vehicle status.

Source: EPRI

Test Components, Pairwise Interactions, and End-to-End Communications

The project team first validated the power conversion hardware and energy management capabilities of the SPIN system at the component level and focused on pairwise interactions. Hardware components and embedded control software for bidirectional charging were tested using a bench mounted proof of concept system at Oak Ridge National Laboratory (ORNL) National Transportation Research Center (NTRC) under a previous award from the DOE Vehicle Technologies Office.[13] Tests conducted at ORNL NTRC included a full power sweep for charging and discharging; automatic transition between grid-following and grid-forming modes; voltage, current, and power controllability; and system cycling to exercise the internal switching matrix.

- Building on this testing, the team developed the first production-intent prototype of the SPIN system with support from DOE Solar Energy Technologies Office.[14] The verified software code based on proof-of-concept system testing was embedded into the EVCC, SPIN master controller, and supply equipment communication controller boards.

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[13] Comprehensive Assessment of On- and Off-Board Vehicle-to-Grid Technology Performance and Impacts on Battery and the Grid. 2021. EPRI. DOE-EPRI-EE7792. https://www.osti.gov/biblio/1829576.

[14] Solar Power Electronics Modular Integrated Node Platform. 2018. Flex Power Control. https://www.energy.gov/sites/default/files/2019/03/f60/Power-Electronics-Kickoff_Flex-Power-Control-Inc.pdf.

Figure 5 and

Figure 6 show an external and internal view, respectively, of the SPIN system prototype used for testing. Several sub subassemblies contained in the SPIN system are highlighted, including the following:

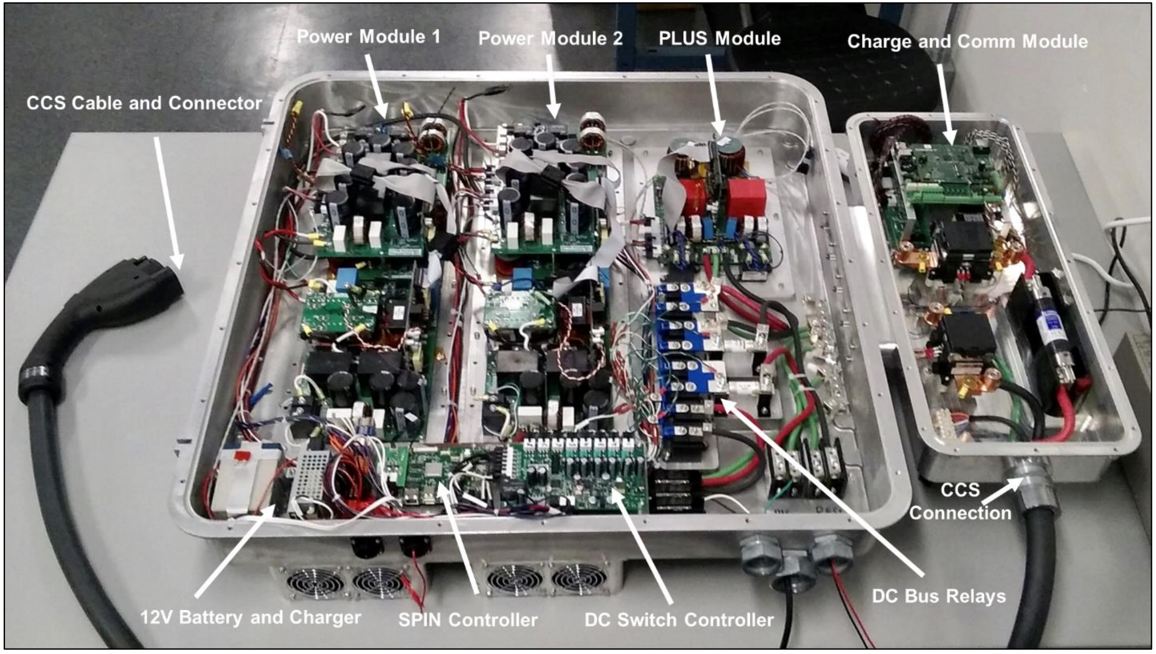
- Power modules 1 and 2 are bidirectional, dual-active bridge converters built using silicon carbide semiconductors that operate at higher temperature, have higher efficiency, and minimize cooling requirements. Power module 1 was designed to be connected to the PV array while power module 2 was designed to be connected to the bidirectional PEV or optional residential storage.
- DC switch controller that manages the DC bus relays for power routing.
- The SPIN master controller running software that orchestrates the overall system functionality. Only one energy source sends or receives energy at a given time, even in a home with both a PEV and an energy storage system.
- The plus module and charge and communications module (SECC) manage the DIN communications and the DC bus pre-charge control while the SPIN is connected to the PEV for bidirectional charging.
- Integrated 12V battery and charger to keep the SPIN system active during the transition between grid-tied to grid-forming modes, while the transfer switch operates, to keep its software running.

Figure 5: External View of SPIN System Prototype

The first-ever SPIN system prototype showing the main unit and the CCS charging component housing and cable on the right.

Source: Flex Power Control

Figure 6: Internal View of SPIN System Prototype



Internal layout of SPIN system prototype highlighting functional subsystems managed by the SPIN master controller.

Source: Flex Power Control

Test the SPIN System and Evaluate Battery Impacts

With virtual bench testing of the SPIN system complete, the prototype assembled, and the modified EVCC installed on the Stellantis PEV, the next step was to ship all components to the same location for physical testing and validation of specific use cases. Despite delays due to COVID-19 related facility closures, the modified PEV was shipped to Rhombus Energy Solutions in San Diego, California in early 2021. The results of SPIN system testing are discussed in Chapter 3.

In a real-world installation, the SPIN system is designed to mount on a wall inside a garage or be placed outside near where vehicles park since it is air cooled and outdoor rated (designed to meet IP6K9K, the highest ingress protection grade for dust and sprayed high-temperature liquid).[15] In a stand-alone installation, the SPIN system is connected in series with the main service panel and an automatic transfer switch that detects a power outage and disconnects the main panel from the utility service. The automatic transfer switch simultaneously connects SPIN to either the main circuit for whole-facility backup or to a critical load panel to power only select loads. The SPIN control algorithms put the system in grid-forming inverter mode automatically and provides a 110/220 V AC power to any connected facility loads. The system is designed to operate at 10kW continuous and 20kW peak so it can support AC or refrigerator motor starting transients. The SPIN system specifications are included in Appendix A. The SPIN system continually monitors the available energy from the PEV, local PV, and/or optional stationary storage to meet building energy needs.

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[15] Green, S. Guide to IP (Ingress Protection) Codes for Vehicle Electrical Components. 2021. WayTek. https://www.waytekwire.com/datasheet/LandingPages/IP_IngressProtection_RatingGuide.pdf.

Customers input a minimum level of acceptable SOC for their connected PEV that SPIN will discharge down to, reserving some energy for mobility services. In an outage event during which the PEV battery is discharged to the lower SOC threshold, the SPIN system disconnects from all household loads and is no longer able to provide backup power. When power from the grid is restored, the automatic transfer switch reconnects the SPIN system to the main AC utility feed, the inverter transitions back to grid-following mode, and the local controller resumes balancing PEV charging and discharging with other local DERs based on customer selected use cases or in response to commands over IEEE 2030.5 CSIP signaling from the distribution system operator. The customer benefits analysis described in Chapter 5 suggests that the SPIN system could power critical building loads for up to 24 hours with approximately 40 kWh of PEV battery capacity.

Accelerated Testing of Battery Degradation from Bidirectional Charging

Leveraging DOE funding, this project also evaluated how bidirectional charging and discharging of PEV batteries for the purpose of performing grid services impacts capacity degradation and cycle life.[16] Lithium-ion batteries used in PEVs have improved substantially since the mid-2000's (for example, in terms of chemistry, manufacturing consistency, control systems, and lifetime), but the incremental degradation from bidirectional operation has not been clearly measured. Providing this information to automotive OEMs and battery manufacturers can inform product development and build broader market confidence in bidirectional charging technologies. For example, knowledge of battery degradation could help clarify potential warranty considerations or potentially support more active approaches to monitoring and managing a PEV battery for both mobility and electric services throughout the vehicle's operating life.

Stellantis shipped two 17.6 kWh lithium-ion nickel-manganese-cobalt (NMC) LG Chem batteries used in Chrysler Pacifica plug-in hybrid electric vehicles (PHEV) to the NREL Energy Systems Integration Facility for accelerated testing. The useable battery capacity was fixed at 12.8 kWh, representing approximately 65-70 percent of the nameplate capacity. The project team defined two battery test cycles. The first battery test cycle (Baseline) represented driving only and was approximately 15 miles with a net energy consumption of 5 kWh based on a blend of city and highway driving cycles. The second battery test cycle (Test) represented both driving and additional discharge for grid services.

Table 1 summarizes the daily drive cycle simulated including total energy throughput and net energy consumed (accounting for energy recovered through regenerative braking), as well as the amount of energy remaining for grid services. Cycle Discharge (CD) indicates the energy utilized while driving the CD1 City and CD US06 test cycles from the Environmental Protection Agency (EPA) used for vehicle fuel economy assessment.

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[16] Comprehensive Assessment of On and Off-Vehicle V2G Technology Impacts on the Batteries and the Grid. 2021. DE-EE-0007792. https://www.energy.gov/sites/default/files/2021-06/elt187_Chhaya_2021_o_6.7_11.05am_LS.pdf.

Table 1: Simulated Drive Cycles and Energy Consumption

<table>
<tr><th></th><th>Cycle</th><th>Time (hr)</th><th>Distance (mi)</th><th>Energy Throughput (kWh)</th><th>Net Energy (kWh)</th></tr>
<tr><td rowspan="2">Cycle Discharge</td><td>CD1 City</td><td>0.3811</td><td>7.44</td><td>3.96</td><td>2.24</td></tr>
<tr><td>CD US06</td><td>0.1667</td><td>8.01</td><td>5.27</td><td>2.81</td></tr>
<tr><td>Total</td><td></td><td>0.5478</td><td>15.45</td><td>9.22</td><td>5.05</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="4">Total Usable Energy from Battery (kWh)</td><td colspan="2">12.8</td></tr>
<tr><td colspan="4">Usable Energy Remaining After Both Drive Cycles (kWh)</td><td colspan="2">7.75</td></tr>
<tr><td colspan="4">Discharge Power for Grid Services (kW)</td><td colspan="2">7.6</td></tr>
<tr><td colspan="4">Discharge Duration (hr)</td><td colspan="2">1</td></tr>
</table>

Simulated drive cycles, energy consumption, and remaining energy for grid services used for accelerated testing. The simulated distance driven during Cycle Discharge is approximately 15 miles one-way.

Source: Stellantis and National Renewable Energy Laboratory (NREL)

Table 2 shows how the Baseline and Test battery packs were cycled for a representative day. With a total cycle time of six hours, each battery pack could complete the test cycle four times per day.

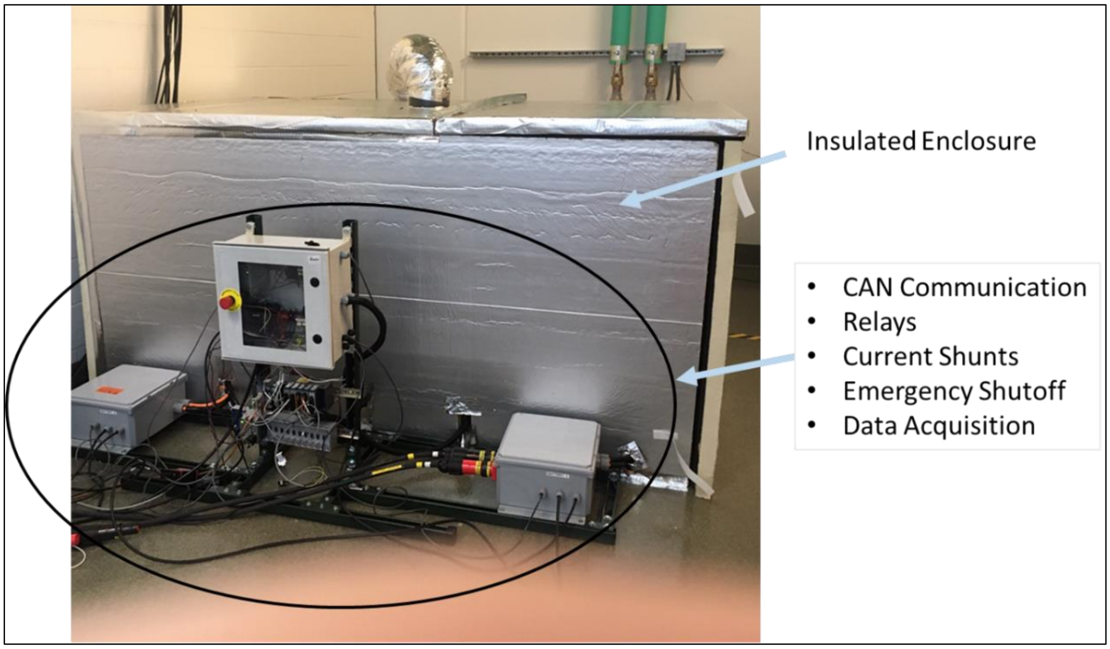
Table 2: Baseline and Test Battery Pack Cycle Durations

	Test (V2G) Cycle Time (hr)	Baseline Cycle Time (hr)
Drive Home from Work	0.5	0.5
Home Discharge at 7.6 kW	1	0
Charge to 100%	2	1
Wait (Contactor Open)	1	3
Drive to Work	0.5	0.5
Charge 50 to 100% at Work	1	1
Total Time/Cycle	6	6

Source: Stellantis, NREL

Each pack was cycled in a dedicated thermal chamber at NREL, with the experimental setup including safety and data collection equipment shown in Figure 7. The controlled thermal environment ensured the two battery packs experienced identical conditions during testing.

Figure 7: Controlled Battery Testing Setup at NREL



Accelerated battery testing setup in which the Baseline and Test battery packs both operated inside a thermally insulated chamber at a constant temperature. The data acquisition system was connected directly to the battery management system of each pack and the entire process was automated for continuous operation and maximum throughput during laboratory testing.

Source: NREL

The team compared capacity degradation between the Baseline and Test battery packs to measure the incremental contribution of discharging for grid services. Despite initial delays setting up the testing equipment and debugging the battery testing software interface with the battery management system (BMS), automated testing began in mid-2020 and ran for approximately one year. The year of accelerated testing data collected is representative of more than three years of daily use. The results of the battery degradation testing are described in Chapter 3.

Analyze Customer and Ratepayer Benefits

This project evaluated several forms of customer and ratepayer benefits achievable through bidirectional charging technologies, assuming different levels of technology adoption. Analysis of economic and resilience benefits for the individual customer, distribution system operator, and independent system operator was conducted using the Distributed Energy Resource Value Estimation Tool (DER-VET) previously developed by EPRI with support from CEC.[17] Specific applications of bidirectional charging evaluated included customer resilience, distribution system peak shaving, system-wide peak shaving through aggregated demand response, system-level renewable integration, and greenhouse gas emissions reductions through avoided curtailment. The results of the benefits analyses conducted are presented in Chapter 5.

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[17] EPRI. Distributed Energy Resource Value Estimation Tool (DER-VET). 2021. https://www.der-vet.com/.

Technology and Knowledge Transfer

Technology and knowledge transfer began early in the project by involving key commercialization partners on the team, including an automotive manufacturer, vehicle-grid integration software and hardware developers, and participants on standards setting bodies. The project team participated in workshops and other outreach events to raise awareness about the SPIN system and bidirectional charging technologies more broadly. Flex Power Control is continuing discussions with utilities for future testing opportunities as well as with potential investors to pursue certification and early manufacturing runs. Additional details of technology and knowledge transfer activities are discussed in Chapter 4.

Chapter 3:
Project Results

This chapter presents the results of testing completed with the SPIN system prototype and the modified and production PEVs. The chapter also discusses the results of the accelerated battery degradation testing.

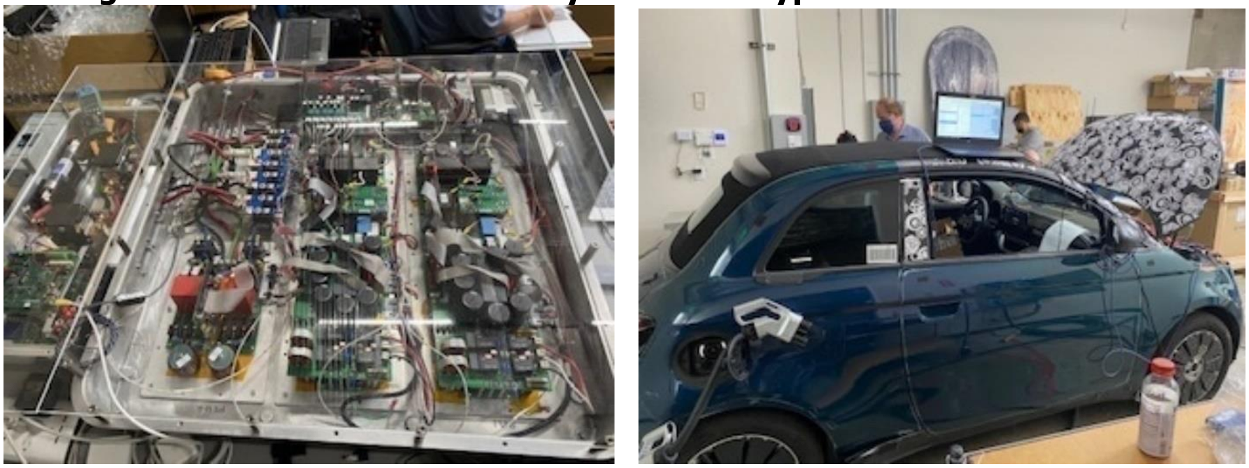
Testing and Validating SPIN System Performance

After simulated testing and integration of the different components described in Chapter 2, Stellantis shipped a PEV (European version of Fiat 500) with a modified EVCC to Rhombus Energy Solutions in San Diego, California, where the prototype SPIN system was assembled. Testing occurred over several months and involved technical experts from Rhombus Energy Solutions, Flex Power Control, EPRI, Kitu Systems, and Stellantis.

The SPIN system and PEV ran through a series of tests to verify safety conditions were met and proper electrical connection existed between the two. During this process, the SPIN bias power supply powered the on-vehicle pre-charge circuit that established the DC bus voltage on the vehicle power electronics side. Once either the mechanical lock was released and the charge coupler was pulled out of the receptacle or the charging/discharging process was complete, the system returned to standby state by safely discharging the DC bus pre-charge capacitors and opening the contactors between the DC bus and battery. The team verified the SPIN system and modified PEV progression through these stages to establish a complete charge circuit in preparation for data acquisition.

Figure 8 shows the instrumented SPIN system prototype during data collection (left), in which it is connected to the AC main power supply (representing the building where installed) and the vehicle through the DC CCS connector. The right shows the Fiat 500 with modified bidirectional capable EVCC board connected to a computer running the monitoring program. Because the PEV was a European version and fitted with a CCS Type 2 connector, an adaptor was required to communicate properly with the CCS Type 1 connector used for US vehicles and included on the SPIN system prototype.

Figure 8: Instrumented SPIN System Prototype and Modified Stellantis PEV



SPIN system (left) instrumented for real-time monitoring during testing, and modified Fiat 500 PEV (right) connected to the SPIN system. The Type 1/Type 2 CCS connector adapter is visible near charge port.

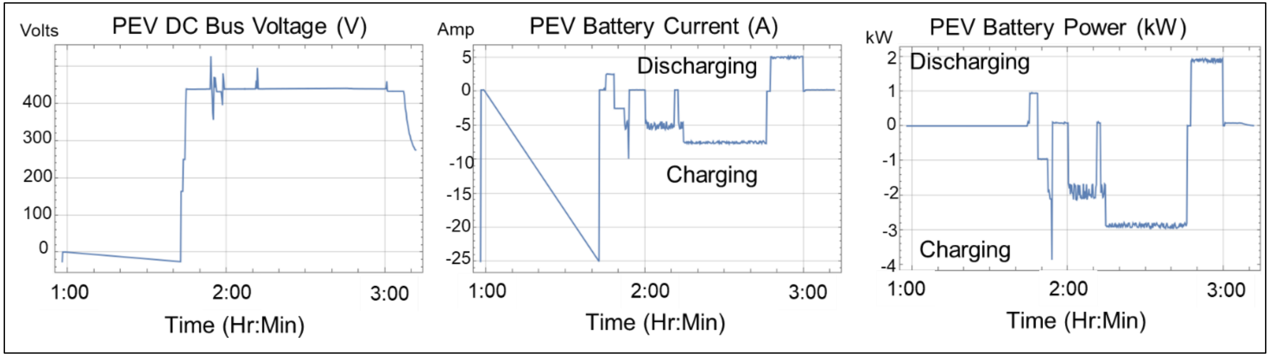
Source: Flex Power Control

The team began initializing the charging sequence to verify the ability of the SPIN system to both charge and discharge the modified Stellantis PEV. Although bench testing and simulations were completed for each component individually, this was the first time all components were physically connected to each other. The SPIN system and PEV progressed through the first stages of the DIN SPEC 70121 charging protocol but stalled near the end when the SPIN system was supposed to charge the PEV power circuit before energizing. The team identified a software version mismatch that prevented the charging process from initiating and worked to synchronize the two versions and re-test the system. Unfortunately, the Fiat 500 provided by Stellantis had to be returned after a 10-day testing period and before a complete charging and discharging sequence was completed.

Testing of the SPIN System with a Production PEV

After the modified Stellantis PEV was returned, the team borrowed a production (that is, unmodified) model year 2020 Chevy Bolt to continue testing charging and discharging functionality with the SPIN system using the DIN SPEC 70121 protocol. Without updating software on the vehicle, the SPIN system was able to charge the Chevy Bolt at up to 10 kW (transiently, to quickly verify SPIN charge function connected with the PEV) as well as discharge at up to 2 kW before the Chevy Bolt detected the reverse power flow and interrupted the charging process. Because the team was unsure how the production Chevy Bolt would respond to the negative current flow from the PEV, the charge power during testing was limited to 3kW for extended period of time and the discharge power was limited to around 2 kW, so appropriate testing could be performed for longer than transient. The transient power data was not recorded. Figure 9 shows the steady-state Chevy Bolt – SPIN integrated testing results in the form of the DC voltage (left), current (center), and power (right) measured during a representative charging and discharging test. The experimental setup is shown in Figure 10. This testing validated the SPIN system bidirectional charging functionality using the CCS coupler and DIN SPEC 70121 on a production PEV.

Figure 9: 2020 Chevy Bolt Charging and Discharging Validation



Testing of the 2020 Chevy Bolt was exercised with caution with the charge power limited to about 3 kW and discharge power at about 2 kW to test sustained operation with the SPIN system. The voltage, current, and power traces validate bidirectional functionality.

Source: Flex Power Control

Figure 10: Testing SPIN System Charging and Discharging with a Chevy Bolt

Model year 2020 Chevrolet Bolt connected with the SPIN system to validate bidirectional charging using the CCS connector and DIN 70121. The system was able to charge at 10 kW transiently, and for the testing data, was limited to a charge power of 3 kW and discharge power at 2 kW, both of which the team limited to protect the borrowed privately owned Bolt PEV.

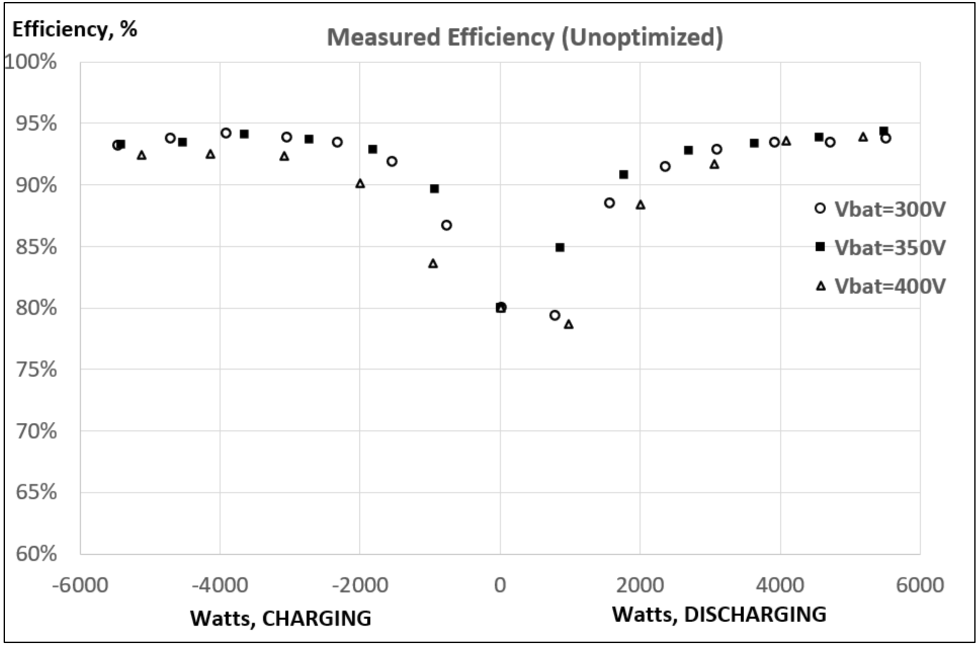
Source: Flex Power Control

As the SPIN system and other bidirectional charging technologies mature, any CCS-equipped PEV should be able to discharge DC power with a relatively simple update to its charging management software that implements DIN SPEC 70121. As part of technology transfer activities, the team continues sharing these findings with relevant standards setting bodies including the SAE J2847/3 (reverse power flow) and SAE J2847/2 (DC charging communications) committees. Interoperability with multiple PEVs equipped with a CCS connector and running a revised version of the DIN 70121 (SAE J2847/2 is defined with DIN70121 as the foundation) increases customer flexibility and could enable provision of building backup power for even longer.

Bench Testing of the SPIN System with Power Supplies and Load Banks

The project team continued bench testing the SPIN system using power supplies (representing DERs such as solar PV and stationary storage) and power sinks (representing building load). The measured efficiency of the prototype — calculated as the ratio of output to input power — is shown in Figure 11. The efficiency of the prototype during charging and discharging was approximately 95 percent at the tested power of 5 kW. The system efficiency drops to around 80 percent at low power (which is typical of systems designed to operate at rated power), since the fixed losses such as internal switching losses and energy consumed by support electronics are a higher proportion of the output power at lower outputs. Further marginal improvements in charging and discharging efficiency may be possible as this prototype was designed for reliable performance and testing and not optimized for maximum efficiency.

Figure 11: Efficiency During Charging and Discharging

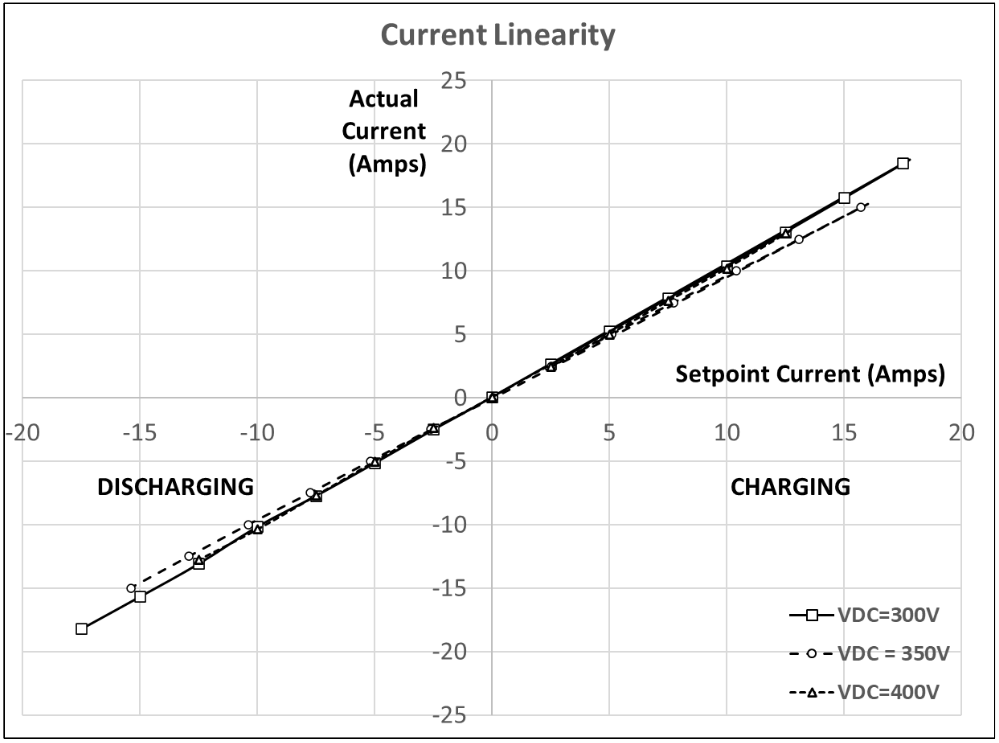


Measured efficiency of the SPIN system prototype during charging and discharging. A voltage source was used to simulate the PEV battery with different state of charge levels indicated by different voltage levels.

Source: EPRI

Figure 12 shows the measured current delivered by the SPIN system at different voltage levels versus the commanded current, which was provided as setpoints from the SPIN master controller (or potentially from an external EMS if the SPIN system was installed as a bidirectional charger in a larger microgrid). This was measured using a variable power source/sink and demonstrates close alignment between current provided and commanded across different power levels.

Figure 12: Linear Response of Current Commanded Versus Delivered



Measured current delivered by the SPIN system prototype, which is linear with requested current across different DC bus voltages representative of various levels of battery state of charge.

Source: EPRI

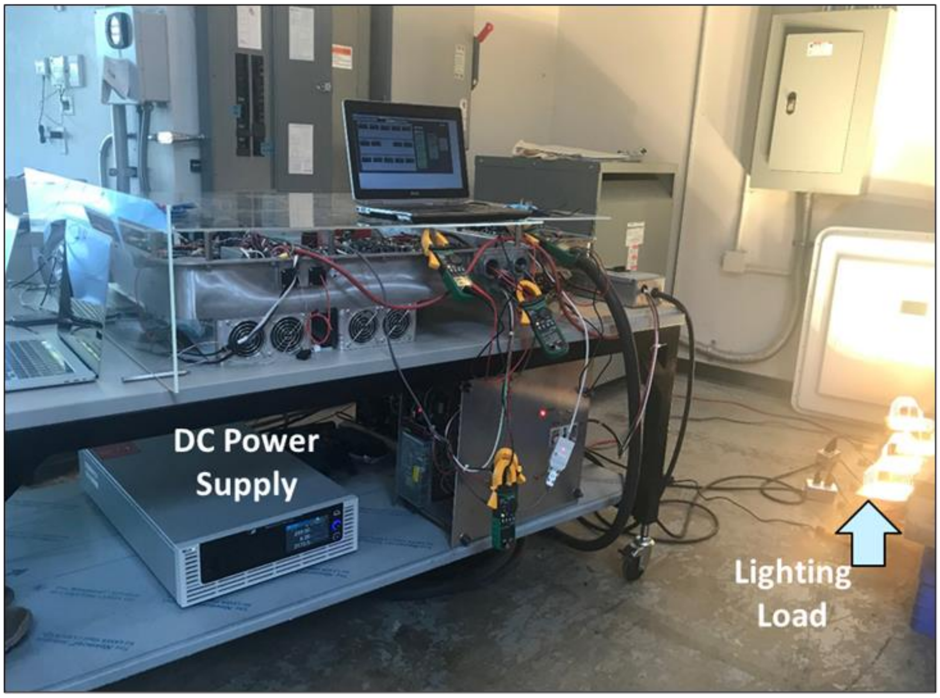
Bench Testing Backup Power Capabilities of the SPIN System

The SPIN system can operate as either a grid-following or grid-forming inverter, providing customer value whether connected or disconnected from the utility distribution system. When the SPIN is connected to the grid and the grid is energized, SPIN presents itself as a grid-following inverter that supplies or absorbs commanded current based on voltage supplied by the grid. During an outage, the connected circuit is isolated from the grid and the SPIN system detects a loss of grid voltage and automatically converts itself into a voltage source (grid-forming) inverter. This enables the operation of all the building loads connected to it.

The project team tested the capability of the SPIN system to transition seamlessly between grid-following to grid-forming mode, by testing its capability to power local loads from a DC power source (representing a PEV) during outages or intentional islanding events (that is, when the building or facility is disconnected from the local AC power feed), which is representative of vehicle-to-building (V2B) operation. Upon loss of AC grid voltage, the SPIN system transitioned to grid forming mode and converted DC voltage from emulated PEV to AC to power the attached lighting load of approximately 2 kW, as shown in

Figure 13.

Figure 13: Testing SPIN System Capability to Provide Backup Power to Local Loads When Disconnected From AC Grid Power

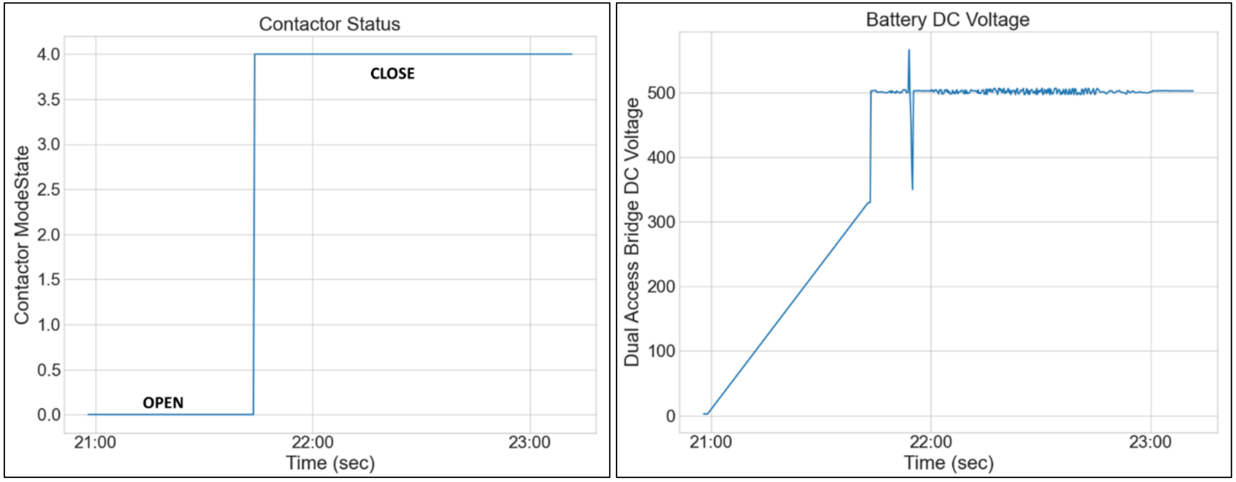


Backup power functionality of the SPIN system prototype was validated using a DC power supply emulating discharge from a PEV battery to power approximately 2 kW of lighting loads. The SPIN system automatically transitions from grid-following into grid-forming mode once isolated from the grid by the utility transfer switch.

Source: Flex Power Control

The project team measured voltage and current of the SPIN system prototype during the V2B functionality testing, shown in Figure 14. The voltage trace on the left shows the battery contactor closing on the PEV battery input to the SPIN system. When the contactor closes, the DC bus is charged by precharge capacitors that establish the DC voltage. The voltage trace on the right shows the appearance of the DC voltage on the SPIN system internal DC bus, which is maintained at 500 V and is DC coupled to the PEV battery (which is in the 350–400 V range). The SPIN system is internally DC-coupled with local DERs regulated through DC/DC converters when the system is islanded and through AC/DC converters when connected to the grid.

Figure 14: Contactor State and DC Bus Voltage During V2B Testing

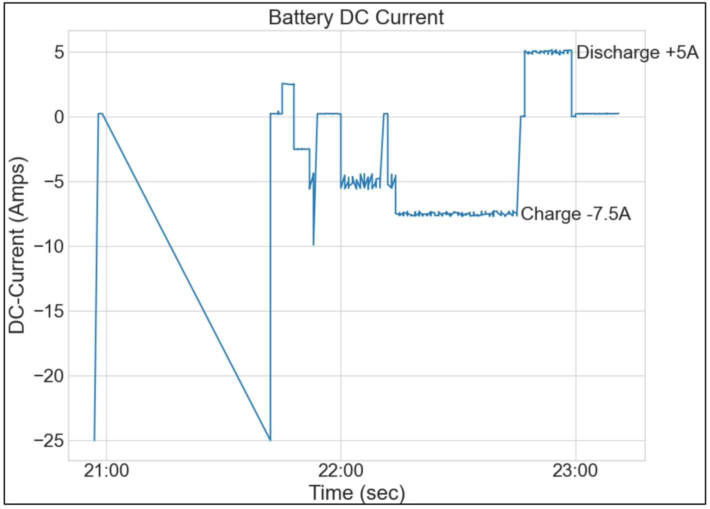


Measured contactor state and voltage on the SPIN system internal DC bus during V2B testing.

Source: Flex Power Control

In stand-alone V2B operation, power flow of the SPIN system is determined by the algorithm running on the embedded master controller. When this algorithm detects surplus energy from the local solar PV beyond what is needed to power building loads, the SPIN system begins charging the PEV. The power level and current supplied to the PEV varies based on changing building loads. Charging stops when local PV generation equals the building load. When building load exceeds local PV generation, the SPIN system seamlessly begins drawing current from the PEV over the CCS connector to supply needed power to the building. Testing of this near real time control occurred at approximately 3 kW for charging and 2 kW for discharging, as shown in Figure 15.

Figure 15: Current Exported from SPIN Responding to the Master Controller During V2B Testing

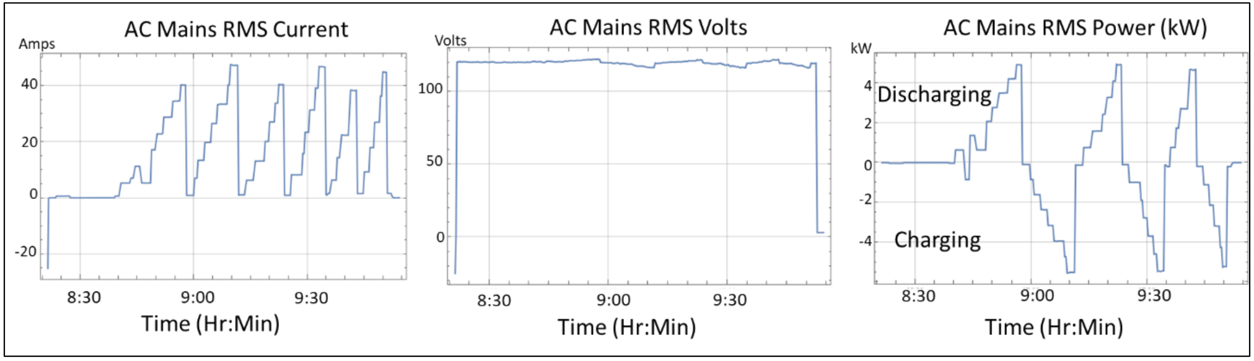


Measured current of charging and discharging of the SPIN system showing instantaneous balancing performed by the master controller responding to changes in load.

Source: Flex Power Control

The SPIN system was connected to a DC power supply and sink (simulating the PEV battery) to measure the charging and discharging current across the full operating range. The power supply was used for testing to extend the duration of testing that could be performed, since it was deemed risky to perform the same tests with a Chevy Bolt PEV whose internal power export functionality was not fully verified at the time (Chevy Bolt production PEVs are not advertised to be reverse power flow capable). Testing with the power supply showed consistent and stable power conditioning and operation in grid forming mode. Figure 16 shows the AC current demanded (left) while the grid-forming inverter maintains stable AC voltage (center) to meet the variable power requirements for connected loads (right). Figure 17 shows the corresponding measurements for the DC current (left), voltage (center), and power (right) at the CCS plug on the SPIN system.

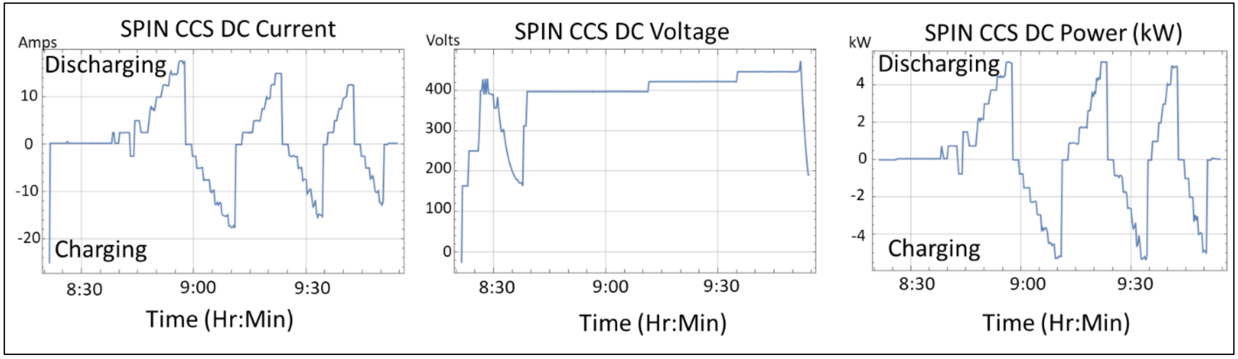
Figure 16: AC Current, Voltage, and Power During Charging and Discharging



In grid-forming mode, the measured AC RMS current (left), voltage (center), and power (right) sweep results show consistent current and power profiles over two hours of testing.

Source: Flex Power Control

Figure 17: DC Current, Voltage, and Power During Charging and Discharging



In the grid-forming mode, DC current, voltage and power sweep results show consistent current and power profiles, with over 2 hours of testing.

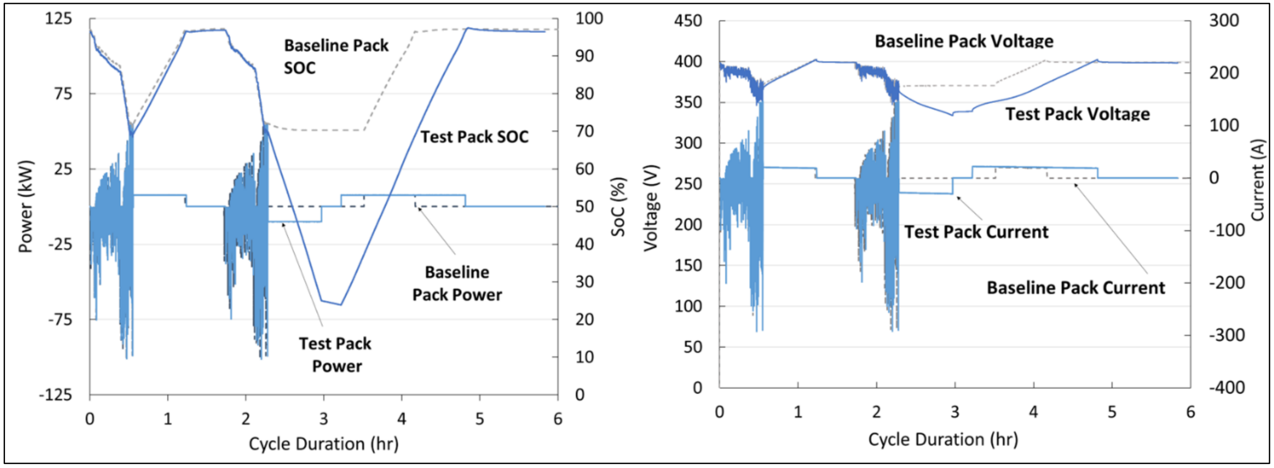
Source: Flex Power Control

Evaluating Battery Degradation from Bidirectional Charging

The accelerated battery testing (with approach and experimental setup described in Chapter 2) occurred at NREL from June 2020 through July 2021. The approximately 6-hour test cycle was run three times a day generating data equivalent to more than three years of daily operation. After discovering an error in the test profile in which the battery did not recharge with the energy recovered from braking while driving, the test profile was corrected in August 2020 and run continuously. Every month, reference performance test data was collected for the mobility only (Baseline) and mobility plus grid services (Test) batteries.

The corrected battery test cycles are shown in Figure 19, with the left image showing power and battery SOC and the right image showing battery current and voltage for both the Baseline and Test batteries. The driving and workplace charging sections of the profiles are identical for both packs (approximately hour 0 to 2.3). At home (approximately hour 2.3 to 3.3), the Test battery began discharging (representing V2B operation) at approximately 7.6 kW for approximately one hour. Over this time, the SOC of the Test battery declined from 73 to 25 percent (a change of nearly 50 percent) while the SOC of the Baseline battery remains stable at 73 percent. After discharging, it takes longer for the Test battery to fully recharge (approximately hours 3.2 to 5), at a steady rate of 7.6 kW (a 75 percent increase in SOC over 1.8 hours, or 13.68 kWh) at which point both packs are fully charged and ready to be cycled again after a period of minimum one hour of stand time. The magnitude of power and current fluctuations for driving are significantly larger than for bidirectional operation, reflecting the relatively low power requirements of building electric loads compared to driving.

Figure 18: Power, State of Charge, Current, and Voltage Profiles for the Baseline and Test Battery Packs



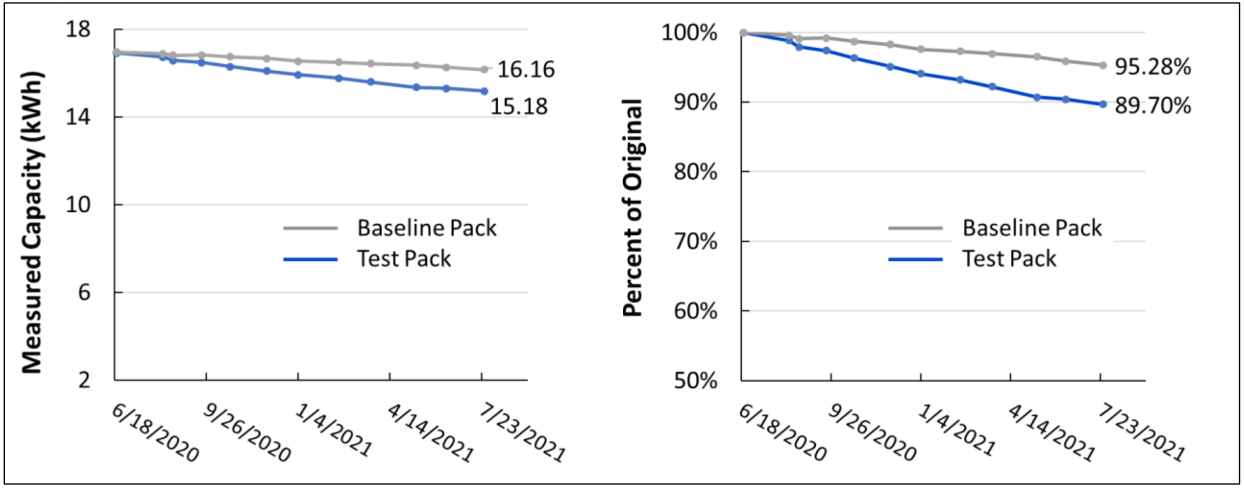
The Baseline and Test battery power and SOC profiles (left) and current and voltage profiles (right) used during accelerated degradation testing. The Test pack included additional discharge beginning around 2.3 hours into the cycle.

Source: NREL

The modeled test cycle used about 8 kWh (50 percent for driving to and from work) of battery capacity daily for mobility services, which was approximately 36 miles total. The Test battery discharged an additional 8kWh daily, which represented nearly 50 percent of the total nameplate capacity (17.6 kWh) or 66 percent of the usable 12 kWh. While aggressive for daily use, this discharge profile was developed intentionally to accelerate the degradation and enable measurable differences between the Baseline and Test batteries.

The team measured the capacity degradation in both the Baseline and Test packs at monthly intervals over the duration of testing. The left pane of Figure 19 shows the measured kWh capacity loss over time and the right pane shows degradation as a percent initial capacity. The slope of capacity loss was flatter during initial cycling with the error in the test profile (approximately June through August 2020). When the error was corrected, the slope of capacity loss became steeper for both packs (after August 2020), which makes sense as degradation increases with greater cumulative throughput. The loss in kWh capacity reflects both decreasing ampere-hour (Ah) capacity as well as the effects of increasing internal resistance, which grows with cumulative throughput and calendar aging. Although not shown, comparison of the percent kWh and Ah capacity loss suggests that increasing internal resistance has relatively limited impact on capacity loss (although it can result in power fade).

Figure 19: Capacity Loss in Baseline and Test Battery Packs Over Testing



Measured kWh battery capacity degradation in kWh (left) and as a percent of initial nameplate (right) collected monthly during accelerated testing. The Test battery degraded more rapidly than the Baseline pack although both remained above 89 percent of original capacity at the end of testing.

Source: NREL and EPRI

The measured energy (kWh) capacity degradation in the Test pack is 10.3 percent (declining from 100 to 89.7 percent) compared to 5.7 percent for the Baseline pack (declining from 100 to 95.3 percent). The system was tested at four cycles per day, for a period of 12 months, which is a total of 1460 cycles. Assuming a year with 260 working days, this implies about 5.6 years of battery cycling resulting in an incremental capacity degradation of about 5.5 percent or approximately 1 percent capacity loss every year due to the aggressive discharging cycle. Extrapolating this data linearly, the Baseline pack could lose between 12 and 15 percent of its nameplate capacity at the end of 10 years. If the Test pack continued discharging 8 kWh per day for performing local or grid services, the capacity fade would be an additional 10 percent over 10 years leaving about 75 to 78 percent of the original nameplate capacity available at the end of ten years. This is generally within the terms of most warranty considerations and suggests that even smaller plug-in hybrid electric vehicle batteries have significant potential to provide both mobility and resiliency as well as grid services. After more than one year of accelerated testing, the batteries completed approximately 1,460 full cycles (less than 200 cycles were completed with the erroneous test cycle before correcting). Cumulatively, the Test pack discharged more than 6,700 kWh for grid services such as backup power or rate arbitrage.

Compared to the Baseline pack, the Test pack had 65 or 70 percent greater throughput as measured by kWh or Ah, respectively. On an annualized basis, the Test pack provided an additional 11 percent (65 percent over 5.6 years equivalent) to 12.5 percent (70 percent over 5.6 years equivalent) percent throughput contributing to additional incremental degradation of 1 percent annually. Extrapolating these trends linearly suggests that at the end of 10 years the Test pack providing both mobility and electric services would provide 112 to 125 percent the cumulative throughput of the Baseline pack providing only mobility while experiencing 10 percent additional loss of battery capacity.

Discussion and Implications of Accelerated Battery Testing Results

The accelerated testing quantified the increased degradation experienced by the Test pack relative to the Baseline pack, which was expected given that degradation is a function of cumulative throughput. The relatively aggressive discharge cycle of approximately 8 kWh every day for local and grid services could provide enough energy to power about 46 percent of the average California home's daily energy use.[18] With a less aggressive discharge cycle (that is, less daily energy use as a fraction of the total battery capacity), measured degradation would likely be even smaller. The project team developed the test profiles based on reasonable assumptions that would lead to quantifiable degradation, however no standard test cycles or procedures currently exist for evaluating bidirectional charging impacts on PEV batteries. Automotive manufacturers likely have the driving and battery charging data that could inform holistic management of cumulative energy throughput for both mobility and electricity services over the life of a vehicle. The recent announcements by OEMs to pursue bidirectional charging for backup power applications suggest that they have sufficient confidence in the longevity and health of vehicle batteries for this use case. [19]

Additionally, testing was done with PHEV batteries that are relatively small (generally less than 20 kWh) compared to all electric models (generally 60 kWh or greater). The 8-kWh discharged daily amounted to approximately 50 percent change in SOC. Given the inverse relationship between cycle life and depth of discharge, it is reasonable to expect that PEVs with a larger battery would experience less degradation if discharging the same amount of energy. Alternatively, the larger battery capacity could be used to provide additional electric services — for example a mid-size PEV using 40 percent of a 60-kWh capacity battery could discharge approximately 24 kWh daily. Furthermore, PEV batteries have continued to improve in cycle life and durability compared to the earlier generation batteries tested in this project.

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[18] Energy Information Agency (EIA). Household Energy Use in California. https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf. Note: An annual energy consumption per household in CA is 6400 kWh, which is about 17 kWh per day.

[19] "The Vehicle to Grid Pilot Has Been Inaugurated at Mirafori." 2020. Stellantis; "Honda and Moixa Launch their First V2G Project in London." 2020. electrive.com; "Volkswagen Wants to Stabilize the Grid by Adding V2G to All of its Electric Cars." 2021. The Driven; "Hyundai Auto Group to Demonstrate Vehicle-to-Grid Using New EVs in Jeju." 2021. Aju Business Daily; Patel, Joel. "2022 Ford F-150 Lightning Can Power Your Home." 2021. CarsDirect; "Ford and GM test bidirectional charging with PG&E." 2022. Charged EV Fleet and Infrastructure News.

In real-world use, battery degradation and energy management strategies are significantly more complex than reflected in the accelerated testing conditions. No two PEVs are driven and charged the same and there is wide variability in operating conditions such as ambient and battery operating temperature. While driving is generally more burdensome on PEV batteries than charging or discharging for residential or grid energy services, there are many charging behaviors that can impact battery degradation beyond cumulative throughput. For example, frequently charging at high power levels or leaving PEV batteries at high SOC for long periods of time (for example, fully charged and plugged in when out of town) can also accelerate degradation.

An emerging strategy is to pursue a holistic battery management strategy that continually monitors, predicts, and optimizes battery health based on factors such as age, past usage, and anticipated mobility needs. Such active battery management strategies could include discharging the PEV battery for electric services when there is limited impact on – or potentially even benefits to – battery health or when the value of the electric service exceeds that of lost capacity.[20] This would require greater and more frequent communication between electricity systems, PEVs, and smart energy devices such as the SPIN system based on driver willingness and schedule flexibility. The data collected through this project can help battery and automotive manufacturers understand how discharging for electricity services impacts PEV battery degradation. The project can also inform development of new battery management approaches, for example developing control setpoints based on cumulative kWh throughput and predicted state of health, among other factors.[21]

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[20] PEV battery management systems deployed by automotive manufacturers would likely prioritize preserving battery health and cumulative throughput for mobility applications over the life of the vehicle, which is its primary function. It is unlikely that the value of electricity services provided through bidirectional charging would ever compensate for an unforeseen battery replacement.

[21] An alternative strategy to limit the risk of battery degradation impacting PEV mobility is to intentionally oversize the vehicle battery, which provides a greater range for long trips and could still allow some of the capacity to be reserved for electric services.

Chapter 4: Technology and Knowledge Transfer Activities

Technology and knowledge transfer activities related to the SPIN system began early and progressed throughout the duration of this project. The following sections describe completed and planned activities across several categories of outreach.

Impact of CEC and DOE Funding for SPIN System Development

This project began from a paper design with funding from EPRI's Technology Innovation Program, with a technology readiness level (TRL) of 1 to 2. Funding from the US DOE Vehicle Technologies Office enabled development and testing of the proof-of-concept system at Oak Ridge National Lab, raising the TRL to around 4. Additional funding from the US DOE Solar Energy Technologies Office enabled design of the first production intent SPIN system prototype, bringing the TRL to around 5. CEC funding built on these investments and used the production intent SPIN system prototype for bidirectional charging software development, integration and simulation of grid signaling, and end-to-end testing with modified PEVs. This project demonstrated an integrated system for CCS-based bidirectional DC charging, raising the TRL between 6 and 7. The system is one-step away from deployment and is in the process of obtaining UL certification. A patent for the SPIN system was filed in 2015 and received by Flex Power Control in 2021.[22]

Raising Stakeholder Awareness of the SPIN System

EPRI staff and other members of the project team made numerous presentations to a global group of about sixty utilities spanning investor-owned, publicly-owned, and cooperative ownership structures. These presentations described the SPIN system and discussed opportunities for future utility-hosted pilots. The SPIN system was also presented to the EPRI Infrastructure Working Council multiple times to update members on the project status and learnings as well as to collect feedback and build interest in collaborations. The project team presented the technology at industry conferences including the EPRI Electrification Conference in 2022 and DISTRIBUTECH 2020 to raise awareness and interest in stakeholders. One challenge to disseminating project lessons was that there were limited public and face-to-face events during COVID and much of the data collection occurred between 2021 and 2022 year. Nonetheless, the team presented the fundings of system integration with the OEMs and utilities through web-based meetings.

Interactions with the project TAC — including representatives from automotive OEMs, utilities, the California ISO, standards setting bodies, equipment manufacturers, and third-party service providers — helped direct project activities. The first TAC meeting was held in December of 2018 and included participation from California investor-owned utilities (IOUs), privately owned utilities (POUs), California ISO, universities, research labs and several Automotive OEMs. A second TAC meeting was organized in January of 2020 and included the same TAC members. The third and final TAC meeting was held with the SCE V2G Technical Advisory

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[22] Smith, et al. Multifunction Power Management System. 2021. Patent # 11,011,913.

Board, where the project was presented to a larger, nationwide audience. Additionally, the DOE Vehicle Technologies Office (which co-funded this project) held Annual Merit Review meetings where the SPIN system was presented the last five years.

Two other CEC projects leveraged the SPIN system as a part of technology demonstration activities. As the SPIN system becomes more robust, there is a plan to implement a SPIN demonstration under EPC-17-052 with Gridscape, Urban Microgrids for Grid Resiliency and Disaster Readiness.[23] Discussions are also underway to incorporate the SPIN system into a SCE research project exploring vehicle integration with AC and DC V2G capable systems.

Informing Development of Open Standards

A core component of this project was implementation and verification of open standards including DIN SPEC 70121 for DC charging, SAE J2847/3 for reverse power flow functions and signaling, and IEEE 2030.5-2018 for grid communications (among other protocols) to enable secure and reliable bidirectional charging. During validation of the SPIN system, this project identified advancements and learnings that the project team shared with standards setting bodies actively developing updates. Specifically, the SAE EV committee — led by the project team's OEM partner, Stellantis — reopened revision of the J2847/2 and J2847/3 standards with the plan to revise and implement language that enables CCS-enabled PEVs to facilitate bidirectional power flow. This update will be coordinated with recent activity initiated to revise the DIN 70121 spec for reverse power flow. The project team expects a revised version of the CCS bidirectional capable SAE protocol to be ratified by end of 2022 or early 2023, giving a clear direction to the US market to begin making interoperable systems for testing and scaled deployment.

Advancing the SPIN System Toward Commercialization

Flex Power Control continues discussions with venture capital investors, philanthropies, and other government funding programs to raise capital to advance the SPIN system through certification with Underwriters Laboratories. Two large automotive OEMs are actively working with Flex Power Control to integrate their PEV offerings with the SPIN system to offer an integrated home backup power package that connects with rooftop PV. There is growing interest from homebuilders in offering SPIN as a part of a bundled advanced energy system. When incorporated into the 30-year financing package, the incremental cost of a SPIN system is a few dollars per month, while delivering significant benefits without the need for additional hardware. The project team believes there is high likelihood that Flex Power Control will raise sufficient capital to enable accelerated product-level testing, UL certification, and manufacturing and supply chain partnerships.

Future Technology and Knowledge Transfer

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[23] EPC-17-052, Urban Microgrids for Grid Resiliency and Disaster Readiness. California Energy Commission. https://www.energizeinnovation.fund/projects/urban-microgrids-grid-resiliency-and-disaster-readiness.

All standards and communications protocols used in this project were implemented in an open and transparent manner that can inform future deployments of bidirectional vehicles and charging infrastructure. Based on learnings from this project, EPRI is planning to develop an implementation guide for practical, end-to-end managed and bidirectional charging with CCS-equipped vehicles. The team is also planning to release an open-source version of the implementation code for bidirectional charging that can be adapted by other researchers or innovators working on chargers or PEVs. Public access to this code can accelerate technology adoption and evolution. EPRI is also planning to initiate efforts to transfer the technology, enabling CCS-based bidirectional charging to school bus and charger manufacturers, as the CCS connector is widely used by school buses and other commercial vehicles.

Chapter 5: Benefits to Ratepayers

This project used the Distributed Energy Resource Value Estimation Tool (DER-VET) previously developed by EPRI to conduct techno-economic analyses on bidirectional charging technologies such as the SPIN system.[24] DER-VET uses load data and site-specific information to calculate the value of DERs such as discharging PEVs. Several benefits analyses were conducted for different applications of bidirectional charging based on different assumptions regarding the number of PEVs deployed, battery size, vehicle availability, and other factors described below. Scenarios of benefits evaluated include use of a stand-alone SPIN system to provide resilient backup power at a single site as well as to provide distribution and bulk power system applications.

Customer Resilience Improvement

This analysis evaluated the potential site resilience and economic benefits achievable through bidirectional PEV charging with the SPIN system when used to provide power to critical loads during outages. The analysis assumed the PEV battery had a usable capacity of 40 kWh for grid services (representing approximately 60 to 70 percent of a commercially available midsize PEV battery capacity) and could discharge at 10 kW peak with a round trip efficiency of 85 percent. Load profile assumptions for a residential and commercial customer are shown in Table 3.

Table 3:Customer Load Profile Characteristics Used for Resilience Analysis

	Residential Customer	Commercial Customer
Average Annual Load (kW)	0.79	4.44
Peak Annual Load (kW)	12.88	28.78
Average Daily Energy (kWh)	19.06	106.50
Peak Daily Energy (kWh)	90.96	209.73

Source: DER-VET

Based on these assumptions and load requirements, a critical load coverage probability metric was calculated for all outage durations up to 96 hours. This metric represents the likelihood that the 40 kWh bidirectional PEV and charger could meet the peak load requirements of the site. The critical load coverage probability was calculated by taking the ratio of all the times the system was able to meet the required load to the total number of simulations which includes instances when the system was not able to meet the site load.

The critical load coverage probability for a representative commercial and residential customer is shown in Figure 20. With the assumed 40 kWh battery capacity, the PEV could serve the commercial customer through an outage lasting up to approximately 10 hours with load

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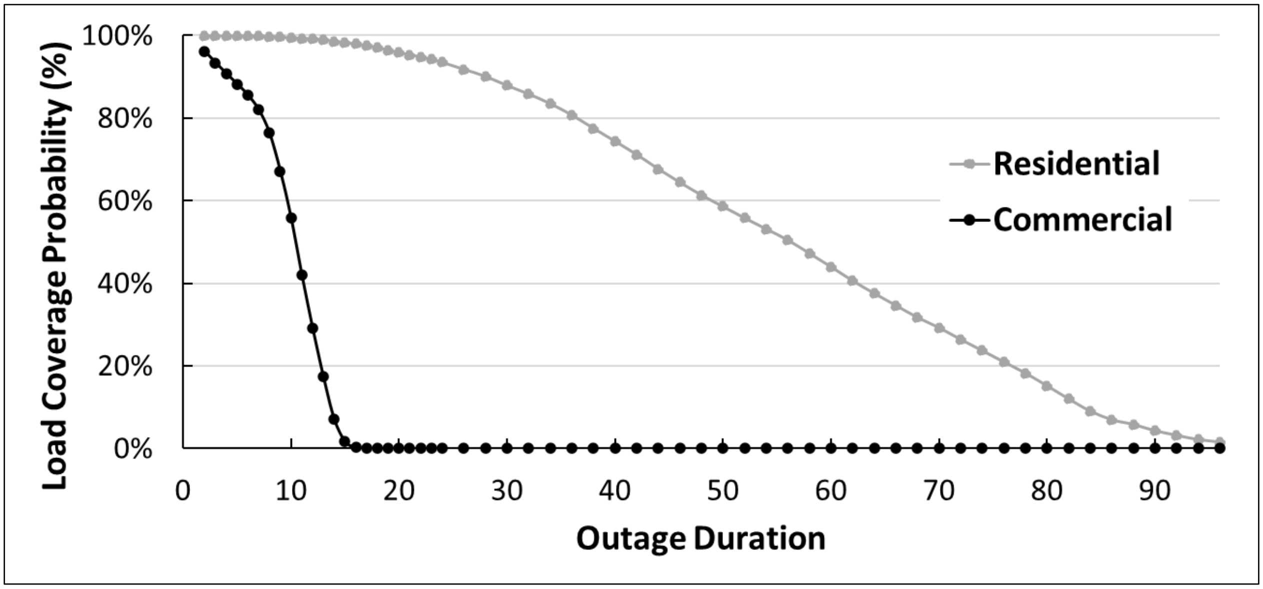
[24] EPRI. 2021. Distributed Energy Resouce Value Estimation Tool. https://www.der-vet.com/.

coverage probability around 60 percent. The system could serve a residential customer for around 50 hours with a load coverage probability of about 60 percent. It is intuitive that the residential customer would be served for longer given their smaller power and energy requirements compared to commercial customers.

Figure 20: Critical Load Coverage Curve for Representative Residential and Commercial Customer



Load coverage probability for representative residential and commercial customers assuming 40 kWh battery capacity capable of discharging at 10 kW.

Source: EPRI Analysis

Economic Assessment of the SPIN System for Site Resilience

Because electricity outages are relatively infrequent, it can be difficult to quantify the economic cost of short- and long-duration outages or estimate the value provided by backup power solutions. For residential customers, one approach is to consider their willingness to pay for available alternatives (for example, diesel backup generators or stationary storage) as a measure of their monetary value of that service. A diesel generator rated at 7.5 kW could be purchased for approximately $6,500 and be installed for around $8,000 not including operations and maintenance. However, because diesel generators release local air pollutants and greenhouse gas emissions, this analysis focuses on a comparison to commercially available stationary lithium-ion battery energy storage systems (BESS).

SPIN system cost estimates are derived from bottom-up accounting of the part costs, in addition to the amortized investment, warranty, distributor, and sales mark-ups that are prevailing in the industry, assuming a production volume of 10,000 units per year. Purchase and installation prices for both BESS products were obtained from Energysage data.[25] The upfront capital cost of two equivalently sized (40 kWh) commercially available stationary storage systems are compared to the SPIN system in Table 4.

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[25] Marsh, Jacob. 2021. "The Tesla Powerwall Home Battery Complete Review." EnergySage. https://news.energysage.com/tesla-powerwall-battery-complete-review/.

Table 4: Upfront Capital Cost Comparison of 40 kWh BESS Products and SPIN System for Residential Customer Resilience

	BESS Product 1	BESS Product 2	SPIN System
Battery Cost ($)	21,000	36,000	N/A
Inverter and Installation Cost ($)	2,000	2,000	1,000
Hardware Cost ($)	1,000	1,000	6,000
Total ($)	24,000	39,000	7,000

Source: EnergySage.com data (BESS products 1 and 2) and Flex Power Control (SPIN System)

While 40 kWh is an unrealistically large size for residential BESS installations, it reflects the advantage of large available storage capacity built into PEVs. Because battery cost is the largest fraction of total system cost (around 90 percent for both BESS products shown), bidirectional charging with a vehicle purchased for mobility is a significantly lower cost strategy to providing backup power for infrequent outages (effectively subsidizing home electricity storage costs with the vehicle purchase).

Unlike most residential customers, commercial customers can more easily quantify the value of outages as the economic loss incurred if an outage were to occur (for example, in lost sales or spoiled merchandise). For a commercial customer like a supermarket, the annual benefit of resilience improvement was estimated to be $3,660 using Lawrence Berkley National Laboratory's ICE calculator tool.[26] The upfront capital cost and net present value of the different backup options, assuming 2 percent inflation and a 7 percent discount rate over 15 years, is shown in Table 5.

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[26] Interruption Cost Estimate (ICE) Calculator. DOE, Berkeley Lab, and Nexant. https://icecalculator.com/home. Note: The following inputs were provided into the tool: Location – California; Annual customer income – $56,800; System Average Interruption Frequency Index – 10; System Average Interruption Duration Index – 10.

Table 5: Cost Comparison of 40 kWh BESS Products and the SPIN System for Commercial Customer Resilience

	Gas Generator	BESS Product 1	BESS Product 2	SPIN System
Upfront Capitol Cost (Year Zero $)	($8,000)	($23,600)	($38,600)	($7,000)
Nat Present Value (Year 15 in Year Zero $)	$26,346	$10,746	($4,254)	$27,346

Source: Homeguide.com (generator), Energysage.com (BESS products 1 and 2), and Flex Power Control (SPIN system)

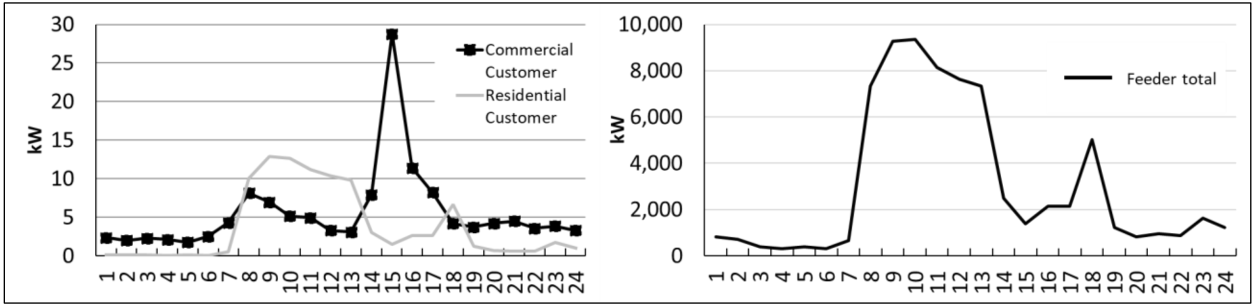
The gas generator is shown as a reference, although it is not an equivalent comparison because it relies on fossil fuels and has high emissions. The SPIN system and PEV with up to 10 kW discharge and 40 kWh capacity provides approximately the same value as the gas generator, which only improves with increasing gas prices*.* Furthermore, this analysis quantifies only resilience benefits and does not include additional savings or revenue generating opportunities from performing electric services. This suggests that on a direct cost basis, the SPIN system coupled with an PEV capable of bidirectional charging provides significant customer benefit with an estimated the $6,000 purchase price.

Customer Bill Savings and Distribution System Peak Shaving

This analysis evaluated the potential electricity bill savings for individual representative residential and commercial sites using bidirectional charging to shift building load to low-cost times and limit site peak demand based on a time-of-use (TOU) tariff. Building on these individual customer savings, DER-VET was used to evaluate how aggregation of many customers' bidirectional PEVs can help smooth demand on a single distribution feeder based on different scenarios of the number of bidirectional PEVs available. The total annual bill savings were estimated and allocated evenly between all customers participating in the service.

For this analysis, the PEV battery capacity was assumed to be 20 kWh for grid services (representing approximately 20 to 30 percent of a commercially available midsize PEV battery capacity) with a power rating of 10 kW and a round trip efficiency of 85 percent. The distribution feeder is assumed to serve 700 residential and 100 commercial customers. The representative load profile of the commercial and residential customers as well as the distribution circuit for the peak day of the year is shown in Figure 21. The annual peak load of the commercial and residential customers is approximately 28 kW and 12 kW, respectively, while the distribution circuit has an annual peak load of 9.35 MW.

Figure 21: Customer and Distribution Circuit 24-Hour Peak Load Profile



Peak day load profile for individual residential and commercial customers (left) and the total modeled load on the distribution feeder (right). The residential customer demand peaks earlier in the day compared to commercial customers that peak later in the day. The distribution feeder reaches a peak of 9.5 MW early in the day driven predominantly by residential load.

Source: EPRI based on DER-VET data

The commercial and residential customers are assumed to be subscribed to SCE's TOU GS-1 Option D and Option E tariff, respectively.[27] The utility bill consists of energy charges ($/kWh) that vary based on season and time of day as well as a demand charge ($/kW) for commercial customers, as summarized in Table 6 and Table 7.

Table 6: Representative Time-of-Use Tariff Structure

Customer	Summer			Winter			Summer & Winter	Summer
	Energy Charge ($/kWh)						Demand Charge ($/kW)	
	On Peak	Mid Peak	Off Peak	Mid Peak	Off Peak	Super Off Peak	All Hours	On Peak
Commercial	$0.177	$0.16	$0.104	0.172	$0.113	$0.092	$13.25	$4.41
Residential	$0.491	$0.299	$0.194	0.319	$0.242	$0.150	-	-

Source: SCE

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[27] Southern California Edison (SCE) Rates and Pricing Choices. https://www.sce.com/regulatory/tariff-books/rates-pricing-choices.

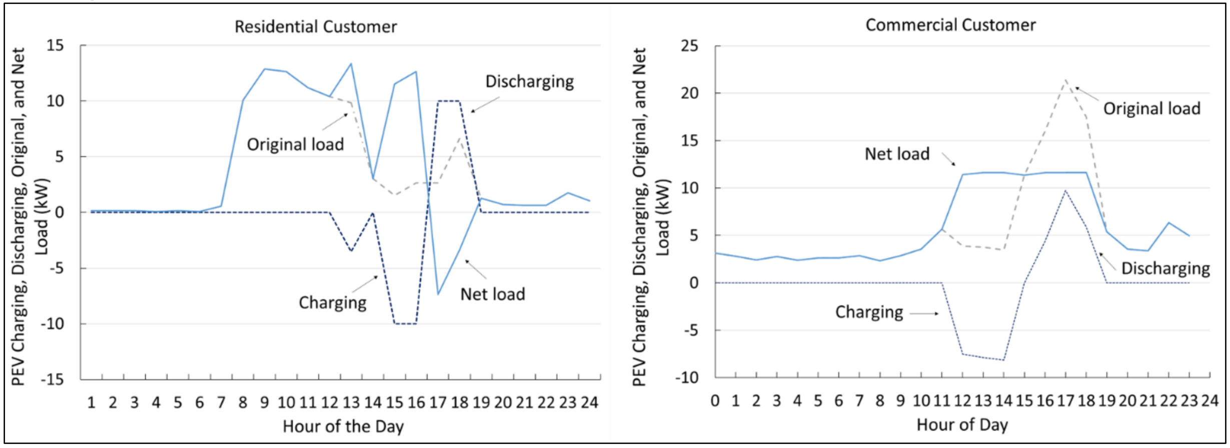
Table 7: Time-of-Use Tariff Schedule

Season	Period	Hours
Summer	**On Peak**	4:00pm – 9:00pm (Weekdays)
	Mid Peak	4:00pm – 9:00pm (Weekends)
	Off Peak	12:00am – 4:00pm & 9:00pm – 12:00am (Weekdays & Weekends)
Winter	**Mid Peak**	4:00pm – 9:00pm (Weekdays & Weekends)
	Off Peak	12:00am – 8:00am & 9:00pm – 12:00am (Weekdays & Weekends)
	Super Off Peak	8:00am – 4:00pm (Weekdays & Weekends)

Source: SCE

PEV charging and discharging is managed differently for commercial and residential customers because of the different rate structures. The residential customer charges during low energy price hours and discharges during high energy price hours. Conversely, the commercial customer discharges the PEV predominantly to shave the peak load of the individual customer to avoid demand charges. Figure 22 shows the original facility load, modeled charging and discharging behavior, and resulting net load for the residential and commercial customer. For a distribution feeder serving 700 residential and 100 commercial customers, aggregation of hundreds of PEVs operating the same bidirectional charging pattern could contribute 300 kW and 750 kW peak load reduction for 100 and 200 participating PEVs, respectively. Figure 23 shows the net load reduction on the distribution circuit assuming different numbers of participating PEVs.

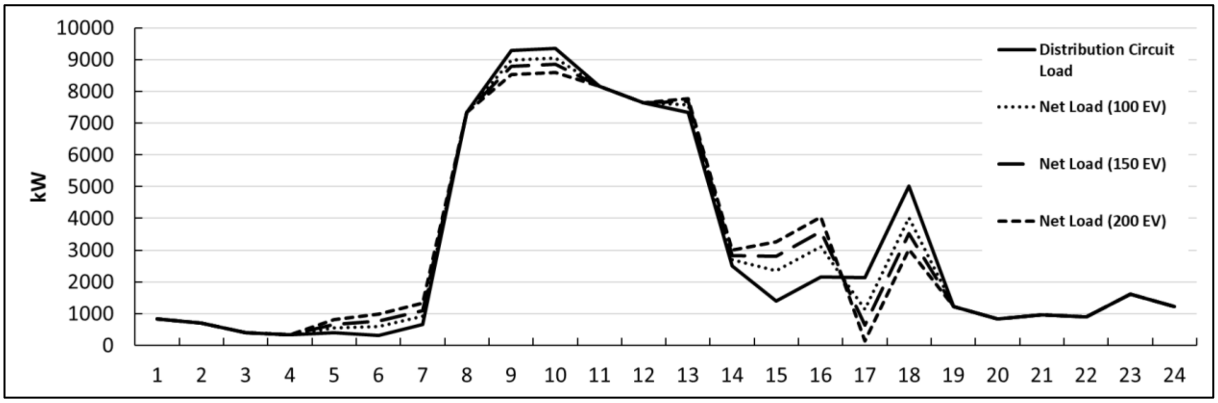
Figure 22: Customer Load Profiles with and Without Bidirectional PEV



Effect of bidirectional charging on net demand of a residential (left) and commercial (right) facility.

Source: EPRI

Figure 23: Distribution Feeder Load Profile on Peak Day with Different Numbers of Bidirectional PEVs



Peak load on the distribution feeder can be reduced with increasing numbers of bidirectional PEVs on the feeder operating to minimize commercial and residential customer electricity bills.

Source: EPRI

Peak load on the feeder reduces linearly with increasing numbers of bidirectional PEVs, as shown in Table 8. Thus, the majority of PEVs are operated for TOU bill reduction, with increased charging at low-cost times (between 4:00am – 7:00am and 2:00pm – 4:00pm) as well as discharging (between 8:00am – 11:00am and 4:00pm – 6:00pm) at total of 20 kWh capacity at 10 kW per PEV daily.

Table 8: Distribution Circuit Peak Load Comparison with Different Numbers of Bidirectional PEVs

PEV Count	0	100	150	200
Annual Peak Load	9.348 MW	9.048 MW	8.848 MW	8.598 MW

Source: EPRI

Economic Assessment of the SPIN System for Customer Bill Savings

Simulations of daily operation for a full year using PEV characteristics, load data, and TOU tariff structure described above suggest a commercial customer with a bidirectional PEV charger like the SPIN system could save approximately $2,070 per year on their electricity bill. This annual savings comes from use of lower cost electricity (approximately $400 in savings representing an 8 percent reduction) as well as avoided demand charges ($1,660 in savings representing a 46 percent reduction). Similarly, for a residential customer the annual bill savings is estimated to be $1,195 (representing a total savings of 73 percent) annually that comes entirely from lower cost electricity based on TOU rates.

The cost comparison of the two equivalently sized 20 kWh BESS products and the SPIN system are shown in Table 9. Based on an estimated annual bill savings of $2,070 and $1,195 for a commercial and residential customer, respectively, the 15-year net present value (NPV) is thousands of dollars greater for the SPIN system for both customer types.

Table 9: Cost Comparison of 20 kWh BESS Products and the SPIN System for Customer Bill Savings

	BESS Product 1	BESS Product 2	SPIN System
Battery cost (S)	10,500	18,000	N/A
Inverter and installation cost ($)	2,000	2,000	1,000
Hardware cost ($)	1,000	1,000	6,000
Total upfront cost ($)	13,500	21,000	7,000
Net present value at year 15 (Residential/Commercial)	$4,967 / $14,435	($1,915) / $8,297	$6,681 / $16,710

Source: Energysage.com (BESS products 1 and 2) and Flex Power Control (SPIN system)

There would also be potential for utility and ratepayer savings arising from the annual peak load reduction of 300 kW, 500 kW, and 750 kW achievable with 100, 150, and 200 bidirectional PEVs, respectively. For example, assuming an avoided cost of infrastructure upgrade of $25/kW-year in the SCE service territory, the net savings for the utility could be anywhere between $112,500 and $281,250 over the 15-year period.[28]

System Wide Demand Response

This analysis explored opportunities for bidirectional charging to contribute to system reliability by having PEVs discharge during times of peak demand with a compensation structure like resource adequacy demand response programs administered by utilities. Specifically, this analysis assumed 10 demand response events per year with a duration of 4 hours for which participants are paid $9.50 per kW load reduction provided.[29] Scenarios of different levels of PEV deployment and participation were evaluated, assuming each bidirectional PEV and charger pair has 20 kWh capacity rated at 5 kW and with a round trip efficiency of 85 percent.

The ten days with highest peak demand of 2021 were identified using historical load data from the California ISO, all of which occurred in the months of July, August, and September.[30] The impact on net California ISO system load of the aggregated charging and discharging of 100,000, 200,000, and 300,000 bidirectional PEVs participating in the modeled demand response program is shown for September 8, 2021 in Figure 24.

Figure 24: Original and Net California ISO Load with PEV Participation in Demand Response Programs

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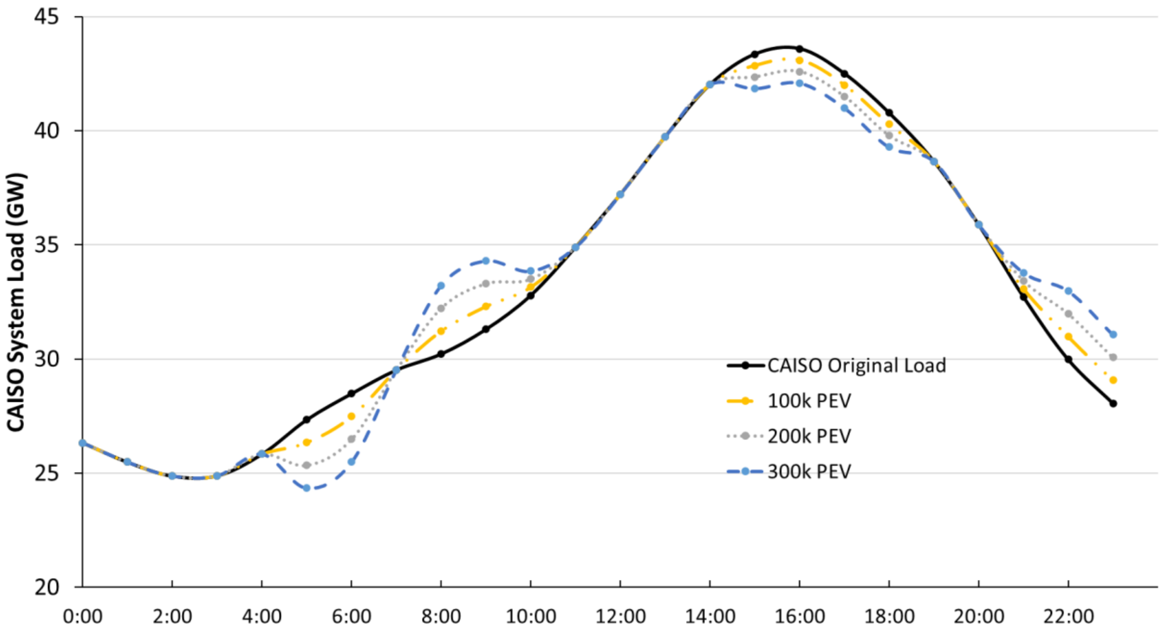
[28] 2021 Distributed Energy Resources Avoided Cost Calculator. 2021. CPUC. https://willdan.app.box.com/v/2021CPUCAvoidedCosts/file/825224047481.

[29] PG&E Demand Response Program (ELECTRIC SCHEDULE E-BIP Sheet 1 BASE INTERRUPTIBLE PROGRAM). 2020. PG&E. https://www.pge.com/tariffs/assets/pdf/tariffbook/ELEC_SCHEDS_E-BIP.pdf.

[30] California ISO Open Access Same-time Information System. California ISO. http://oasis.caiso.com/mrioasis/logon.do.



Source: EPRI analysis

Effect of bidirectional charging on net demand of the California ISO, with 100,000, 200,000 and 300,000 PEVs participating and available results between 500 MW and 1.5 GW of net demand reduction.

The potential California ISO annual peak load reduction increases with the number of bidirectional PEVs participating in the customer load reduction service, as shown in Table 10. The PEV batteries charge more during nighttime and early morning (approximately 8:00pm to 12:00am) and discharge to reduce peak load (approximately 1:00pm to 7:00pm) contributing between 0.5 and 1.5 GW reduction in peak load for 100,000 and 300,000 PEVs participating, respectively. Given forecasts for millions of PEVs to be deployed in California over the coming decade, these estimates are reasonably achievable target.[31]

Table 10: California ISO Peak Load Comparison with Different Amounts of Bidirectional PEVs

Number of participating PEVs	0	100,000	200,000	300,000
Peak Load (GW)	43.59	43.09	42.59	42.09

Economic Assessment of the SPIN System for Demand Response

Assuming a monthly payment of $9.5/kW-month for participating in the demand response program, the annual revenue per PEV could be up to $570.[32] With the 20 kWh BESS product and SPIN system costs estimated in Table 9, an inflation rate of 2 percent and discount rate of

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[31] California Energy Commission. Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment – Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030. https://efiling.energy.ca.gov/getdocument.aspx?tn=238853

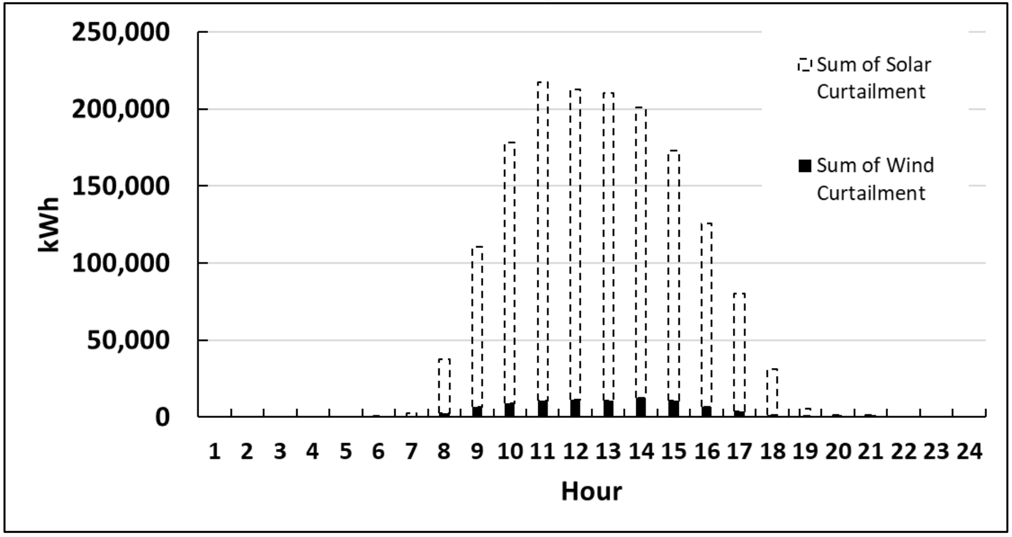
[32] PG&E Demand Response Program (ELECTRIC SCHEDULE E-BIP Sheet 1 BASE INTERRUPTIBLE PROGRAM). 2020. PG&E. https://www.pge.com/tariffs/assets/pdf/tariffbook/ELEC_SCHEDS_E-BIP.pdf. Note: This level of compensation is similar to existing demand response programs in California.

7 percent, the 15-year net present value is estimated as negative $474, reflecting the relatively low compensation associated with demand response.

System Wide Renewable Curtailment Mitigation

This analysis evaluates the potential reductions in renewables curtailment and greenhouse gas emissions enabled through aggregated charging and discharging of bidirectional PEVs and chargers following changes in locational marginal prices (LMP) across the California ISO system. The LMP reflects a combination of the cost of generation, congestion on the transmission system, and line losses when delivering power to a specific location. The LMP is calculated for thousands of market nodes in real-time. Renewable wind and solar resources have a near-zero marginal cost of generation and when combined with inflexible baseload plants, can result in negative LMPs at some locations where generation exceeds demand. Most utilities or grid operators curtail generation from wind and solar plants when minimum generation levels of baseload generation are reached. This is because frequent stopping and restarting these units for short periods of time can be significantly more expensive than paying for curtailed renewable generation. In California in 2020, approximately 1,500 GWh of renewable energy was curtailed. The hourly breakdown of the total curtailment is shown in Figure 25, with about 80 percent of this curtailment occurring between January and June.[33]

Figure 25: Renewable Curtailment by Hour in California ISO in 2020



Renewable energy curtailment by hour for all of 2020.

Source: EPRI Analysis with data from California ISO

Customers with flexible resources such as bidirectional PEVs and chargers could charge during instances of low or negative LMP, consuming renewable electricity that would otherwise be curtailed. The aggregate impact of different numbers of PEVs operating to mitigate curtailment was evaluated assuming each bidirectional charger and PEV discharges an average of 20 kWh daily at 10 kW with a round trip efficiency of 85 percent. The charging and discharging behavior of a single bidirectional PEV and charger is shown in Figure 26 along with the battery state of charge and LMP profile of a representative California ISO market node.

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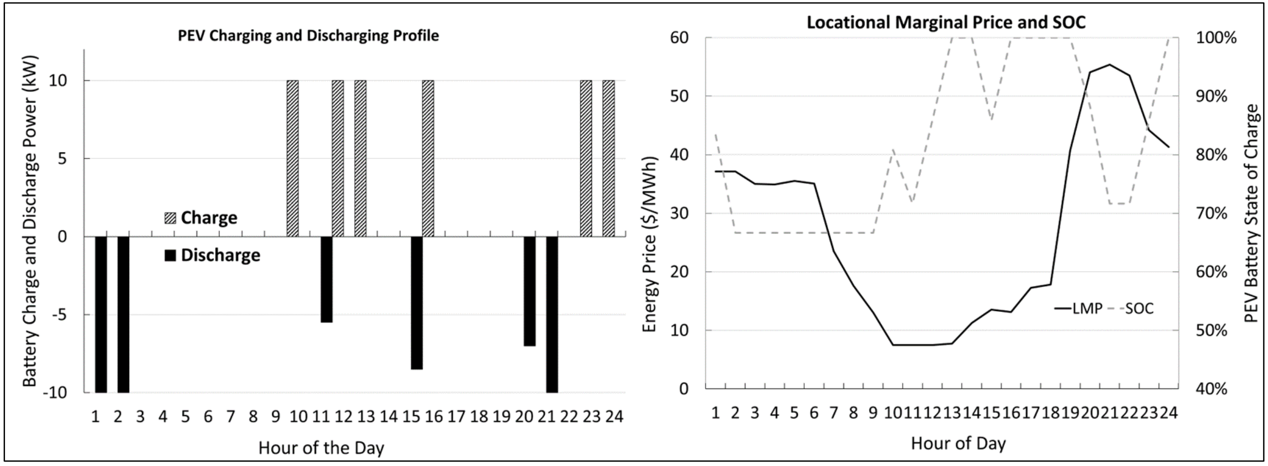
[33] CAISO Managing Oversupply. http://www.caiso.com/informed/Pages/ManagingOversupply.aspx.

It should be noted that the day shown in Figure 26 (June 7, 2017) is one of the high-curtailment days in the year in which large changes in LMP result in more extensive discharge in excess of 40 kWh. In most months the variation in LMP is smaller and the PEV is discharged less, thus the energy drawn from the battery on an annualized basis averages out to be about 20 kWh per day. The DER-VET algorithm is simplified and does not consider factors such as temperature, warranty, degradation, and customer constraints. Consequently, the benefits estimated in this analysis are likely the upper limit of the values.

Figure 26: Daily PEV Charging and Discharging Profile, Battery SOC, and LMP



Modeled charging and discharging profile of PEV batteries is closely aligned with changes in LMP on June 7, 2017, with charging occurring during low-cost times and discharging occurring at high-cost times.

Source: EPRI Analysis with California ISO Data

The PEV charges during hours of low LMP (predominantly late morning and late night) and discharges during times of high demand and price (early morning and later afternoon). The aggregated impact of 100,000, 250,000, and 500,000 PEVs following this charging and discharging pattern could reduce annual curtailment in 2020 by 66.6 GWh, 165 GWh, and 332 GWh, corresponding to a 4.2, 10.4, or 20.9 percent reduction, respectively.

The otherwise-curtailed renewable energy stored in the PEV battery is discharged later (minus conversion losses), offsetting production that would otherwise come from conventional resources such as natural gas plants. This would contribute to electricity sector greenhouse gas emissions reductions. Based on the marginal hourly emission of CO_2, approximately 16,484 metric tons, 41,412 metric tons, or 82,424 metric tons of CO_2 emissions could be avoided annually with 100,000, 250,000, or 500,000 PEVs, respectively.[34]

Summary of Value Assessment for Bidirectional Applications

Table 11 summarizes the estimated potential economic, environmental, and resilience benefits of the SPIN system for residential and commercial customers as well as distribution and bulk power system operators.

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[34] Energy Efficiency Data. 2021. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2021-10/13_GFO-21-303_Energy_Efficiency_Data_ADA.xlsx.

Table 11: Summary of Analyzed Benefits of the SPIN System

Application	Customer Resilience Improvement	TOU Optimization and Distribution Feeder Peak Shaving	System Wide Demand Response	Renewable Curtailment Mitigation
PEV Capacity and Power Rate	40 kWh 10 kW	20 kWh 10 kW	20 kWh 10 kW	20-40 kWh 10 kW
Number of PEVs	At least 1 per site	At least 1 per site, scenarios of 100, 150, and 200 per distribution feeder	Scenarios of 100,000, 250,000, and 300,000 (statewide)	Scenarios of 100,000, 250,000, and 500,000 (statewide)
Annual Benefit Realized	24 hours backup residential/ 8 hours backup commercial/ value of lost load is $3,661 for commercial customer	300–750 kW load reduction with 100–200 PEVs. $2,070 and $1,195 savings per commercial and residential customer respectively	$1,140 per PEV/ 500–1,120 MW load reduction with 100,000–300,000 PEVs	$460 per PEV/ 363 lb. CO2 avoided per PEV/ 16,484 MT CO2 reduced per 100,000 PEVs

Source: EPRI Analysis

In conjunction with rooftop solar, the SPIN system can both power the building and charge the PEV during the daytime and then discharge the PEV to power the building during night or an outage (for up to 24 hours depending on the building's energy use). Beyond resilience applications, the SPIN system can manage PEV charging and discharging to mitigate demand charges and limit distribution level peaks resulting in local grid benefits of approximately $1,140 per year per PEV. If bidirectional charging is coordinated with renewable overgeneration, the SPIN system could enable savings of $460 per year while reducing 363 lb. of greenhouse gases per year per PEV from avoided fossil generation. Even if system operation is non-ideal due to variability in PEV availability, building energy use, electricity greenhouse gas intensity, or tariff structure, the SPIN system remains a lower cost substitute for stationary battery storage or polluting and noisy fossil-based generators. In the near-term, backup power applications that require limited use of PEV batteries during occasional outages can drive market growth for the SPIN system and other bidirectional charging technologies while other compensation mechanisms for grid services mature.

Chapter 6:
Conclusions and Recommendations

The SPIN system combines a DC bidirectional PEV charger, a smart inverter for integration of local PV and optional stationary storage, and an energy management system capable of responding to grid signals. When combined with an automatic transfer switch, the SPIN system can provide power to building loads during outages or intentional islanding events. When operated in response to time variant rates that reflect grid conditions (for example, time of use or dynamic real time tariffs), the SPIN system can reduce peak load on specific distribution feeders or system wide as well as avoid curtailment of renewables and reduce marginal greenhouse gas emissions.

Project Accomplishments

Important accomplishments during this project include:

- Development of the prototype SPIN system and implementation of software enabling specific customer use cases to provide resilience, economic, and environmental benefits.
- Integration testing of the prototype SPIN system with both modified and production PEVs to validate end-to-end communication, proper functioning of the internal multimode inverter, and bidirectional charging functionality using the standard CCS1 coupler.
- Standards development and updates (specifically SAE and DIN), which will support automotive OEMs and charging equipment manufacturers in commercializing and deploying interoperable PEVs and DC chargers that are capable of bidirectional charging.
- Controlled accelerated testing of battery degradation associated with bidirectional charging, which can help automotive and battery manufacturers calibrate anticipated battery impacts relative to potential customer benefits in development of new product offerings with bidirectional charging capabilities.
- Economic analyses of potential customer and ratepayer benefits enabled through different applications of bidirectional charging technologies such as the SPIN system.

The project identified several challenges and opportunities to advance bidirectional charging technologies and inform development of supportive policies and programs. While the project is complete, future efforts to advance the SPIN system are planned.

Challenges and Opportunities

There are multiple challenges limiting commercialization and adoption of the SPIN system and other bidirectional charging technologies, which can broadly be categorized as technical, commercial, and regulatory as outlined below.

Technical Challenges and Opportunities

Obtaining the necessary safety certifications from UL for the SPIN system will take significant resources and time due to the complexity and the numerous operating modes of the system as tested. Flex Power Control is developing a longer-term plan to receive UL certifications for the full product but has simultaneously developed a simplified product (SPIN EVO) that requires fewer certifications and will be brought to market first. Flex Power Control and EPRI have created a project that will enable testing of SPIN as a smart inverter product to identify and eliminate issues with certification.

Another challenge for commercializing the SPIN system and other bidirectional chargers is reducing the time, cost, and complexity of installation and interconnection. Bidirectional chargers are a new class of product, which can result in commercial installers and utilities not having sufficient experience to qualify them for interconnection and safe wiring. Development of streamlined interconnection process and standardized wiring templates will allow for low-cost and rapidly scalable installation of SPIN and similar devices on customer premises and interconnection with utility distribution systems. The Flex Power Control team is planning to work with existing PV and storage installers, IOUs, and automotive OEMs to develop an end-to-end installation template and easy-to-use customer app that facilitates installation with limited customer intervention.

A final technical challenge relates to the relatively limited number of suppliers for HomePlug GreenPHY power line communications (PLC) chipset used for communications between the PEV and charger. Beyond limited supply, there is little technical support available for integration and verification testing with these chipsets which can require significant engineering resources to implement reliably at scale. To address this challenge, EPRI is evaluating alternatives to PLC for high level communication between the PEV and EVSE. EPRI has also recently reached out to the key chipset vendors and is working to develop reference designs of open-source control boards that can serve as SECC and EVCC.

Commercialization Challenges and Opportunities

Development and testing of the SPIN system spanned seven years with internal funding from EPRI and external funding from the CEC and the DOE. Nonetheless, obtaining UL certification and delivering early production runs will require raising significant capital. In previous fund-raising discussions, investors required that the product be UL certified prior to investment. Flex Power Control originally planned to submit the complete SPIN-MPX system as tested in this project, which would require significantly more certification testing, time, and resources due to its complexity.

Recently, Flex Power Control developed the SPIN-EVO product that offers CCS-based bidirectional charging with reduced requirements for testing and certification. This product enabled Flex Power Control to establish working relationships with three major automotive OEMs in addition to Stellantis, which improved fund raising prospects. The SPIN-EVO will be one of the first CCS-based bidirectional chargers certified using the modified DIN70121, which will be available for customers in 2023 and be ahead of other equipment manufacturers. Flex Power Control has been receiving significant investment and partnering interest from key investment and distribution partners, in addition to four automotive manufacturers who are working to develop integrated EV-SPIN solutions. Without the timely CEC support and guidance with prioritizing the testing and integration work for SPIN on this project, it would have been impossible for EPRI, Flex Power Control and the partners to have achieved these milestones.

Regulatory Challenges and Opportunities

Regulations in the form of authorized rates, customer programs, planning processes, and market design significantly influence the incentives and barriers for bidirectional charging of PEVs and other DER more broadly. One challenge is that today, flexible PEV charging and discharging is difficult to forecast compared to other generating resources particularly for meeting resource adequacy requirements. PEV availability statistics are becoming more widely available through larger-scale customer programs and deployments, which can inform probabilistic forecasts of resource availability performed by California ISO.[35] Future pilots of bidirectional charging should design data collection plans to help inform development and improvement of these models.

Another challenge is development and implementation of rates and other grid signals to end-customers that accurately reflect grid conditions and appropriately incentivize flexible PEV charging and discharging. Many existing time-of-use rate structures incentivize charging over-night, but do not adequately encourage daytime charging when renewable generation is abundant nor compensate for export of energy. Further expansion of pilots of more dynamic, real-time rates such as being launched by SCE and considered in the California Flexible United Signal for Energy framework could improve better incentivize charging and discharging aligned with grid conditions.[36,37]

Recommendations for Key Stakeholders

To accelerate the adoption of the SPIN system and other bidirectional charging technologies, the project team identified multiple recommendations for different stakeholders.

Standards Development Organizations

- Update of standards: Applicable standards for PEV charging, discharging, and grid interconnection are established and updated by IEEE, UL, SAE, IEC/ISO and DIN. Most standards today only address charging and are just beginning to accommodate discharging (reverse power flow, along with smart inverter functions). Not only do standards for bidirectional charging need to be ratified and implemented, but they also should be harmonized globally to the extent practicable. This will enable the manufacturers and component suppliers to produce larger volumes of equipment and components and ultimately help drive down customer costs.
- Reference designs and implementation guides: Standards development organizations should also create thorough implementation guides, open-source code bases, and reference designs to release along with standards updates. These resources will assist

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[35] 2022 Summer Loads and Resources Assessment. 2022. California ISO. http://www.caiso.com/Documents/2022-Summer-Loads-and-Resources-Assessment.pdf.

[36] SCE Dynamic Rate Pilot. https://www.dret-ca.com/dynamic-rate-pilot/.

[37] Advanced Strategies for Demand Flexibility Management and Customer Compensation. 2022. CPUC Energy Division White Paper. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/demand-response/demand-response-workshops/advanced-der---demand-flexibility-management/ed-white-paper---advanced-strategies-for-demand-flexibility-management.pdf.

automotive and equipment manufacturers to eliminate errors and develop more uniform implementations of ratified standards and could enable streamlined conformance verification, particularly for specific safety-related standards. This will help accelerate development, interoperability certification, and broad deployment of this technology.

Automotive OEMs, Equipment Providers, and Third-Party Providers

- Automotive OEMs, charging equipment manufacturers, and third-party service providers should all participate in the standards ratification process and work cooperatively to test implementations and verify compatibility across each-others product offerings.
- Automotive OEMs and hardware providers should prioritize customer ease of use and installation, including through partnerships with established installation contractors. At a minimum, providers should publish an installation manual and training materials for electrical contractors to facilitate safe, replicable, and scalable installation practices.
- Automotive OEMs should track cumulative discharge for energy services and any associated battery degradation and make this information visible to customers. This can help inform driver decisions about how frequently and to what extent they should discharge their PEV battery for electric services.

Utilities and Regulators

- Utilities and regulators should ensure that the grid interconnection requirements for bidirectional chargers are streamlined and consistent with other DERs.
- Regulators should evaluate a portfolio of incentive mechanisms including more dynamic rates and emergency event-based programs that incentivize charging and discharging behavior that is beneficial to the grid.
- Utilities and regulators should establish large scale pilots with targeted data collection requirements that can help inform resource forecasts for bidirectional charging and other DERs.

LIST OF ACRONYMS

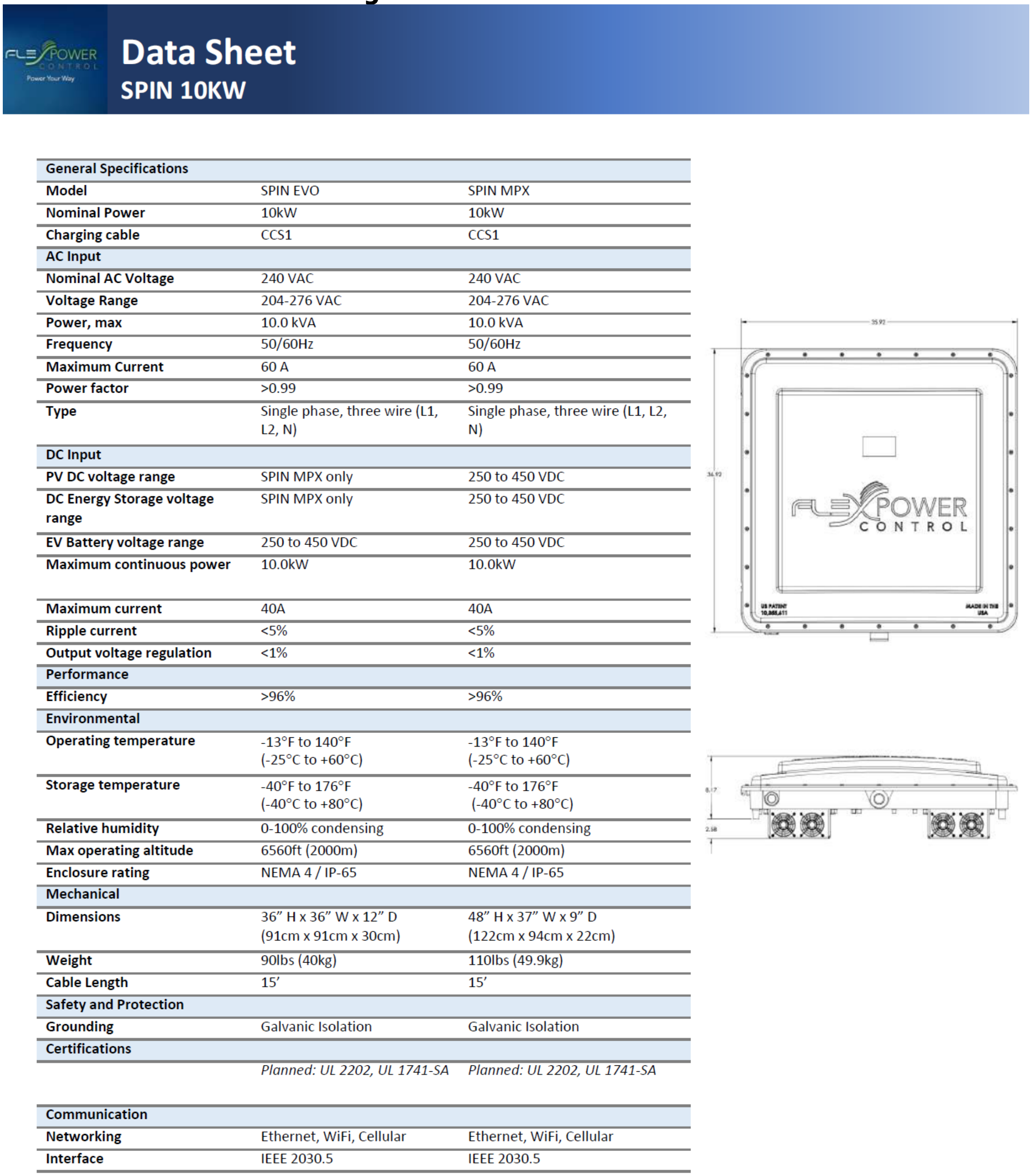
Term	Definition
AC	alternating current
Ah	amp hour(s)
BESS	battery energy storage system
BTM	behind-the-meter
California ISO	California Independent System Operator
CAN	Controller Area Network
CD	cycle discharge
CCS	combined charging system
CEC	California Energy Commission
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
CSIP	Common Smart Inverter Profile
DC	direct current
DER	distributed energy resource(s)
DER-VET™	EPRI’s Distributed Energy Resource Value Estimation Tool
DOE	US Department of Energy
DR	demand response
DSO	distribution system operator
EMS	energy management system
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
ESIF	Energy Systems Integration Facility (NREL)
EU	European Union
EVCC	electric vehicle communication controller
EVSE	electric vehicle supply equipment
GHG	greenhouse gas
GWh	gigawatt-hour(s)

Term	Definition
HPGP	HomePlug Green PHY
hr	hour(s)
Hz	hertz
IEC	International Electrotechnical Commission
IOU	investor-owned utility
ISO	independent system operator
kW	kilowatt(s)
kWh	kilowatt-hour(s)
LMP	locational marginal price
mi	mile(s)
NREL	National Renewable Energy Laboratory
NTRC	National Transportation Research Center (ORNL)
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PLC	power line communications
PSPS	public safety power shutoff
PV	photovoltaic
RA	resource adequacy
RPT	reference performance test
SCE	Southern California Edison
SOC	state of charge
SOH	state of health
SPIN	Smart Power Integrated Node
TAC	technical advisory committee
TOU	time-of-use
VGI	vehicle-grid integration
V2B	vehicle-to-building
V2G	vehicle-to-grid

Term	Definition
V2H	vehicle-to-home
V2M	vehicle-to-microgrid
VTO	DOE Vehicle Technologies Office
ZNE	zero net energy

APPENDIX A:
SPIN System Specifications

Figure 27: SPIN Data Sheet



Data Sheet
SPIN 10KW

General Specifications		
Model	SPIN EVO	SPIN MPX
Nominal Power	10kW	10kW
Charging cable	CCS1	CCS1
AC Input		
Nominal AC Voltage	240 VAC	240 VAC
Voltage Range	204-276 VAC	204-276 VAC
Power, max	10.0 kVA	10.0 kVA
Frequency	50/60Hz	50/60Hz
Maximum Current	60 A	60 A
Power factor	>0.99	>0.99
Type	Single phase, three wire (L1, L2, N)	Single phase, three wire (L1, L2, N)
DC Input		
PV DC voltage range	SPIN MPX only	250 to 450 VDC
DC Energy Storage voltage range	SPIN MPX only	250 to 450 VDC
EV Battery voltage range	250 to 450 VDC	250 to 450 VDC
Maximum continuous power	10.0kW	10.0kW
Maximum current	40A	40A
Ripple current	<5%	<5%
Output voltage regulation	<1%	<1%
Performance		
Efficiency	>96%	>96%
Environmental		
Operating temperature	-13°F to 140°F (-25°C to +60°C)	-13°F to 140°F (-25°C to +60°C)
Storage temperature	-40°F to 176°F (-40°C to +80°C)	-40°F to 176°F (-40°C to +80°C)
Relative humidity	0-100% condensing	0-100% condensing
Max operating altitude	6560ft (2000m)	6560ft (2000m)
Enclosure rating	NEMA 4 / IP-65	NEMA 4 / IP-65
Mechanical		
Dimensions	36" H x 36" W x 12" D (91cm x 91cm x 30cm)	48" H x 37" W x 9" D (122cm x 94cm x 22cm)
Weight	90lbs (40kg)	110lbs (49.9kg)
Cable Length	15'	15'
Safety and Protection		
Grounding	Galvanic Isolation	Galvanic Isolation
Certifications		
	Planned: UL 2202, UL 1741-SA	*Planned: UL 2202, UL 1741-SA*
Communication		
Networking	Ethernet, WiFi, Cellular	Ethernet, WiFi, Cellular
Interface	IEEE 2030.5	IEEE 2030.5

Source: Flex Power Control