**Project Final Report**

**EERE award number**: DE-EE-0007792

**Prime Recipient**: Electric Power Research Institute (EPRI), Inc.,

**Project title**: Comprehensive Assessment of On-And Off-Board Vehicle-To-Grid Technology Performance and Impacts on Battery and the Grid

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**Teaming Organizations**:

Flex Power Controls
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Oak Ridge National Laboratory
National Renewable Energy Laboratory

**NOTICE**

This work was authored by the Electric Power Research Institute (EPRI), Inc, for the U.S. Department of Energy (DOE) under Contract No. DE-EE-0007792. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

## 1. Executive Summary

This project defined, developed, and tested the open standards-based requirements, engineering design and system integration of on and off-vehicle Vehicle-to-Grid technologies both on the grid and on the PEV, to assess their effectiveness in implementing the use cases that create value for the grid, which in turn, can be passed on to the ratepayers and the PEV owners. The project comprised of three key categories of work and four key sub-areas of work. The three key categories were: On-Vehicle V2G, Off-Vehicle V2G, and impact of V2G operation on the battery capacity degradation. The four key sub-areas of work under each of these categories were: defining requirements, implementing the technology, performing system integration testing, and estimating the value of each of the grid services under specific assumptions, on a per-vehicle and on an aggregated basis. The technical implementation demonstrated the validity of standards-based approach to grid integration that led to interoperability, in addition to assessing the operational details with grid constraints imposed at the transformer level. The technology implementation also identified the subtle gaps in the standards definition to close the feedback loop on the accuracy of the standards as written, which are being implemented as revisions to the appropriate protocols. The battery impacts assessment developed a test cycle that the batteries from a real PHEV were subjected to for both the mobility-only and mobility with V2G specific energy cycling. While the battery impact results show a clear incremental degradation in response to additional throughput for V2G application purposes, the amount of additional kWh that can be made available without exceeding the end-of-life capacity definition of the battery at its 10-year warranty period was found to be significant. Given that the PEV battery being exercised during testing was a PHEV battery (smaller energy capacity), and 44% of its usable energy (i.e., SOC) was utilized daily for V2G applications, the EVs with much larger batteries will fare much better, either in terms of extracting more value in terms of incremental kWh for V2G, or in terms of relative incremental degradation of the capacity through the battery lifespan. Further, this battery was the second-generation Lithium-Ion chemistry circa 2015, which is at least two generations ago. Continual improvements in electrochemistry and manufacturing techniques as well as on-board capacity will enable the future batteries to provide even more energy for non-mobility-related services. Finally, the valuation of V2G energy services at the premise, distribution, and the ISO/market level was carried out for both the on-vehicle and off-vehicle cases, to understand both the GHG mitigation and operational efficiency improvements in quantitative terms. The analysis indicates that between $400 and $1400 per year of total value to the grid can be realized. When netted of costs to implement V2G either on or off-vehicle, the net value is available to be shared between the ratepayers and the EV owners. Over the life of the EV, therefore, this value becomes significant and can easily provide both ratepayer and EV owner benefits more than the cost of the equipment, either on or off-board, in addition to providing GHG mitigation benefits both on the grid and on the mobility sides. For these benefits to accrue, the key learnings from both the on- and off-vehicle V2G parts of the project indicate the need for at-scale demonstrations through involvement of real EV owners

to validate both the technical feasibility, interoperability, as well as real grid benefits by performing extensive data collection and analysis. This will help inform the grid planners, the program designs, and tariff designers, as well as automotive and equipment manufacturers how best to create their products to maximize grid, ratepayer, and EV owner value.

2. Provide a comparison of the actual accomplishments with the goals and objectives of the project.

The overall objective of the project was to analyze, through physical demonstration and experimentation, the performance of on- and off-vehicle V2G technologies on the grid as well as the EV batteries, by building prototype systems with the functional attributes, and putting it through the test regimen, in addition to configuring the EV batteries for eMobility and grid services test cycle and cycling them over a period of time to collect battery capacity degradation impacts.

The goals and objectives of the project were as follows:

A. Provide experimental and analytical basis to V2G technology as a key enabler in improving the value of owning a Plug-in Electric Vehicle.

**Accomplishments –** Defined, designed, developed, integrated, and tested an open standards-based AC and DC V2G system as a part of a residential resiliency enabling integrated DER solution in the form of Smart Power Integrated Node (SPIN).

B. Demonstrate the usefulness of off-vehicle Smart Power Integrated Node (SPIN) system to further enhance the value of V2G by enabling increased renewable generation on the grid and providing Vehicle to Home type services in conjunction with on-vehicle and off-vehicle storage.

**Accomplishments**: SPIN module was analytically shown to improve renewable penetration by reducing renewable curtailment, and was shown to demonstrate both V2H (resiliency) and V2G (analytically)

C. Provide experimental and analytical basis for assessing effect on EV batteries from their application to grid services

**Accomplishments:** Testing that spanned over 3.8 calendar years was completed over 10 months of 3-cycles per day on a battery identical to what is in Pacifica PHEV. Two batteries- one reference (mobility only) and another exercising mobility and V2G cycles were cycled. The results showed great promise in terms of the battery's ability to provide value-added services in addition to providing mobility.

D. Provide key metrics for evaluation of performance and value of an off-vehicle V2G system in comparison to an on-vehicle V2G system

**Accomplishments:** The key metrics were on-vehicle packaging space, weight, cost, and convenience (or lack thereof) of having mobile power capability, in addition to ease of integrating local resources as well as ease of interconnection.

E. Assess the effect of transformer constraints on grid service implementation

**Accomplishments:** End to end functionality of transformer capacity-constrained V2G operation was developed and tested to stay within the transformer capacity (accounting for thermal constraints)

F. Provide analytical framework and research results on the valuation of V2G services for high-impact (high-stress) regions of the distribution grid

**Accomplishments:** Extensive modeling and analysis was performed to detail the value of V2G to the premise, distribution system as well as the ISO to identify opportunities for value-optimized operation of V2G capability.

3. **Summary of Project Activities Throughout the Period of Performance:**

The project activities are broken down by Budget Periods 1 through 3 tasks as defined in the SOPO (Statement of Project Objectives).

i. **Budget Period 1 – System Development, Test and Evaluation:**

Task 1.0 - SPIN System Development, Simulation Modeling, and Testing

The tasks included assessing and defining grid user cases and system requirements to address integration of PEVs and renewables at the node (micro) level and gather relevant data for comparison as appropriate. The goal was to design, build, and test ≥6kW bi-directional converter with communications to integrate and control dynamic energy flows at the node to efficiently integrate into grid PEVs and renewables.

Task 1.1 – Grid Control Development

Use cases were defined and assessed, and the grid requirements were developed in the System Technical Specification (STS). The communication architecture was determined for the grid and Smart Power Integrated Node. The types of data, time lag, and frequency from grid (i.e. transformers, voltage, frequency) will be determined. The test plan was developed and use case modeling and analysis was performed.

Subtask 1.1.1 – Use Cases Evaluation/Determination – The available data was collected and use cases were assessed, defined, and prioritized.

Subtask 1.1.2 – System Requirements/Specifications – The SPIN and sub-system requirements was defined based on use case scenarios.

Subtask 1.1.3 – Define System Communications Architecture Design – Assessed, evaluated, and defined communications requirements based on previous program and SPIN requirements.

Subtask 1.1.4 – Developed Use Case Cycle Plan, and Verification Test Plan – The test plan was developed.

Subtask 1.1.5 – Conducted Use Case Modeling. Analysis, and Evaluation – Developed the real-time emulator, performed an assessment, and evaluated the SPIN system performance and impact to grid.

Task 1.2 – SPIN Hardware Development: Bi-Directional DC Converter Design with IGBTs

This task included developing the SPIN Bi-Directional DC Converter Component Technical Specifications. Designed, built, and tested the Bi-Directional DC Converter, controls and software. Hardware in the Loop (HIL) testing was performed with the Bi-Directional DC Converter, simulated solar array, charging load, stationary energy storage, and grid simulation at Oak Ridge National Lab.

Subtask 1.2.1 – CTS Requirements Design – Develop requirements based on solar, stationary energy storage, PEV charging and Grid Control Development.

Subtask 1.2.2 – Design - Detailed Bi-Directional Converter design will be conducted in this task. The detailed electrical and mechanical design will be finalized. Modeling will be performed and a detailed Bill of Material (BOM) will be generated. The system will be designed to meet CTS requirements and manufacturability and a detailed test plan will be developed.

Subtask 1.2.3 – SPIN POD Build – The parts will be ordered according to the BOM. Create manufacturing process plans, build parts and measure compliance to process plan.

Subtask 1.2.4 – Controls and Software – Converter (V2G, Solar, Charging) – Implement controls in unit and verify functionality.

Subtask 1.2.5 – SPIN POD Bench Testing - Perform unit electrical bench testing.

Task 1.3 – SPIN System Integration HIL

Perform Hardware in the Loop (HIL) testing with Bi-Directional DC Converter, simulated solar array, charging load, stationary energy storage, and grid simulation.

Task 1.4 – On-Vehicle V2G Technology Development, Deployment, and Test

This task is to create the end-to-end system with open standards communications and interfaces comprising an ISO simulator, DSO interface with a detailed distribution system model, aggregator, transformer monitor-integrated local controller, an EVSE and a V2G capable PHEV.

Subtask 1.4.1 - Integrate Open Standards Communications Interfaces Across the System.

Subtask 1.4.2 - Integrate the different algorithms to test grid services (DER, DR, Flow Reservation and Pricing).

Subtask 1.4.3 - Extend functionality of V2G capable PHEV to make its operation safe, with open standards interfaces, interoperable and outage-immune.

Subtask 1.4.4 - Develop and integrate open standards-based communications within the EVSE.

Subtask 1.4.5 - Develop DSO Interface, Distribution Circuit Model, Aggregator Control Algorithms and ISO Simulator.

Subtask 1.4.6 - Deployment, Test, Data Collection - test in stages the different algorithms and features developed in the development phase and collect data from the performance evaluation of distribution grid and ISO-aware V2G system.

Subtask 1.4.7 – Critical Project Reviews (2).

Task 1.5 – Critical Design Review

Review of HIL and Bi-Directional Converter Testing. Assess functional capability and determine the capability to proceed to characterization testing.

| Milestone | Type | Description |
|---|---|---|
| Use cases defined | Technical | Use cases are defined and prioritized. |
| Bi-directional converter design complete | Technical | The initial design for the bi-directional converter is completed. |
| SPIN build complete | Technical | SPIN assembled and is functional. |
| SPIN HIL testing complete | Technical | The Hardware in the Loop (HIL) testing is complete. |

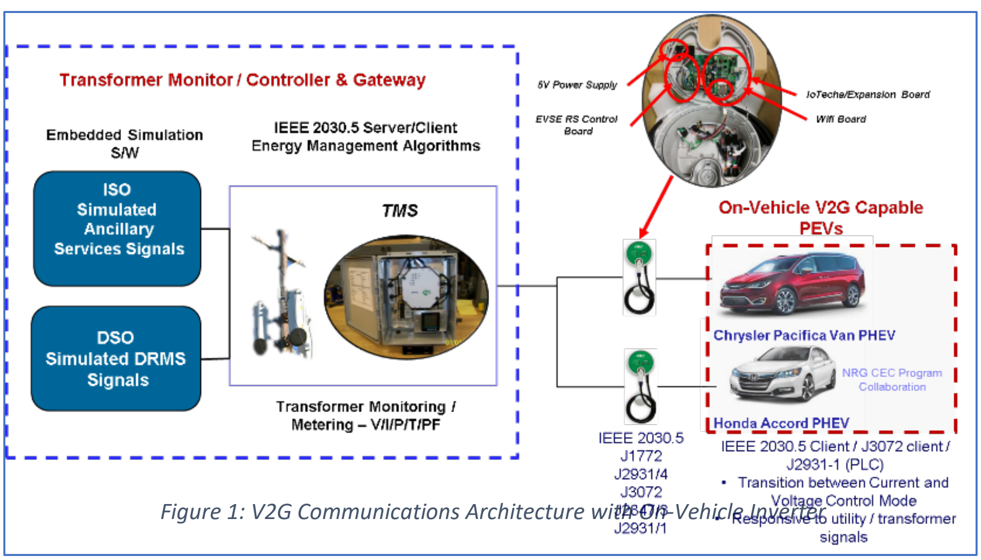



*Figure 1: V2G Communications Architecture with On-Vehicle Inverter*

| | | |
|---|---|---|
| Critical Design Review Complete | Go/No Go | The Critical Design Review confirms device meets requirements and can proceed. |

The following activities were carried out in Budget Period 1 against the tasks outlined above:

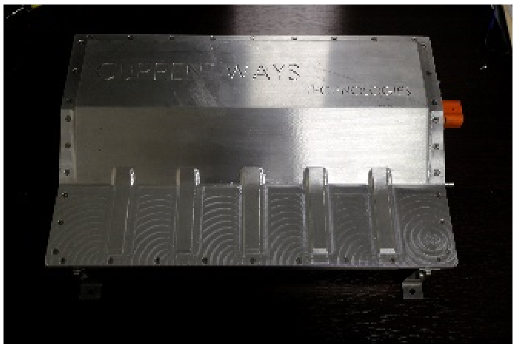



*Figure 2: On Board Charge Module Providing Bidirectional Power Conversion*

The project kick -off meeting was conducted 9 Nov 2016. The primary results achieved within BP1 were:

- Development of the V2G control algorithms and simulation test verification using an EV Emulator representing multiple V2G capable PEVs associated to a Transformer Management and Monitoring System within a residential application. Residential load and solar generation profile data used for the simulation testing is extrapolated from US Energy Information Administration data sources. The ISO and DSO signal simulators have been implemented into the simulation testing model for DR and DER functions and parameters.
- Development of the Smart Power Integrated Node (SPIN) system design architecture and Component Technical Specification
- Developing the SPIN master controller which integrates power electronics mode control functions for bi directional power flow management between DER assets (including PEV), the grid, and facility loads, Includes implementation of IEEE 2030.5 server /client software (DER and Demand Response Load Control (DRLC) function sets) for utility DSO /DRAMS interface and communications, meter telemetry for energy consumption and power flow data monitoring, and data analytics processing algorithms for energy utilization and cost optimization.
- Integrating the bidirectional on-board charge modules (OBCM) into the Chrysler Pacifica PHEV Vans. Four production vehicles provisioned for the project. The bidirectional OBCMs (Figure 2) will provide reverse power flow functionality with both AC charging (on-vehicle inverter) and DC charging (off-vehicle inverter). On-

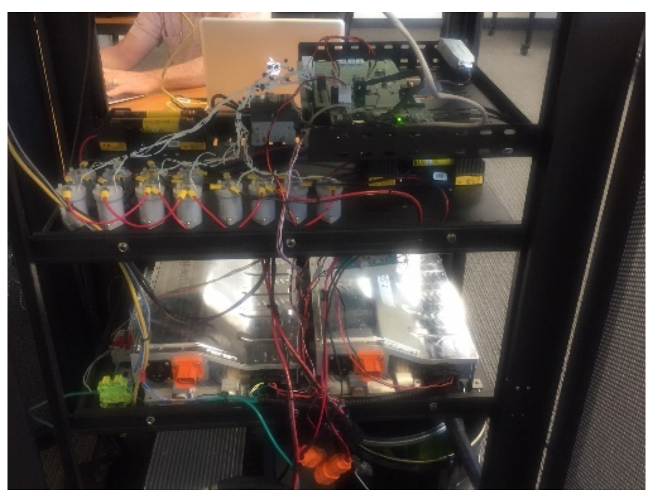


*Figure 3: SPIN Rack Mounted Unit for Power Controls and Analytics Algorithmic S/W Integration and Testing*

vehicle V2G communications module is undergoing development and implementation, providing IEEE 2030.5 smart inverter functional communications with DER and DRLC functionality, IEEE 2030.5 translation/interoperability with vehicle CAN protocol/communications., J2931/1 Power Line Communications implementation utilizing HomePlug GreenPhy chipset, and J3072 vehicle grid interconnected authentication and authorization standard.

- Assembled SPIN proof of concept rack system (Figure 3) with 2 6kW bidirectional converters (OBCMs), DC Switching, and battery simulator; and conducting integration with the master controller for multi-mode operational testing with power flow monitoring and configuration control, and implementation of data analytics algorithmic functionality for optimized DER/V2G energy management.
- Determined use case scenario for testing and data modeling: peak shaving for locational and wide area demand response, renewables or PV overgeneration mitigation in response to day ahead forecasts and response to observed grid conditions (volt/var); PV under generation ramping support in response to day ahead forecast and real-time response to latent grid conditions due to intermittent weather; ancillary services such as reg up/down; and cost optimization.

**BP1 Work Summary**

The primary conclusions to date are derived from the PEV V2G simulation testing wherein the PEV charge/discharge control algorithms are executing as planned. The basis for the control algorithms is the capability to manage the V2G cycles within the constraints provided by the EV driver for minimum SOC, max SOC, and time charge in needed. Figure 4 below is an example of graphic results of the V2G algorithms controlling charging and discharging of three vehicles in sync with solar generation profile. Additionally, with the application of real time data analytics, it is desired to verify the capability of the SPIN to configure the power flows of the DER assets with the grid to be able to comply with the requests by the utility and without inconvenience to the residential or facility owner. This coming year will provide the analysis and assessment of the cost benefit, distribution circuit impact, and deferred infrastructure upgrade costs.

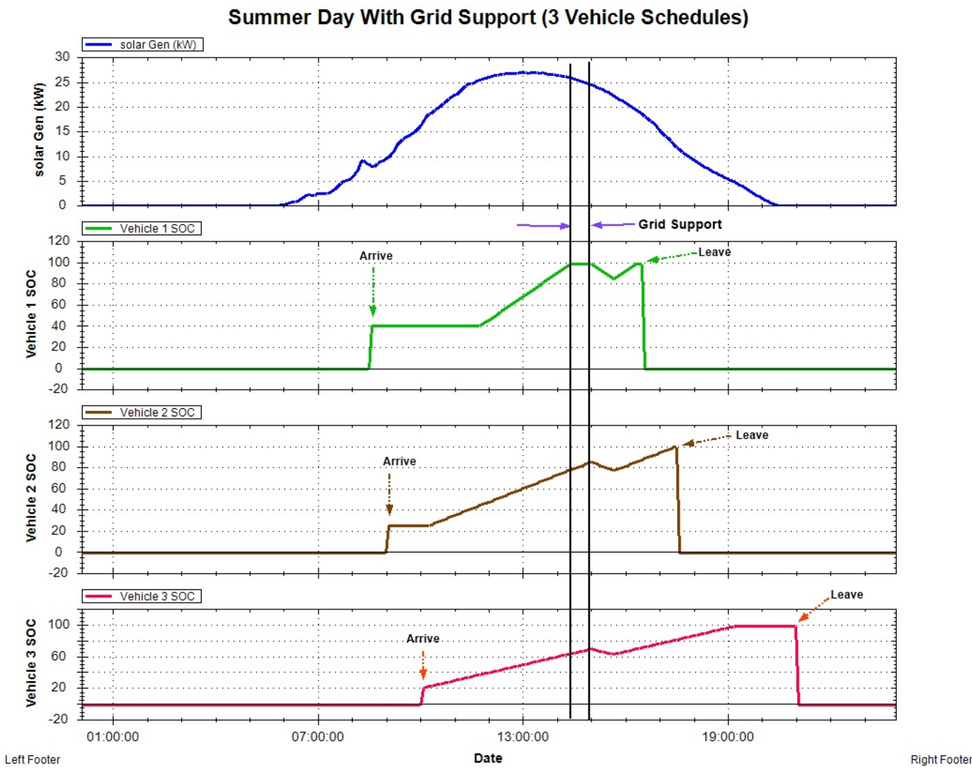



*Figure 4: Simulation Results of V2G (Charging/Discharging) Control with Solar Generation*

**Budget Period 2 Tasks per SOPO:**

**Budget Period 2 – Systems Integration, Test, and Evaluation:**

Task 2.0 - Integrate communications, vehicle charging, solar, and micro energy storage to test and evaluate functionality based on use cases defined in Budget Period 1.

The test station will be setup with appropriate loads, sources, and data acquisition. The node control and integration will be demonstrated with the grid and improvements will be made as necessary to the SPIN system and UL certification testing will be performed. The vehicles will be prepared with the appropriate upgrades for V2G functionality using on-board and off-board resources.

**Task 2.1 – System Lab Test Plan and Set Up**

The system test plan development was performed based on Grid Control Development requirements. The lab was prepared to execute the test plan.

In light of the plan to reuse the bidirectional converter hardware based on IGBTs from the on-vehicle V2G, the system functional testing and verification of the WBG (Wide BandGap) power electronics dual active bridge was nixed. The team felt (and the VTO management approved) that it was premature to work on power device swap when the basic system testing with IGBTs would yield more valuable results.

~~Task 2.2 – System Functional Testing and Verification~~

~~The SPIN functionality will be verified as prescribed by the CTS and STS. The system test plan development will be done based on Grid Control Development. The lab will be prepared to execute the test plan.~~

Task 2.3 was postponed at a later stage since the SPIN construction was not yet completed. Instead, much of the effort focused on system integration related software development.

~~Task 2.3 – Use Case Communications and Controls/Duty Cycle Testing~~

~~Characterization testing of SPIN system according to the test plan will be performed. The SPIN system includes micro stationary energy storage that will be evaluated for the impact of utilizing for grid services. Assessments on SPIN performance against the projected performance will be made.~~

**Task 2.4 – Converter Enhancements**

Software and hardware improvements based on test results was incorporated as appropriate. ~~to prepare for UL testing.~~

~~Task 2.5 – V2G Distributed Energy Resources (DER) Integration Testing and Evaluation~~

~~Evaluation of the V2G with the SPIN system according to defined grid services based on Grid Control Development will be performed.~~

**Task 2.6 – Performance Analysis/Test Report**

An analysis of characterization testing was performed, and a report was completed.

~~Task 2.7 – Battery Pack Durability Characterization and Test Report~~

~~An assessment and evaluation of the impact by grid services will be performed. Energy storage will be evaluated before and after the testing.~~

**Task 2.8 – V2G Economic Evaluation**

An economic analysis was performed to determine the value and cost of providing grid services.

Task 2.9 – OEM Vehicle V2G Communications Implementation and Verification

Vehicle modifications were performed as necessary for implementation of V2G communications.

Subtask 2.9.1 – The communication standards were implemented.

Subtask 2.9.2 – Communications and interface testing was performed.

Given the prototype nature of the system, UL testing was considered premature and was nixed, with VTO manager approval.

~~Task 2.10 – SPIN UL Certification Units Build and Test~~

~~The SPIN units will be built and tested to achieve UL certification~~.

**Task 2.11 – On-Vehicle V2G Technology Value/Benefits Assessment and Evaluation**
Tasks were to develop valuation models for storage to include V2G functions, determine distribution avoided cost model using detailed circuit analysis, and assess value of distribution services provided by V2G type system; and to provide transfer of technology learnings and knowledge.

Subtask 2.11.1 - Assessed Incremental Value from V2G Services.
Subtask 2.11.2 - Evaluated Project Benefits - Provided all key assumptions used to estimate projected benefits, including targeted market sector (e.g., population and geographic location), projected market penetration, baseline and projected energy use and cost, operating conditions, and emission reduction calculations.
Subtask 2.11.3 - Technology/Knowledge Transfer Activities - develop a plan to make the knowledge gained, experimental results, and lessons learned available to the public and key decision makers.
Subtask 2.11.4 – Final Report (On-Vehicle V2G Technology Project Summary Report).

Task 2.12 – System Lab Test Plan and Set Up (Go/No Go Milestone)

Characterization test verified SPIN POD system was transitioned to ORNL. The system test plan development was based on Grid Control Development requirements. The ORNL lab was prepared to execute the test plan.

| Milestone | Type | Description |
|---|---|---|
| Test plan complete | Technical | The system test plan is completed and ready. |
| SPIN performance analysis complete | Technical | Analysis of power management characterization testing complete. |
| ~~Vehicle communications implemented~~ | ~~Technical~~ | ~~The SAE communication protocols are implemented.~~ |
| Economic evaluation complete | Technical | Economic analysis completed. |
| ~~SPIN certification achieved~~<br>System Lab Test Plan and Set Up | ~~Go/No Go~~<br>Go/No Go | ~~The SPIN unit is tested and achieves the UL certification.~~<br>Development of the Test Plan – transition of upgraded SPIN rack system to ORNL and lab set up. |

The following was accomplished through the activities in Budget Period 2:

## Results

Completed the implementation and site demonstration of the AC On-Vehicle V2G end to end communications and control technology. Four vehicles (1 Honda Accord PHEV / 3 Chrysler Pacifica Van PHEVs) were upgraded with on-vehicle bi-directional charging inverters (Figure 6) and EV Communications Controllers (EVCC) (Figure 5) incorporating J3072 and IEEE 2030.5 Distributed Energy Resource (DER) and Demand Response Level Control (DRLC) function sets and communications protocols, and J2931/4 Power Line Communications (PLC) utilizing the HomePlug GreenPhy chipset. Included interoperability for CAN communications to the vehicle control module. The Honda Accord PHEV EVCC was developed separately from the Chrysler Pacifica Van EVCC by the University of Delaware. The Electric Vehicle Supply Equipment (EVSE) utilized was the AeroVironment Level 2 AC Charger modified with an IoTecha MEVSE communications module incorporating the HomePlug GreenPhy PLC chipset and the IEEE 2030.5 bridge communications to the EVCC incorporated into the PHEVs. Four of the AV modified EVSEs were installed at the University California San Diego (UCSD) parking lot demonstration site (Figure 7). The site was modified (Figure 9) to provide four modified EVSEs, 75KVA transformer, 400A panel, and 12kW solar conductor from co-located solar panel structure. The primary site controller was the Transformer Management and Monitoring System (TMS) (Figure 8) developed by the Electric Power Research Institute. The TMS contains the V2G control algorithms, metering/measurement devices, and provided the network interface communications for processing of the DSO/ISO simulated commands / requests. The basis for the control algorithms is the capability to manage the V2G cycles within the constraints provided by the EV driver for minimum SOC, max SOC, and time charge in needed. The TMS controls are incorporated using the IEEE 2030.5 server protocol for the Distributed Energy

*Figure 7: EV Communications Controller (EVCC) Chrysler Pacifica Van PHEV*

*Figure 5: Bi-directional Charging Inverter Installed into Chrysler Pacifica Van PHEVs*

*Figure 6: UCSD Parking Lot Demonstration Site and Chrysler Pacifica Van PHEV and Honda Accord PHEV*

Resource (DER) and Demand Response Level Control (DRLC functions with communications to the PHEVs through the EVSE PLC bridge. The site demonstration and testing was conducted over a four week period during the months of May and June 2018. The TMS managed and operated the PHEV charging and discharging controls associated to an aggregated residential transformer application. The residential load and solar profiles utilized for defining solar generation and residential load constraints/conditions were extrapolated from US Energy Information Administration data sources. The control schemes and algorithm validation use cases addressed four areas: Peak Shaving, Over-generation Mitigation, Ramping Power support, and Ancillary Services.

*Figure 8: Transformer Management and Monitoring System (TMS)*

The DC V2G off-vehicle inverter technology application was addressed through the development of the Smart Power Integrated Node (SPIN). The SPIN integrates power electronics mode control functions for bi directional power flow management between DER assets (including PEV DC Charging), the grid, and facility loads. Includes the implementation of the IEEE 2030.5 server /client software (DER and Demand Response Load Control (DRLC) function sets) for utility DSO interface and communications, meter telemetry for energy consumption and power flow data monitoring, and data analytics processing algorithms for energy utilization and cost optimization.

*Figure 9: Demonstration Site Charging Island(4 EVSEs, 75KVA Transformer, 400A Panel, Transformer Management System*

The SPIN proof of concept rack system (Figure 10) consisted of two 5kW bidirectional converters (OBCMs), DC Switching, DC Charging Communications Control Module (CCM), and metering/measurement telemetry that is centrally integrated and controlled through the SPIN Unit Master Controller. The SPIN Unit Master Controller integrates the power electronics controls software, multi operational power configuration controls, and algorithmic functionality for DER/V2G energy management. The SPIN System includes a cloud server providing data analytics and DER optimized utilization strategies based on real time data from the SPIN Unit Master Controller about the local node load (residence/facility) conditions and status of the DER devices, including the EV SOC status and customer charging preferences or constraints. The server merges external data such as weather conditions affecting solar generation, electricity pricing tariffs, etc., and calculates an optimization strategy to maximize energy efficiency or mitigate cost. The primary objective is the functional verification of the SPIN capability to provide DC Charging hardware connectivity to the EV, to integrate the communications and control software requirements for DC charging and discharging, and to manage DC V2G as a local DER asset to support grid reliability.

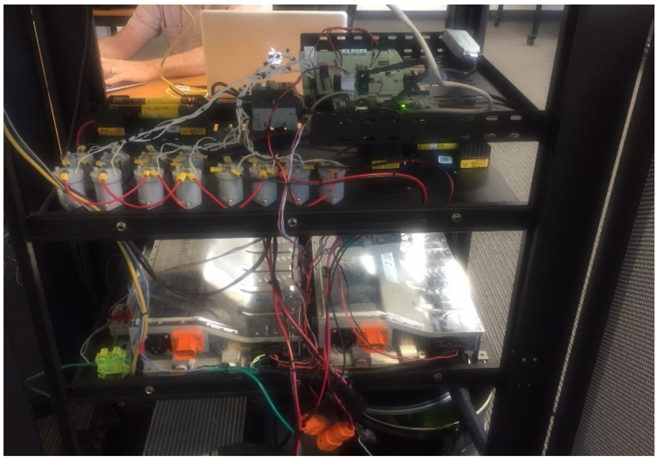


*Figure 10: SPIN Rack Mounted Unit for Power Controls and Analytics Algorithmic S/W Integration and Testing*

Software architecture is developed specifying the development and implementation requirements for the Utility DSO interface communications (OpenADR and IEEE2030.5), SPIN DC charging/discharging communications (J1772, DIN70121, J2847/2, J2847/3), SPIN to EV V2G communications (IEEE2030.5), and application of Rule 21 Common Smart Inverter Profile (CSIP) communications protocol. Developed board specifications for the Supply Equipment Communications Controller (SECC) and the Electric Vehicle Communications Controller (EVCC) which include the Power Line Communications (J2931/1) functionality.

Fiat Chrysler Automobile (STELLANTIS) initiated the modifications of a Chrysler Pacifica Van PHEV to incorporate DC bi-directional charging functionality, DC control protocols, and V2G EVCC module adaptable for DC off-vehicle inverter application.

Developing emulator for simulation and verification testing of the SPIN Unit Master Controller software controls for integrating and managing the utilization of solar, battery energy storage, and EV DC charging/discharging. Determined use case scenario for testing and data modeling are peak shaving for locational and wide area demand response, renewables over/under generation ramping mitigation/offset in response to day-ahead forecasts and real-time response to latent grid conditions due to intermittent weather; ancillary services such as reg up/down; and cost optimization.

**Findings During Budget Period 2:**

Preliminary conclusions based on the resulting evaluations of the AC On-Vehicle V2G implementation and demonstration are:

- Requirement for utility adoption of J3072

  A significant barrier to the commercialization of the electric vehicle onboard V2G technology is the adoption of the SAE J3072 standard to enable automaker self-certification of onboard inverters to be CPUC Rule 21 compliant per IEEE 1547. Recommendation is that compliance can be achieved through electric vehicle compatibility certification with UL marked bi-directional AC EVSEs. The site permit for grid interconnection will be based on the UL listing of the EVSE to be certified for bi-directional power flow. J3072 authenticates the electric vehicle inverter model has been certified to be compatible with the UL listed EVSE. Note that DC V2G does not require utilization of the J3072 protocol. The inverter is located off-vehicle in the DC Charger which would be permitted as a fixed site grid interconnected electronic device.

- Effective for residential transformer and community aggregation application

The Transformer Management System monitoring and control strategy enables improved situational awareness for the utility to manage distribution reliability, and the ability to integrate electric vehicle managed charging for aggregation at the residential transformer and community sub feeder levels. The SPIN System would support residential transformer and community aggregation through utilization of the cloud analytics and optimization functionality. SPIN units will be enables to interface with aggregation control entities or systems either directly or through the cloud server.

- Local site electrical integration evaluation required to identify transients affects

During the UCSD site demonstration experienced circuit voltage and frequency anomalies that affected the continuity of communications between the TMS and the electric vehicles. The electric vehicle onboard charge modules were recording error faults and going to sleep due to frequency

*Table 1 Summary of Objectives, Accomplishments, Learnings and Future Scope for On-Vehicle V2G Development*

| Objectives | Accomplishments | Learnings | Gaps to Scale Implementation |
|---|---|---|---|
| **Develop and implement end to end open standards-based V2G communications system** | Validated end to end interoperability and application of V2G SAE and IEEE 2030.5 standards | J3072 requirement for utility adoption – compatibility certification with UL marked bi directional AC EVSE | Defined SAE J3072 Interoperability Certification body requirements and harmonized UL/SAE labeling |
| **Implement dynamic V2G management use cases** | TMS automated energy management capability implemented – supports interaction with DSO / ISO grid service requests | Effective for residential Transformer energy monitoring for constraints due to load and stress conditions – community aggregation application | Transformer Management System software can be integrated at any edge of the grid node – transformer, DMS, DERMS or Facility EMS |
| **Data collection and performance analysis** | Simulated data verifies algorithmic functionality – Demo data collection ongoing | Local site electrical integration evaluation required to identify transients affects – further research required | Implement more powerful 'edge of the grid' computing tech |
| **Assess cost/benefit – customer, utility, and societal perspectives** | Positive value proposition for EV owners (5X V1G) | The preliminary assessment makes for a strong case for creating incentive structures for V2G | Define, verify and validate through customer participation incentive mechanisms that are viable and acceptable to customers to maximize participation, along with cost analysis for additional hardware on vehicles |
| **Define and implement on-vehicle V2G converter and integrate with grid power and communication systems** | Integrated grid-tied bidirectional charger and J3072 client control module with on-vehicle battery and controller | System integration revealed grid interaction both in terms of compatibility, interconnection requirements and a need to define clearer electrical integration standards | Define electrical grid integration and compatibility requirements for on-vehicle inverters (or align them with the smart inverter requirements), including testing and interoperability protocols. |

and voltage spikes. Preliminary voltage and frequency measurements could not provide any conclusive information to the fault investigation.

- The preliminary value assessment provides strong case for creating incentive structures for V2G

The value and cost benefit assessment and modeling analysis show a cumulative maximum benefit of V2G to the grid (net of cost increment) to be between $450/year per vehicle to

$1850/year/vehicle. This effectively is approximately 5 times the value of V1G for similar grid service applications. The Figure 11 and Figure 12 summarize these findings:

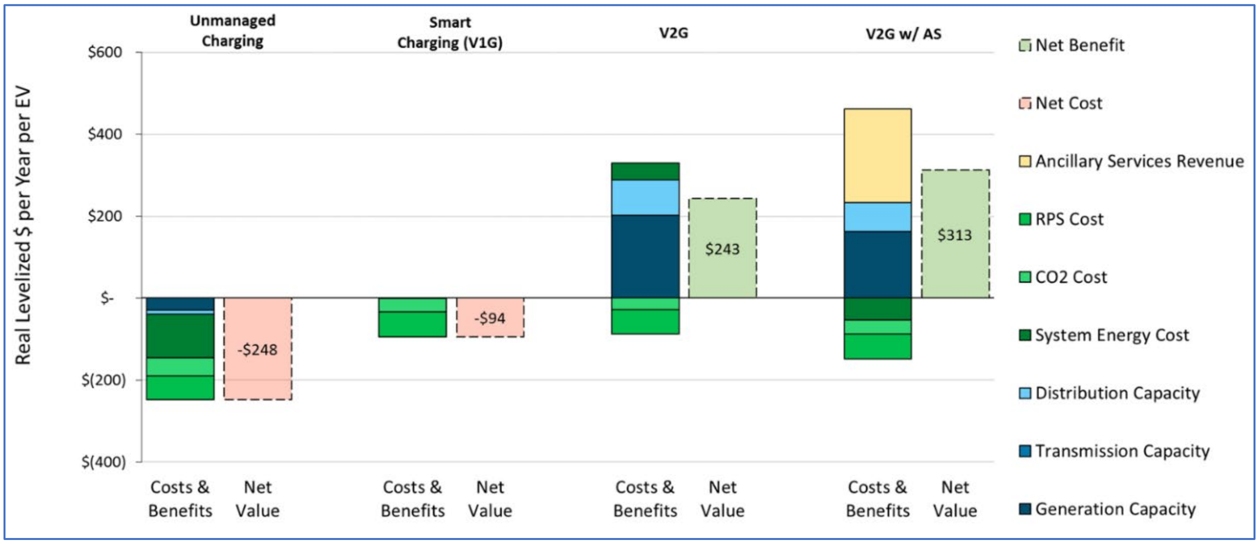



*Figure 11 Levelized Costs and Benefits, Base Case, Managed Charging and V2G with Ancillary Services, Constrained Battery Energy*

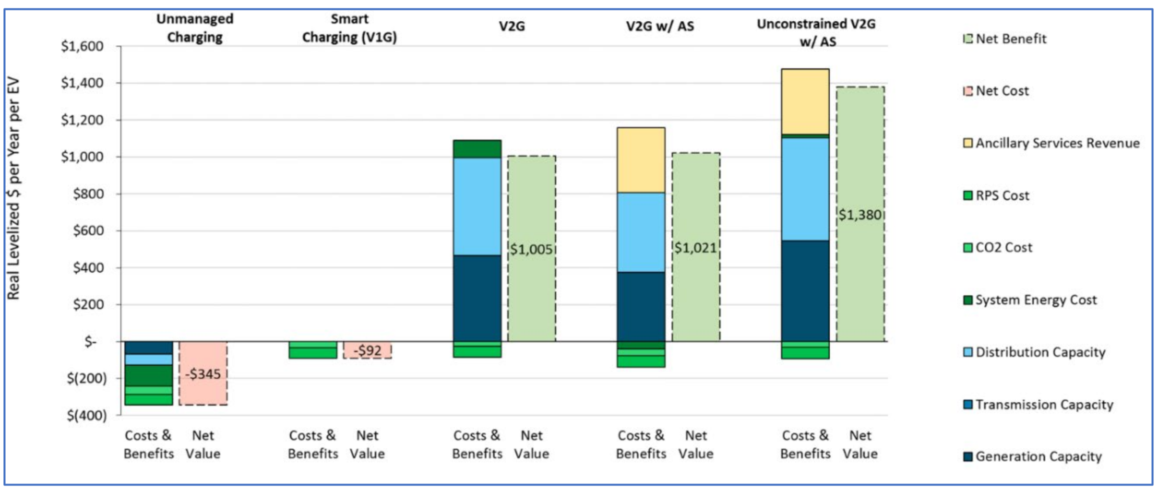



*Figure 12 Levelized Costs and Benefits, Base Case, Managed Charging, and V2G with Ancillary Services, Unconstrained Battery Energy*

And the following tables summarize these findings numerically:

*Table 2 Valuation Range of V2G Services Based on Ancillary Services and Battery Throughput Constraints*

| | | Net Grid Value | Battery Use |
|---|---|---|---|

| Case | Dispatch | Un-managed | V1G | V2G | Battery cycles | Discharge Energy (kWh) |
|---|---|---|---|---|---|---|
| Unconstrained High Value V2G | Utility | ($345) | ($92) | $1,380 | 251 | 15,051 |
| High Value V2G | Utility | ($345) | ($92) | $1,021 | 164 | 10,225 |
| High Value V2G w/o AS | Utility | ($345) | ($92) | $1,005 | 133 | 7,969 |
| Base V2G Case | Utility | ($248) | ($94) | $313 | 158 | 9,454 |
| Base V2G Case w/o AS | Utility | ($248) | ($94) | $243 | 105 | 6,322 |
| Base V2G Bill Optimized Case | Customer | ($248) | ($278) | $105 | 155 | 9,325 |

The impact of each strategy on the battery kWh throughput is important to understand, considering the battery testing data that is shown in the testing phase of the budget period. The EV considered here for modeling was a Chevy Bolt EV with a baseline 60kWh pack, with about 50% of it available for cycling in a value-optimized manner.

*Table 3 Incremental Benefit Summary for V2G Services*

| | | Incremental Benefit | |
|---|---|---|---|
| **Case** | **Dispatch** | **V1G v Unmanaged** | **V2G v V1G** |
| Unconstrained High Value V2G | Utility | $253 | $1,472 |
| High Value V2G | Utility | $253 | $1,113 |
| High Value V2G w/o AS | Utility | $253 | $1,097 |
| Base V2G Case | Utility | $154 | $407 |
| Base V2G Case w/o AS | Utility | $154 | $337 |
| Base V2G Bill Optimized Case | Customer | ($30) | $383 |

**Budget Period 3 Tasks and the Work Performed:**

The following tasks were allocated to Budget Period 3, which, due to COVID19 delays, got extended by about 12 months. However, the end results at the end of Budget Period 3 exceeded the expectations set by the team at the beginning, in a number of ways, as discussed below:

The tasks outlined for Budget Period 3 included the following:

**Task 3.0 - The lab demonstration** will be prepared and implemented to collect and analyze data for review. The data will be compared and analyzed for inclusion in a report.

~~Task 3.1 – Lab Site Demonstration Logistics Planning and Installation~~

~~The SPIN System will be installed in the lab location. The SPIN functionality will be verified as prescribed by the CTS and STS. The system test plan development will be done based on Grid Control Development. The test vehicle will be prepared and deployed for the demonstration.~~

**Task 3.1 – V2G Distributed Energy Resource (DER) Integration Testing and Evaluation**

Implement DC Control Communications Module (CCM) charging connectivity (SAEJ1772) and control communications (DIN 70121 / SAE J2847-2 / J2931-4). Perform system integration testing.

**Task 3.2 – OEM Vehicle DC V2G Communications Implementation and Verification**

DC V2G communications module integration into STELLANTIS Pacifica Van PHEV and interoperability testing with SPIN to Vehicle communications protocols/software (IEEE2030.5/SAE J2948-3).

**Task 3.3 – Preliminary OEM Vehicle and SPIN Communications Interface and Control Simulation Verification**

The communications of the vehicle and SPIN system will be verified and the functionality of communications to enable V2G and grid services will be demonstrated.

**Task 3.4 – Use Case Communications and Control/Duty Cycle Testing**

V2G/DER control integration and functional verification testing with V2G capable SPIN POD rack system and STELLANTIS V2G capable PHEV. VerifyV2G use case functional performance.

**Task 3.5 – Conduct V2G Lab Demonstration**

Perform  demonstration and support as needed.

**Task 3.6 – Progress Review of Demonstration**

Review demonstration data and determine if any modifications need to be made. Update system/component technical specifications and requirements documentation based on learning from testing and analysis results.

**Task 3.7 – Battery Pack Durability Characterization and Test Report**

An assessment and evaluation of the impact by grid services will be performed.  Energy storage will be evaluated before and after the testing.

**Task 3.8 – Data Collection and Analysis**

Collect test data and confirm proper type and format.  The data will be collected and analyzed to evaluate the functional performance, and usage characteristics of the vehicle to grid technology.

**Task 3.9 – Demonstration Report**

A report will be generated covering the demonstration, characterization testing, and review information from outside the project to correlate with project generated data.  An evaluation of the functional performance, and usage of vehicle to grid technology will be performed.

| Milestone | Type | Description |
|---|---|---|
| ~~Lab Site Demonstration installations complete~~ | ~~Technical~~ | ~~The demonstration site logistics, planning, and installation completed.~~ |
| V2G Lab demonstration initiated | Technical | V2G demonstration underway and functioning properly. |
| Demonstration period completed | Technical | Data collection phase is completed for the demonstration. |

| | | |
|---|---|---|
| Demonstration report complete | Technical | The technical report on the demonstration is completed. |
| Battery Pack Durability Characterization and Test Report | Technical | Characterization and Test Report Completed. |

## Results

*Hardware Development / Readiness / Acceptance Testing*

SPIN rack hardware, after delays in the component supplier deliveries, was finally assembled, tested and delivered to ORNL NTRC in December 2018. Following Figure 13 shows the hardware


Figure 13: NTRC Lab Equipment Set Up with SPIN Rack System

and test setup that was utilized to do power mode testing for all the SPIN operating modes. SPIN rack is on the right half inside the yellow oval. This was after the supplier completed the upgrade of the SPIN Proof of Concept Rack System to the latest Version 5 OBCMs (On Board Charge Module). Upgrade was necessary to resolve reliability and software issues with the original Version 3 OBCMs. The upgraded SPIN Rack System was then transitioned to Oak Ridge National Laboratory (ORNL) National Research Technical Center (NRTC) for continued DER/V2G functional integration and testing. The supplier also completed production and shipment of one spare set of OBCMs (2 Each). These units were tested within the SPIN rack system prior to shipment.

*Summary of Testing Results:*

- *Ran all DC Switching modes to full power (AC-DC, DC-AC) – demonstrated 11kW with both OBCs operating*

- *Temperature faults on DC Switch transitions is a known issue - automatically cleared with applied reset/restart software patch*
- *Switching mode 9 (reduce RESS charging/discharging) not functional due to unknown software supplier issue – FPC work around - will not limit SPIN operation*

Following *Figure 14 Power Analyzer Test Trace Showing Sequential Execution of All of the SPIN Operating Modes (Source: ORNL NTRC)* shows the results of the testing across multiple modes and

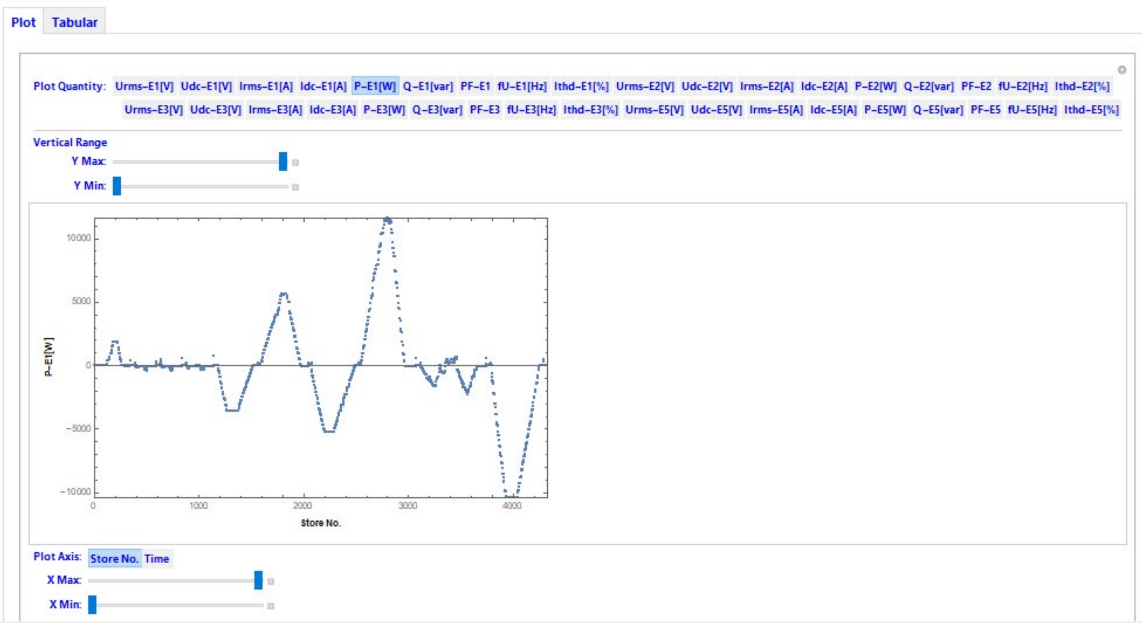



Figure 14 Power Analyzer Test Trace Showing Sequential Execution of All of the SPIN Operating Modes (Source: ORNL NTRC)

transitions through power analyzer test data trace.

*DC Convenience Charge Module*

DC Convenience Charge Module (CCM), as seen in *Figure 15*is the key component of a DC V2G

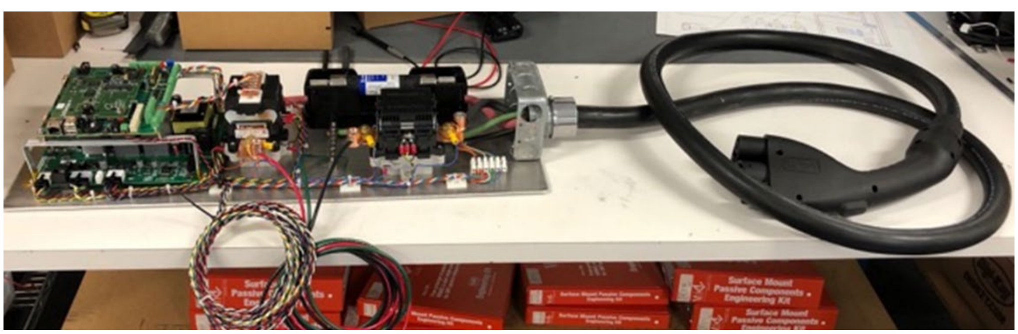


Figure 15: SPIN DC Communications Control Module (CCM) with J1772 Combo Coupler Assembly

system and essentially functions as a DC charger (AC/DC rectifier) with bidirectional power flow capability (Essentially capable of acting as a four-quadrant smart inverter, through its Dual-Active Bridge (DAB) topology). DC CCM is coupled with the DC-connected DERs (EV, PV, storage) powered by SPIN through the switching matrix also via the same DC bus. CCM specification was created and provided to the supplier. The supplier then delivered the hardware and control electronics as seen in *Figure 15*. The CCM connects to the vehicle through CCS (Combo) charging connector. The hardware and firmware allowing the bidirectional power capability was delivered and tested to be functional. This will be part of a setup that will be tested at ORNL NTRC as an integrated system.

*On-Vehicle Hardware Modifications:*
On Chrysler Pacifica PHEVs, the only modification that is being done (as compared to on-vehicle V2G project), is replacing the on-vehicle V2G power electronics (bidirectional inverter)


Figure 16 IoTecha EVCC and SECC Card Facilitates SPIN to PHEV DC Charging Communications (Source: IoTecha, Inc)

with a new V2G communications controller, from IoTecha (EV Communications Controller or EVCC, *Figure 16*). This includes an STMicroelectronics PLC link to facilitate the physical layer for SPIN – EV communications. The firmware includes an implementation of DIN 70121 specification that allows the DC charging messaging communications per SAE J2847/2 between SPIN and Pacifica PHEV, with an on-vehicle CAN link connecting the EVCC to the vehicle BMS (battery management system). Figure 4 shows a picture of the IoTecha control card (EVCC and SECC (Supply Equipment Communications Controller) are physically almost identical).

*SPIN System Hardware Layout in Productized Concept:*
Flex Power Controls-led team won yet another DoE SETO award (DE-EE-0008352) to productize the SPIN technology, under FOA 1740. This project is underway currently and will embody all of the learnings from the various contributing projects to-date, to create an integrated DC-coupled multi-port DER ecosystem that is grid-interactive and resiliency-enabling, replete with the necessary customer interface, open standards-based communications and an ability to operate standalone or in a legacy environment with existing smart inverters with PV and storage while allowing EVs to provide V2G services. *Figure 17* below shows a conceptual layout of this integrated SPIN system.

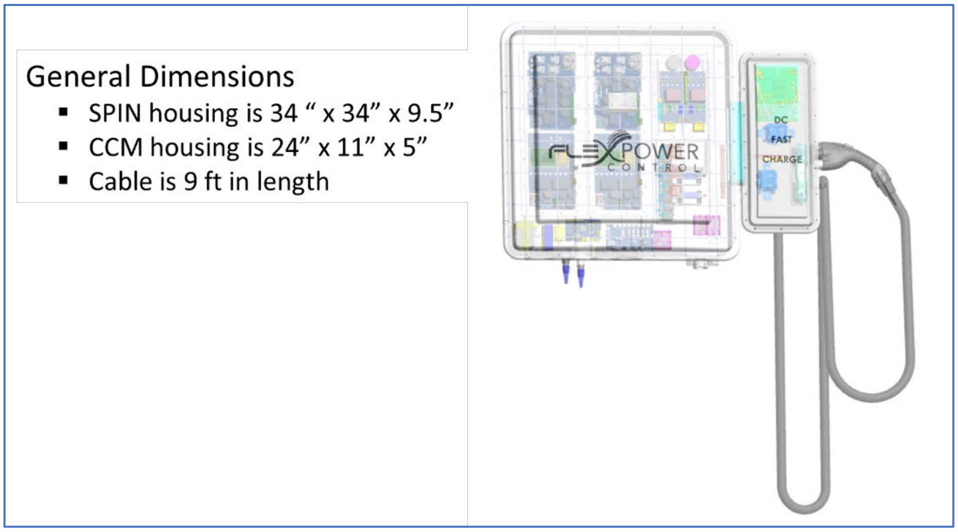



Figure 17 SPIN Product Concept 3D-Layout including DC CCM and Charging Cable

*SPIN System Software: Use Cases, Architecture, Design:*

Through a companion CEC project, the team is implementing applying SPIN module to three distinct scenarios:

1. Standalone, managing residential DERs including V2G capable EV
2. In a grid-interactive building environment, interfacing with the Building Management System (in this case, the BMS resides inside the SPIN itself),
3. In a microgrid interfacing with the DERMS and integrating V2G capable EV.

SPIN also has external interfaces to interact with the grid directly in response to grid signals, as communicated by the DSO (Distribution System Operator) over IEEE2030.5 and to its own

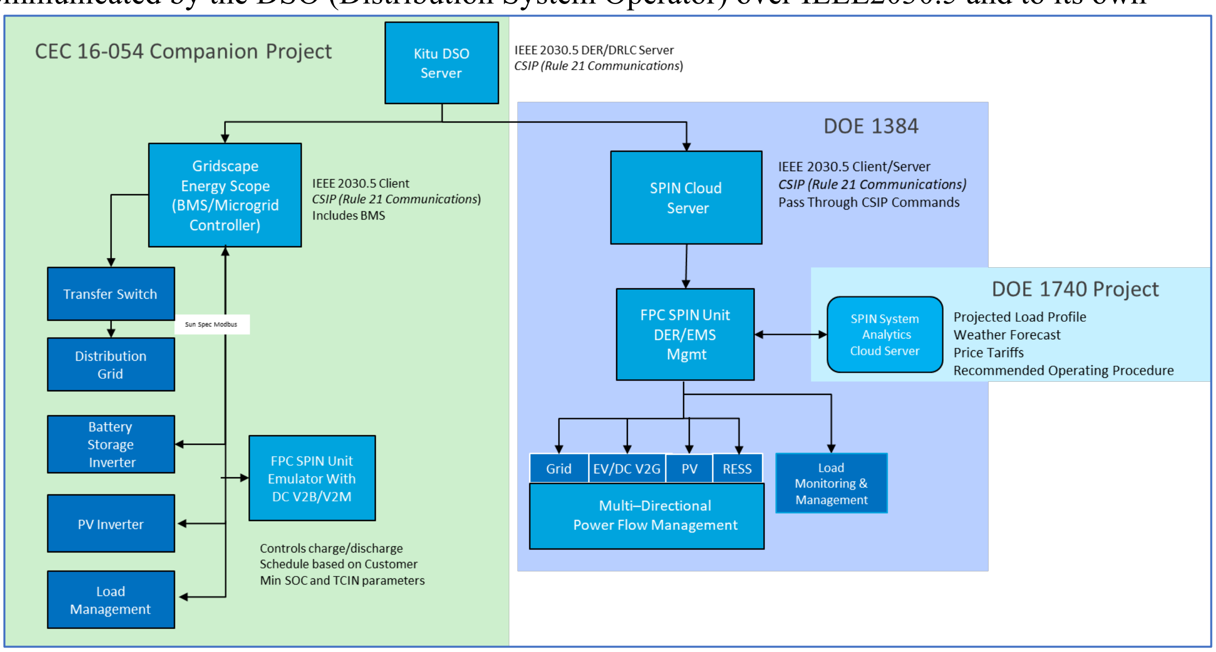



Figure 18 SPIN Application Scenarios being Designed for Verification

proprietary backhaul in the cloud to perform analytics and forecasting functions to enable predictive control algorithms. Figure 18 shows these scenarios in more detail

***System Integration and Testing***

The project team performed system testing in four different phases:

1. Communications system integration to verify and validate end-to-end software verification with simulated physical system responses.
2. Component hardware and embedded software integration testing of reverse power flow functionality—first with the SPIN rack system (proof of concept) at ORNL's NTRC, and then, the fully integrated, design-intent system built at Rhombus Energy Solutions in San Diego, CA.
3. Pairwise integration of vehicle/DC charger/SPIN emulator and DC charger/vehicle emulator to verify EV/SPIN integration functionality while SPIN DC CCS-based V2G system was being developed. This work was performed
    a. At Palo Alto, CA, at EPRI, to verify control system bench including communications protocol integration
    b. At Auburn Hills, MI, at Stellantis Technical Center for EV-charging system integration
    c. At San Diego, CA, at Rhombus Energy Solutions location for SPIN-DSO integration
4. Physical system integration with actual vehicle and SPIN in the same location.

### Communications System Integration

The communications signaling architecture shows three primary actors participating in the process:

1. The IEEE 2030.5 server, residing either at the DSO or at the microgrid controller site
2. SPIN module, which contains IEEE 2030.5 client, SPIN master controller software, and charging process management (DIN 70121)
3. On-vehicle electric vehicle communications controller (EVCC) communicates with SPIN for V2G messages and incorporates IEEE 2030.5 client to enable grid signal decoding/encoding. The EVCC communicates with the SPIN over HPGP (a type of powerline communications) and the Controller Area Network (CAN) bus vehicle. The EVCC also carries the software that accomplishes the HPGP to CAN message translation. Figure 19shows the various components of the control and communication signaling architecture, both inside and external to the SPIN, including the DSO and EV.

The first tasks for integration testing, therefore, were to1) implement the software on the SPIN

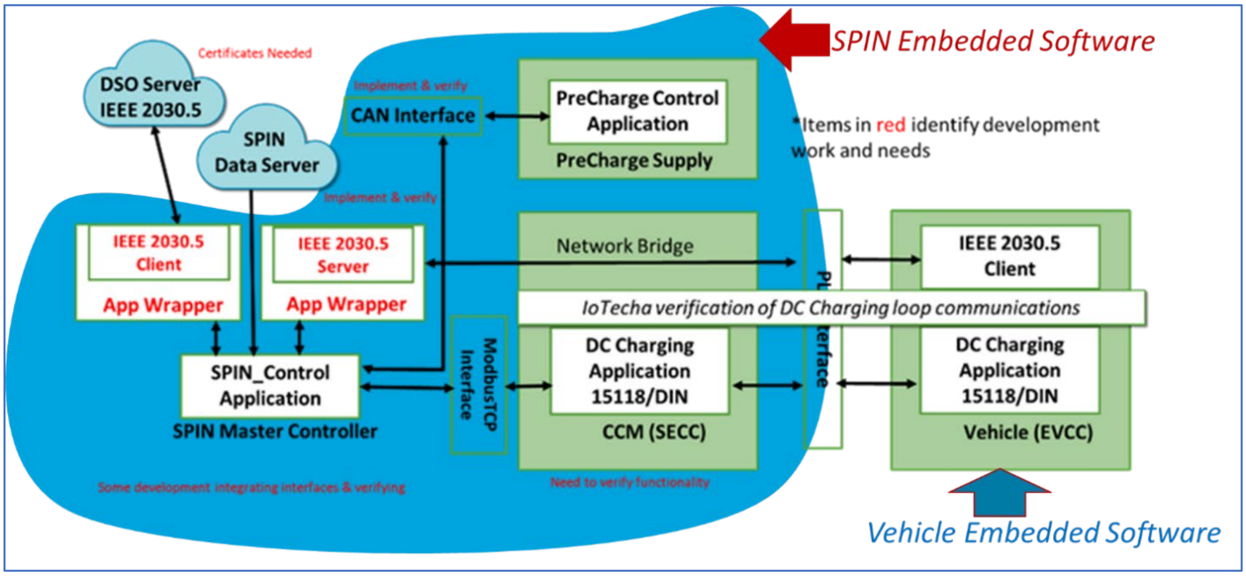



*Figure 19 SPIN V2G Control and Communication Signaling Architecture*

and the EVCC and 2) set up a DSO server instance for IEEE 2030.5 to simulate the interaction between the DSO or the microgrid controller (FEMS) and the SPIN, the DSO and the EV, and the SPIN and the EV. Two sets of functionality were verified: accurate interpretation of the signals and the logic (algorithm) that implements IEEE 2030.5 and DIN 70121 sequence diagrams. To facilitate this, EPRI, Stellantis, and Flex Power Controls engineers set up virtual benches that were identical but ran different integration tests to compare the software implementation for the three actors identified earlier. This same software code base was then embedded into the EVCC and SECC boards and the SPIN master controller.

The next task was to implement SPIN master controller software that managed the SPIN internal


*Figure 21 SPIN System Outside View with CCS Cable*

power flow routing based on the external and internal conditions. The Flex Power Controls team

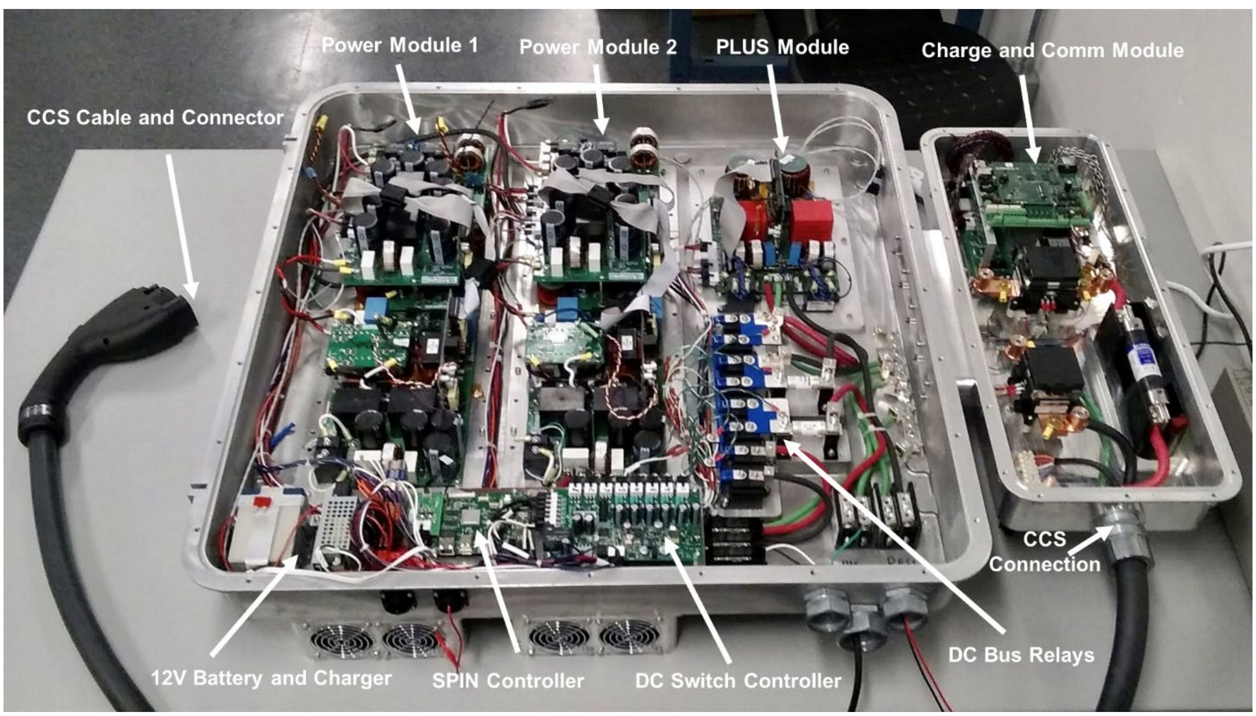



*Figure 20 SPIN System Internal View Showing PV, Storage, and EV Charging Interface, DC Convenience Charge Module, and Control as well as Power Routing Componentry*

spent considerable time and effort integrating the SPIN master controller with an external IEEE 2030.5 server by embedding a matching IEEE 2030.5 client so that the SPIN appears as a smart inverter to an aggregator or a DERMS. Next, SPIN master controller to SECC messaging was implemented through MODBUS TCP protocol. (SECC is the SPIN-resident HPGP board used to implement the DIN specification.) Figure 21 and Figure 20 show the fully integrated SPIN system, both external and internal views.

Lastly, Stellantis engineers worked to implement the revised DIN protocol which would implement reverse power flow over the CCS combo coupler for the DC EVSE (SPIN). The integration verification was done using a local DC unidirectional charger, just so that the DIN implementation on the EVCC is verified. Once this was successfully verified, the next step was to bring all system parts together in the same location so vehicle – SPIN integrated system testing could be performed.

## System Integration and Testing Including Standards Verification

The following three pictures define the entire sequence diagram that is implemented across the major actors during a charging process: the EVSE (J1772), MEVSE, EVCC, and the driver. The driver inserts the charge coupler into the vehicle receptacle. This initiates the electrical circuit integrity verification process, as shown in Figure 22

The process begins with the EV being in a standby state when the charge cable is disconnected. When the cable is connected, through a sequence of tests, the mechanical socket is locked at the charging interface on the vehicle. This allows the charge coupler to be mechanically locked during the charging process. The EV also "associates" itself with the EVSE that it is connected to, so that the communication integrity is maintained.
In the second step, a series of tests verify that the conditions to establish a complete and safe electrical connection exist between the EV and the EVSE. During this process the SPIN bias power supply powers the on-vehicle precharge circuit that establishes the DC bus voltage on the vehicle power electronics side. This process is depicted in the sequence diagrams shown in Figure 22., Figure 23, and Figure 24.

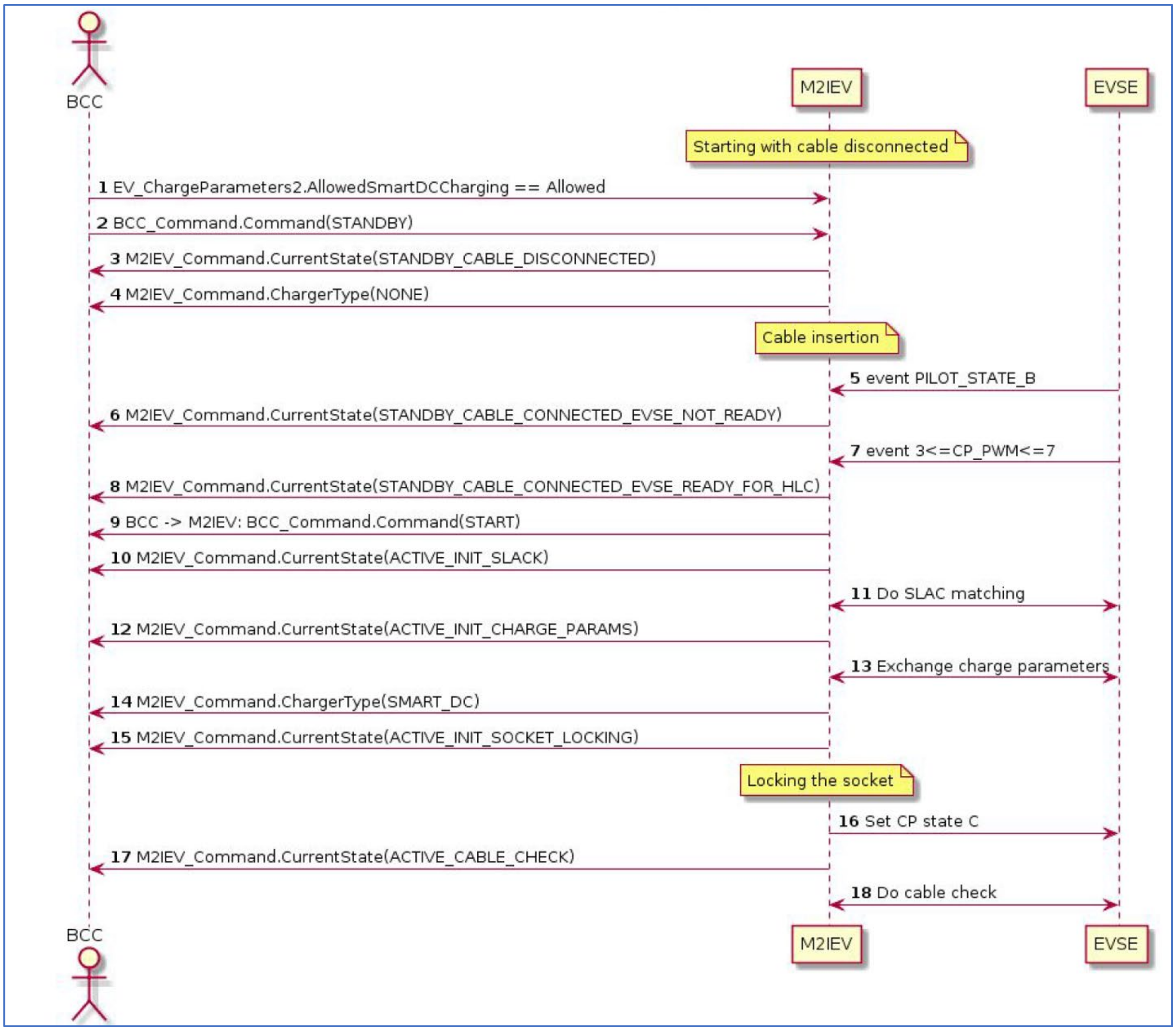



*Figure 22 DIN 70121 Specification-Defined DC Charging Process Sequence Diagram—Step 1: EV-EVSE Association, Authorization, and Authentication*

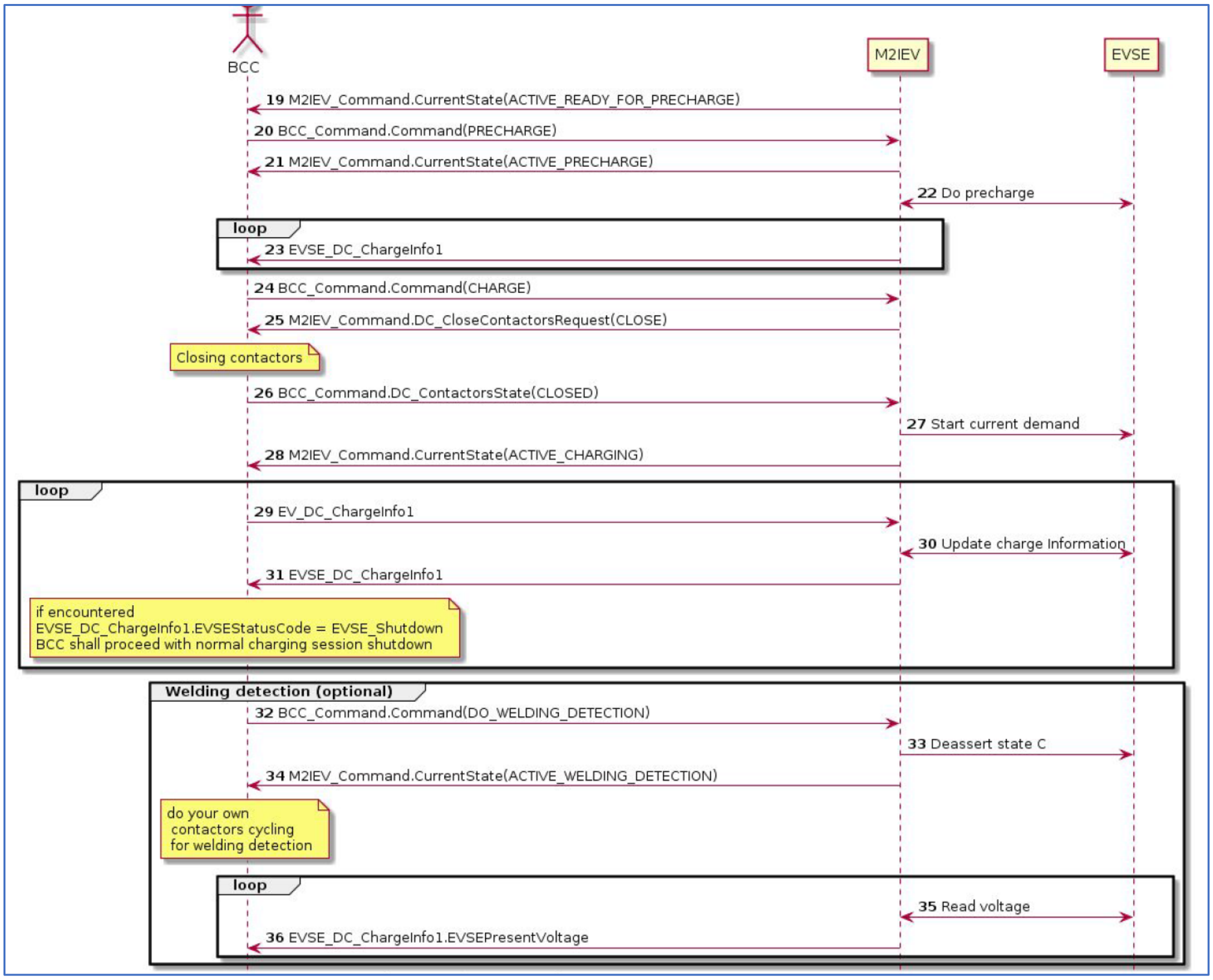



*Figure 23 DIN 70121 Charging Process Continued: Establishing Electrical Integrity and Commencing the Charging*

Finally, once either the charge coupler is pulled out of the receptacle or the charging process is complete, the system returns to standby state by safely discharging the DC bus precharge capacitors and opening the contactors between the DC bus and the battery. This is depicted in the Figure 24

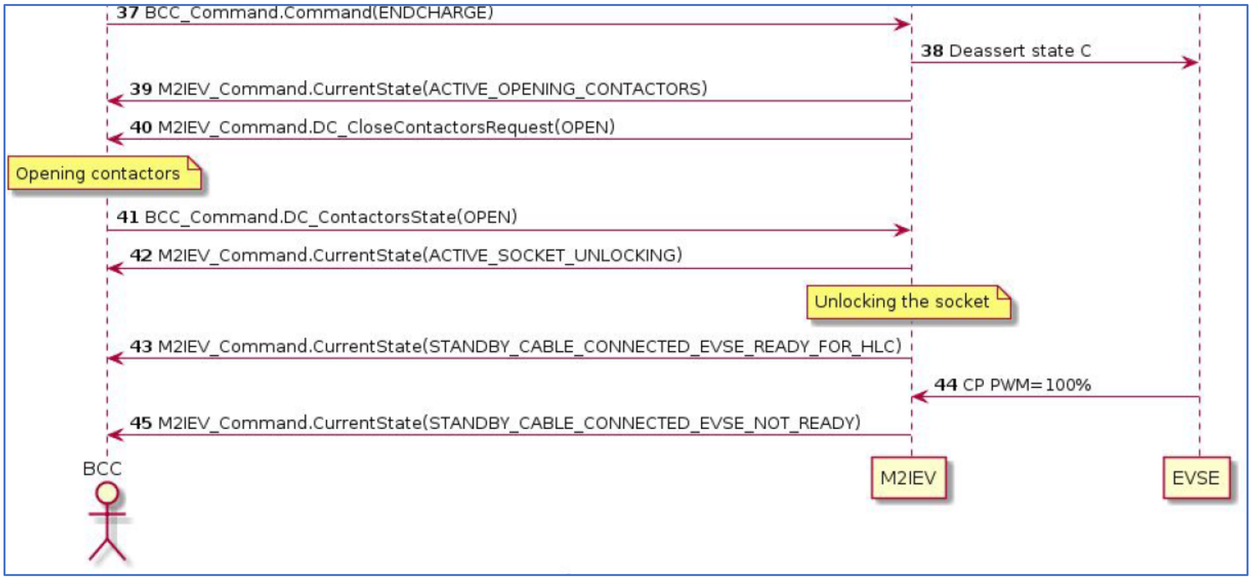
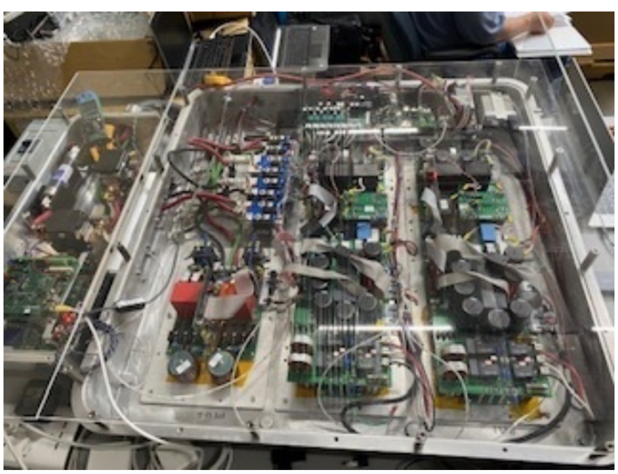



*Figure 24 DIN 70121 Sequence Diagram, Implementing the End of Charging Process stage*

The team exercised the control software to take the process through the three stages to establish a complete charge circuit that can facilitate data acquisition. Some of the pictures below show the team performing the integration tests.

Figure 25 shows a heavily instrumented SPIN module that is connected to the AC mains power supply as well as to the DC CCS connector. The picture on the right shows Europe version of Fiat 500 EV also instrumented and connected with a computer running the monitoring program, in addition to connected to an interface connector that allows the US version of the CCS connector to communicate effectively with the Europe version of the CCS connector found on



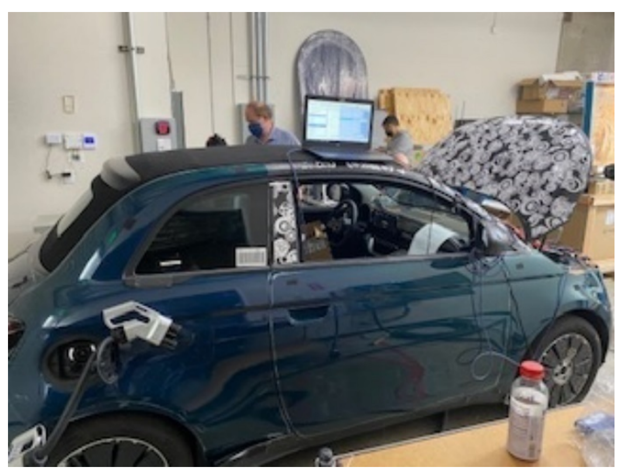


*Figure 25 EV and SPIN System Before Testing*

Fiat 500 engineering electric vehicle. Figure 15 shows Mike Bourton (Kitu Systems) monitoring the integration activity, with the Fiat 500 EV being supplied with the control power supply (given the engineering instrumentation drawing huge power during testing, external power supply is necessary to power it, so the on-board battery is not constantly drained in the process).

The testing involved technical experts from Rhombus Energy Solutions, Flex Power Controls, EPRI, and Stellantis team at the Rhombus facility in San Diego.

### *System Integration Test Results Discussion*

The team's confidence in completing the system integration test in the allocated time of ~10 days was high since each of the subcomponents were tested independently, both for power and control signaling, prior to their integration event. The only unknown was how the interplay between the SPIN and the Stellantis City EV would turn out. The main reason was that this was the first time ever that the SPIN system and the EV were being tested connected with each other.

Figure 26 Stellantis City EV Under Testing, Coupled with SPIN System

where the Type 1 and Type 2 connector interfaces had to be accurately synthesized and some of the timeout functions on both EV and the SPIN calibrated to ensure appropriate signaling and response times were allowed. Once this was accomplished, the team started taking the connected system through the various phases of DIN 70121 specification, as elaborated in the sequence diagrams earlier in Figure 22 through Figure 24. After clearing the first few stages, the system stalled at the second from the last step, when the SPIN system had to charge the EV power circuit before it could be energized from the EV side. The team is currently looking at creative approaches to address this so that a complete suite of results can be collected verifying the integrated system performance.

Figure 27 shows the SPIN CCS connector control board along with the Type 1/Type 2 CCS connector next to the Stellantis City EV. Stellantis City EV was tested in its European edition; the EU version of the DC CCS connector is slightly different from the US version of the DC CCS connector (same geometry, different circuits). The SPIN CCS connector features the US (Type 2) design.

*Figure 27 SPIN CCS Control Board Under Testing with Stellantis City EV EU Edition*

**Post-Stellantis EV Testing with Model Year 2020 and Model Year 2021 Chevrolet Bolt Production EV**

Stellantis City EV (Fiat 500) had a finite window of time available for integration testing. While significant progress was made during the integration time, the EV returned to Auburn Hills Stellantis Technical Center at the end of this period, leaving the team to resolve the remaining issues that would lead to a completed charge/discharge process without an EV. It was therefore decided that since SPIN was capable of implementing a complete DIN70121 specification for DC Charging, any CCS-equipped EV should suffice for charging level testing.

This resulted in the integration team to procure a partner Chevrolet Bolt EV (2020 MY) to continue identifying and fixing the software and hardware bugs. The team, after a defective EV/EVSE interface hardware card swap, some software changes on the SPIN as well as resolving the grounding issue (SPIN likes to keep the negative DC terminal floating but the EV checks for a grounded negative terminal throughout the process), the team finally succeeded in getting the Chevy Bolt to both charge (up to 10kW) *and* discharge (up to 0.8kW) before the ‘charging-only’ capable EV detected the reverse power flow and interrupted the charging process. The team therefore proved the SPIN DC V2G functionality using CCS and DIN spec on a production EV.

The following test results show both the SPIN testing with a power supply as the 'EV Simulator'


*Figure 28 SPIN Setup for Integration with MY2020 Chevrolet Bolt EV*

for full-power testing, as well as the SPIN charge and discharge functionality testing with Model Year 2020 and 2021 Chevrolet Bolt EVs.

The test data in the show the measured efficiency of the first-ever proof-of-design system.

As can be seen in Figure 29 the system currently is about 95% efficient in either direction, at the

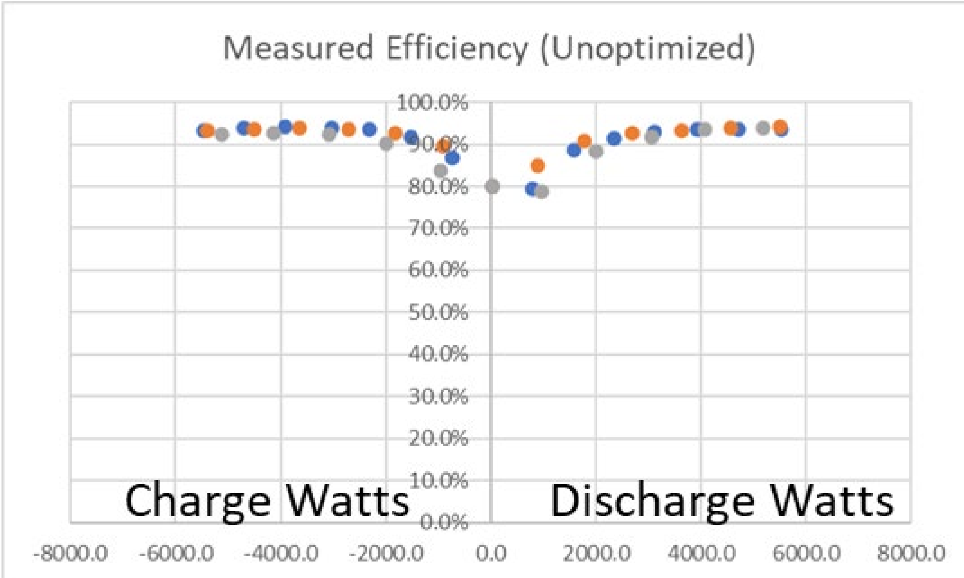



*Figure 29 Measured SPIN Power Conversion Efficiency in Charging and Discharging Modes*

rated power. The efficiency droops to 78% at a 20% power level. This is typical of a system that is designed to operate at rated power. Further, this first prototype was designed to perform its functions without failing, and the conversion efficiency was not an optimization parameter. Yet, it is obvious the system shows inherent design superiority in how it is performing.
Figure 30shows that the actual power delivered follows very precisely the commanded power from the SPIN, showing that SPIN can match the changing power demand on the fly. In the real-

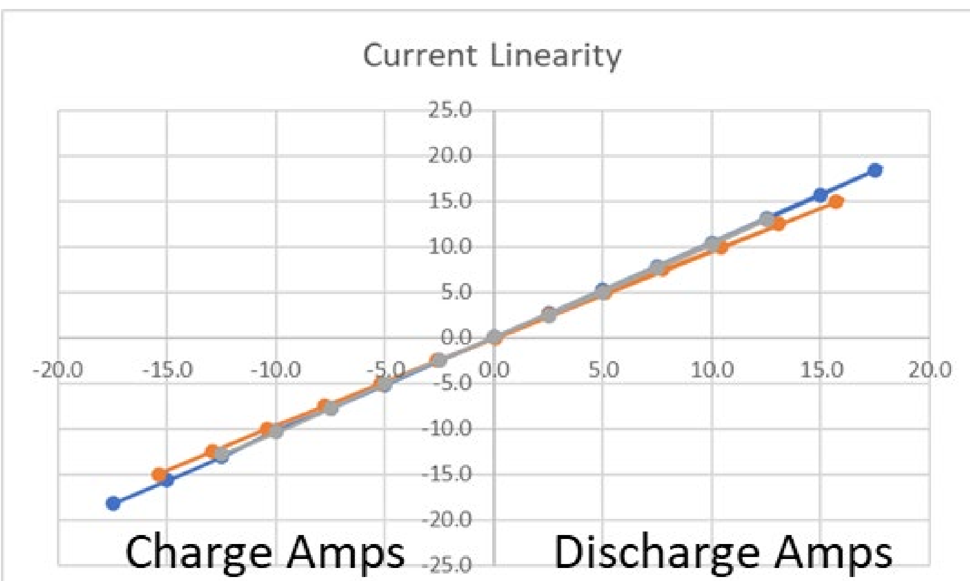



*Figure 30 Linearity of SPIN Current Commanded versus Delivered*

world, this power command signal could be derived from a local controller, a microgrid controller, or a building management system, depending on how the SPIN is configured. Figure 31 shows the testing of the SPIN system in the standalone mode, to demonstrate V2H capability. For this, a DC power supply simulating the EV powered the SPIN, and the lighting load simulated the household load. The SPIN system could isolate itself, and power the load without any grid present.

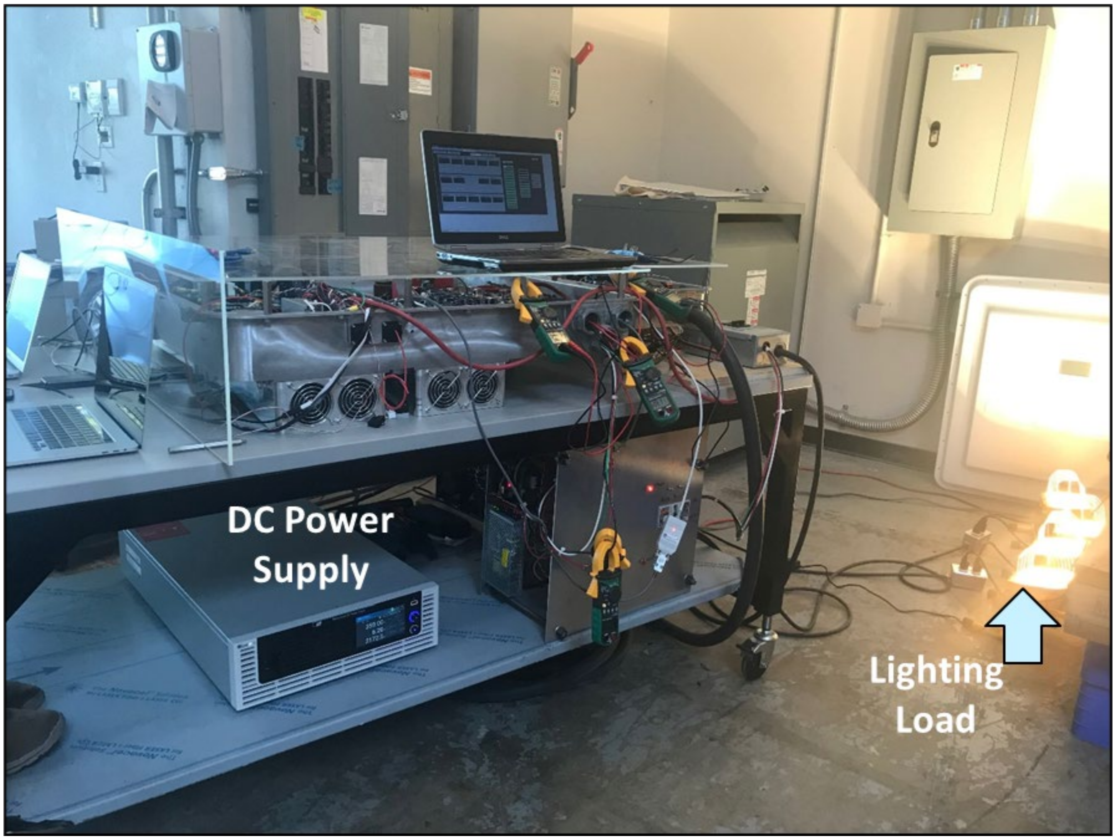



*Figure 31 SPIN Standalone Operation Simulating Vehicle to X Mode*

In a real-world scenario, SPIN system is mounted on the wall in the garage or outdoors (it is outdoor rated, air cooled system), in series with the main service panel and the utility transfer switch, that detects power outage and disconnects the main panel from the utility service, while simultaneously connecting SPIN to the household circuit – either the main circuit (if intended to power the entire house) or to the critical load panel, powering a few critical appliances such as the fridge, lighting, fans and outlets where essential services such as the sump pump, the internet, some computers, and TV are enabled. The SPIN control algorithms put the SPIN in a grid-forming inverter mode automatically, so it can be seen as a 110V power source to the household loads. The SPIN then monitors the energy available from the EV, from a connected PV system (if available), and going into the loads, to continually balance EV charging, EV discharging, the household energy needs, and the supply available from PV. If, during the outage, the SPIN reaches the EV battery state near the lower threshold of the customer setpoint (beyond which, the EV owner wants to reserve this energy for emergency mobility service), the SPIN disconnects from the house loads and the home at that point may have to rely on other sources. Our analysis (see the Benefits chapter) indicates that SPIN can power the critical loads for up to 96 hours (four full days), if it had access to 40kWh of battery energy, without having the connection with a PV panel.

When the power from the grid is restored, the utility switch senses its presence, and switches back the operation to mains-connected, with the SPIN serving more of a local energy balancer between PV, local loads and EV charging, in addition to responding to grid commands by serving as a smart inverter, dispatchable through its link over IEEE2030.5 CSIP signaling to the DSO.

Figure 32 shows the trace of the testing of the system in an islanded mode while performing resiliency service such as energy balancing or critical load balancing. Following paragraphs contextualize the results of this testing.

The top trace in Figure 32 is showing the battery contactor closing. This is the contactor closing on the EV battery side. When the contactor closes, the next trace below shows the appearance of the DC Voltage on the internal DC Bus of the SPIN unit. SPIN unit operates at an internal 500V DC Bus by acting as a DC/DC converter. The EV battery DC Bus voltage is in the 350-400V range. The SPIN system is essentially a DC-coupled system. This is the voltage on the SPIN DC bus that is maintained by all of the connected DC/DC or AC/DC converters. When the SPIN algorithm detects surplus energy available from the local PV, after fulfilling the local loads, it uses this energy (first at a lower level, followed by at a higher level, in response to changing household demand) to charge the EV battery (as indicated by the negative power values). When there is a perfect balance between what the PV is supplying and what the household needs, the energy flow in or out of the EV stops automatically. When the household needs more energy than being provided by the PV array, the V2G inverter connected to the EV via CCS instantly switches over to supply this current seamlessly. The system is rated at 5kW and was tested at about 3kW charging, and 2kW discharging, just to prove its functionality.

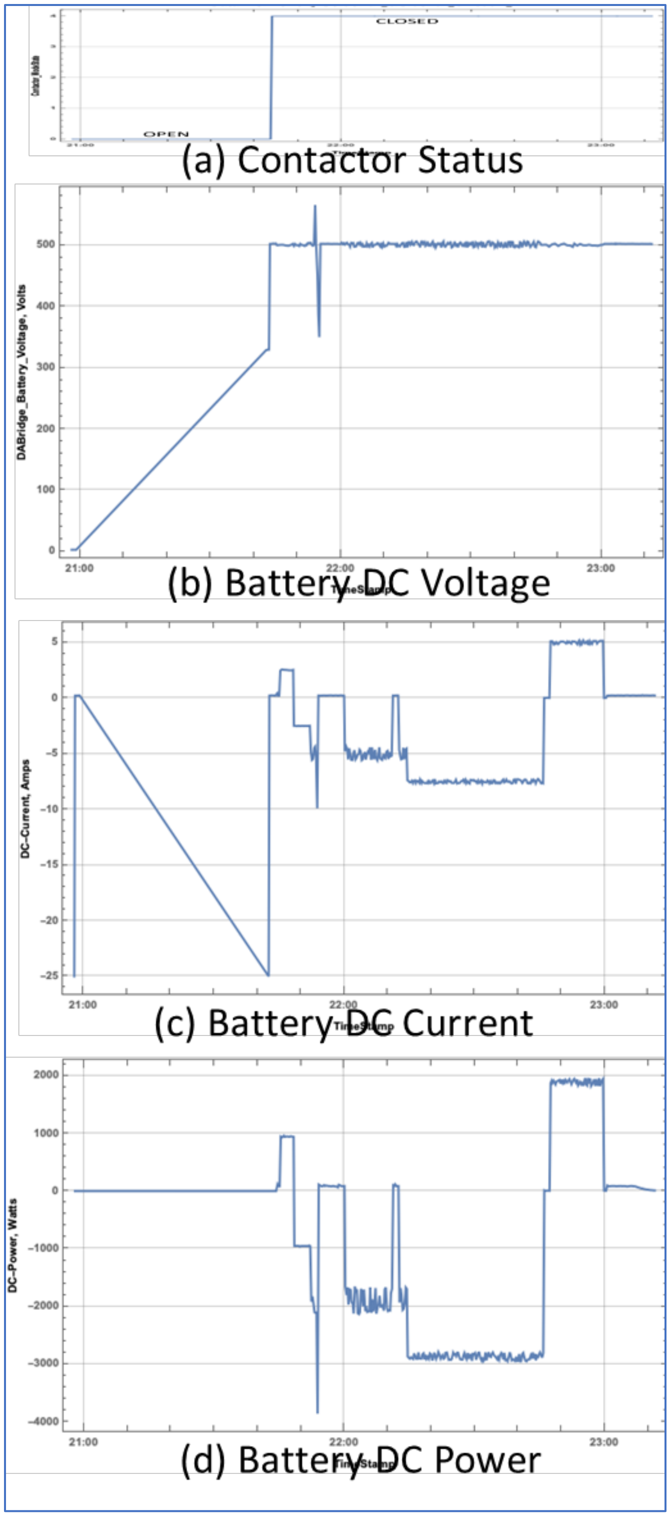



*Figure 32 SPIN – V2H Power Transfer Data Traces*

The implications of this are significant: As SPIN technology goes through its evolution from a proof-of-design hardware/software to production-ready hardware/software. Any CCS-equipped EV should be able to provide resilient power through a simple software change on its charging management software that implements DIN70121. Separately, the team is taking the findings from successful implementation of the V2G functionality into SAE J2847/3 (reverse power flow) and J2847/2 (DC Charging communications) standards development, so all the OEMs and all the providers have access to the same technology. Furthermore, multiple EVs equipped with CCS connector, a revised version of the DIN70121 (SAE J2847/2, SAE J2847/3) spec can operate through the SPIN unit, contributing to longer resilient operation for the household.

### ***Battery Impact Testing***

#### Battery Impact Testing Requirements

The primary purpose of an EV is mobility, and EV batteries are designed for meeting the operational and life requirements related to mobility. These are correlated with the warranty requirements (10-year, 150,000 miles equivalent) as translated to battery cycle life under all operating conditions. The latest generation of lithium-ion batteries was introduced first in the mid-2000s and has since undergone rapid evolution through multiple iterations of development, manufacturing, electrochemistry, and vehicle integration and control systems. As a result, the automotive and battery industries have become more open to exploring the simultaneous use of automotive batteries for mobility and grid services purposes. However, the incremental degradation impact on automotive batteries is as yet not clearly defined.

During the EV's operating life, indiscriminate application of EV batteries for both the mobility and grid services applications could potentially curtail battery operating life or range through rapid battery capacity degradation. Unmanaged application of on-board batteries for grid services would also impact the manufacturer's warranty for the batteries. To avoid this, battery and EV manufacturers can cooperate to understand the intended application of the EV battery for the non-mobility use cases. One way to accomplish this is by characterizing the battery degradation for combined mobility and grid service applications. Once the battery impacts are known, battery and EV manufacturers can design and manage the on-board energy storage system for mobility and non-mobility applications. During the EV operation, manufacturers carefully monitor the system and apply the operating constraints for non-mobility applications as the primary use for the on-board batteries remains for mobility.

While this fact is known to researchers, most battery characterization work remains proprietary to battery and EV manufacturers for competitive reasons. The SPIN project addressed this issue and has been working with research partners, NREL and Stellantis (Chrysler), to define and implement the battery test cycle and conduct testing and analysis of incremental battery impact from grid services. The team specifically examined battery capacity degradation using the same vehicle battery pack that is on the Stellantis Pacifica plug-in hybrid electric vehicle (PHEV) for running both cycles. Table 1 summarizes the two cycles that identical packs operating under identical conditions are being subjected to. Stellantis shipped two Chrysler Pacifica PHEV battery packs to NREL ESIF for performance and impact evaluation. NREL is tasked with testing the two battery packs—one on the regular PHEV mobility-only duty cycle and another on a mobility and grid services combined duty cycle—to assess the impact of grid services on the battery life and performance. Stellantis and NREL agreed to a test protocol that is considered reasonable and more realistic. Table 1 shows the energy consumption estimates related to this protocol.

**Table 4: Energy Consumption Profiles as the Basis for Battery Test Regime for Mobility and Grid Services (DER)**

| **Cycle Discharge ~ 15 mi.** | | | | | |
|---|---|---|---|---|---|
| | **Cycle** | **Time (hr)** | **Distance (mi)** | **Energy Throughput (kWh)** | **Net Energy (kWh)** |
| **CD** | CD1 City | 0.3811 | 7.44 | 3.96 | 2.24 |
| | CD US06 | 0.1667 | 8.01 | 5.27 | 2.81 |
| **CD total** | | 0.5478 | 15.45 | 9.22 | 5.05 |
| **Total pack kW** | | | | | 11.8 |
| **Usable energy after both drive cycles (kW)** | | | | | 6.75 |
| **Proposed discharge power (kW) - available for DER** | | | | | 2 |
| **DER duration (hr)** | | | | | 3.375 |

Table 2 shows how each of the two packs will be tested. The plan is to exercise the batteries with two cycles run per day so as to assess one year-worth of battery impacts in a six-month test window. In addition, there will be one full deep-discharge cycle at C/3 rate + high power pulse characterization (HPCC) cycle.

**Table 5: Battery Test Cycle for Grid Services Impact Evaluation**

| | Cycle Time (Hours) | |
|---|---|---|
| | Pack 1 (Test Pack) | Pack 2 (Baseline) |
| At work | | |
| Drive home | 0.5 | 0.5 |
| Discharge at home (10 kW) | 1hr, to 25% | 0 |
| Charge to 100% | 2 | 1 |
| Wait (key cycle – contactor open) | 1 | 3 |
| Drive to work | 0.5 | 0.5 |
| Charge (50–100%) | 1 | 1 |
| | | |
| Total time/cycle | 6 | 6 |

### Battery Test Setup at NREL ESIF

NREL and Stellantis teams worked to define the test instrumentation requirements. In specific, the NREL team assembled a thermal chamber where both the test and the reference battery packs could be cycled using their specific cycles at the same operating temperature in their respective thermal chambers.

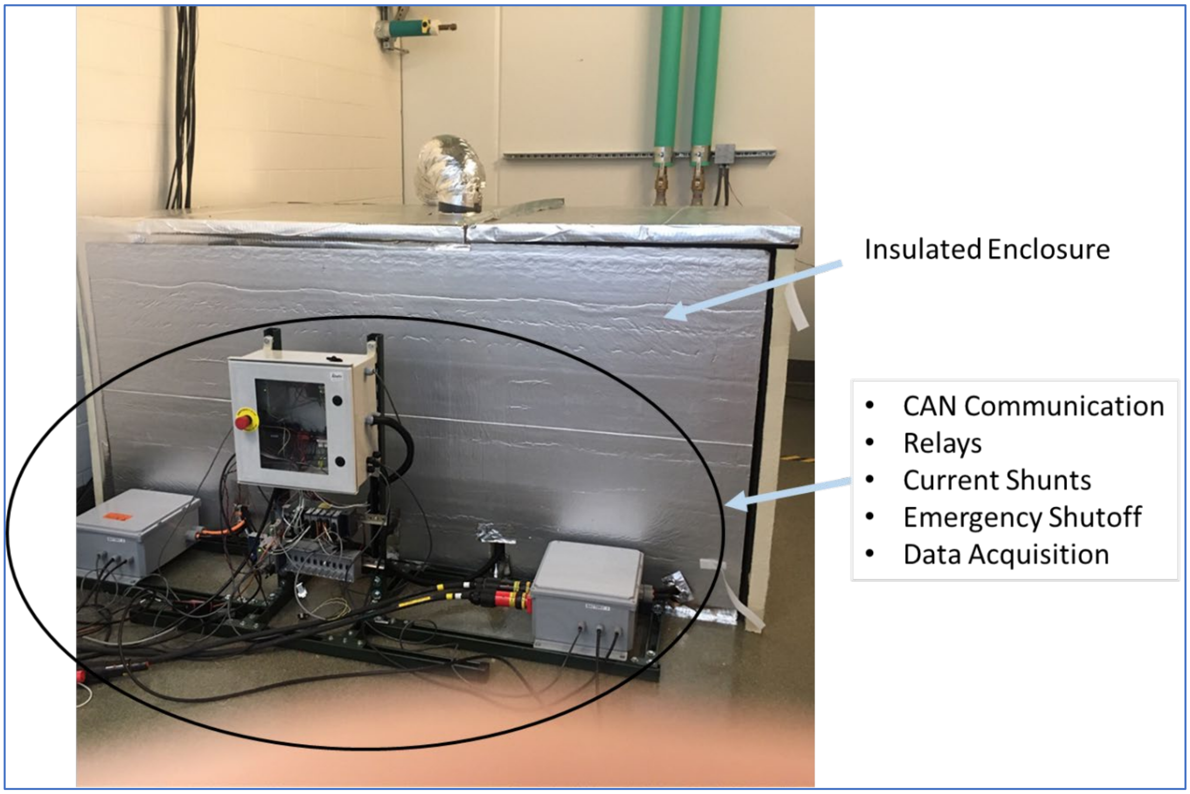



*Figure 33 NREL ESIF Battery Packs for Performance Testing*

The system undergoes three cycles per day, effectively providing one year worth of operating data each quarter. To date, the system has generated more than three years' worth of battery test data. The following images show the current state of the EV battery testing.
The battery cycling took about a year (six months longer than anticipated) to begin. Thus, instead of beginning in mid-2019, battery cycling began in mid-2020. The primary cause for this delay was setting up NREL ESIF battery testing, especially the battery test system software interface with the battery management system. It took NREL and Stellantis teams two quarters to debug and another quarter for the system to be fully operational. Figure 33 shows the battery test setup at NREL ESIF, with a test pack and a baseline pack being subjected to the same operating conditions except for the duty cycle, as described earlier.

By August 2020, the testing at ESIF for the battery packs had begun, with three cycles per day, meaning one month of testing generated three months' worth of test data. This was further automated in September after initial debugging of the parameters was completed.

***Battery Impact Testing Results***

Testing of the battery performance impact from grid services has continued uninterrupted even though the visitor and on-site work restrictions have lifted only gradually. The team continued testing and data collection on battery performance throughout COVID shutdowns and stay-at-home orders in Colorado. The testing has continued through the first half of 2021 as the team has been able to receive a No-Cost Time Extension until June 2021 to finish the work scope for budget period 3 for the DOE-funded work.

Figure 34 shows the test setup validation battery test profile clearly indicating the Drive to Work, Charge at Work, Drive to Home, and Discharge at Home for V2G operation and Charge at Home for both V2G and baseline packs.

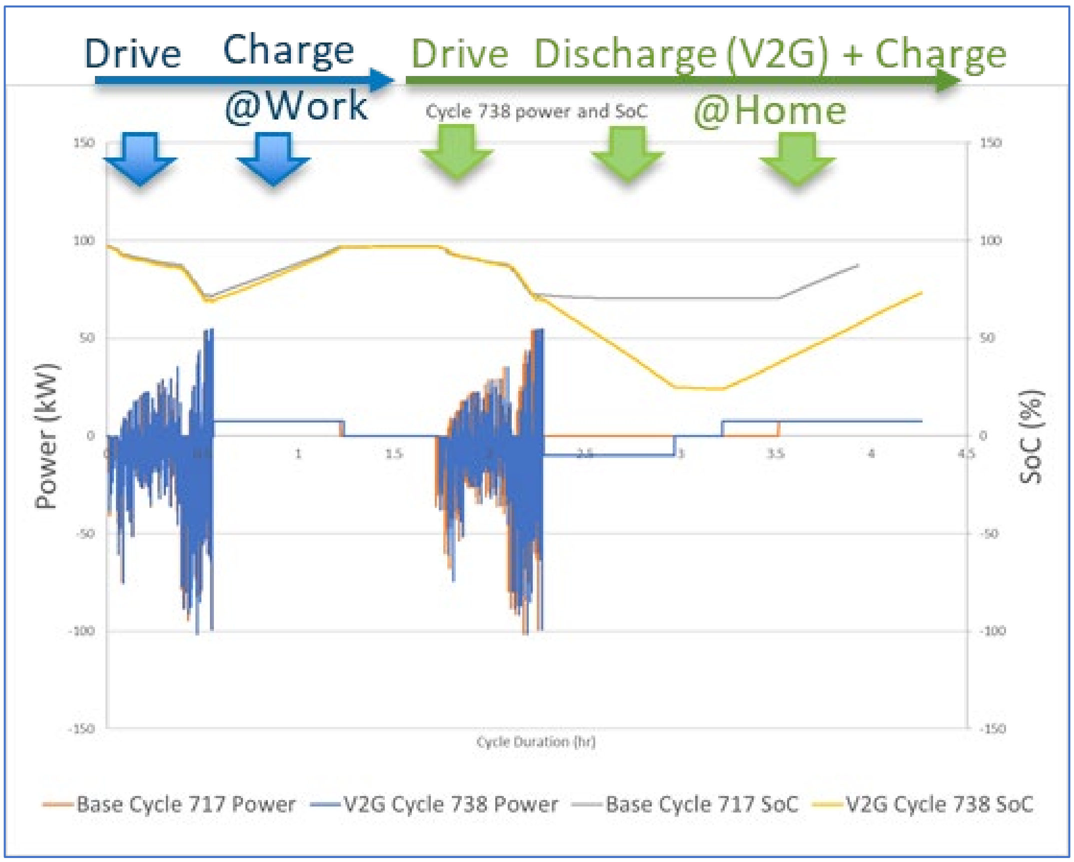



*Figure 34 Battery Test Cycle Power Profile for V2G and Baseline Packs*

Figure 35 illustrates the same data, but now with power, current, and voltage traces under the same test cycle showing the driving, charging, discharging, and recharging pattern, which is repeated once every eight hours. Thus, each calendar day, data are collected that span three days of energy throughput.

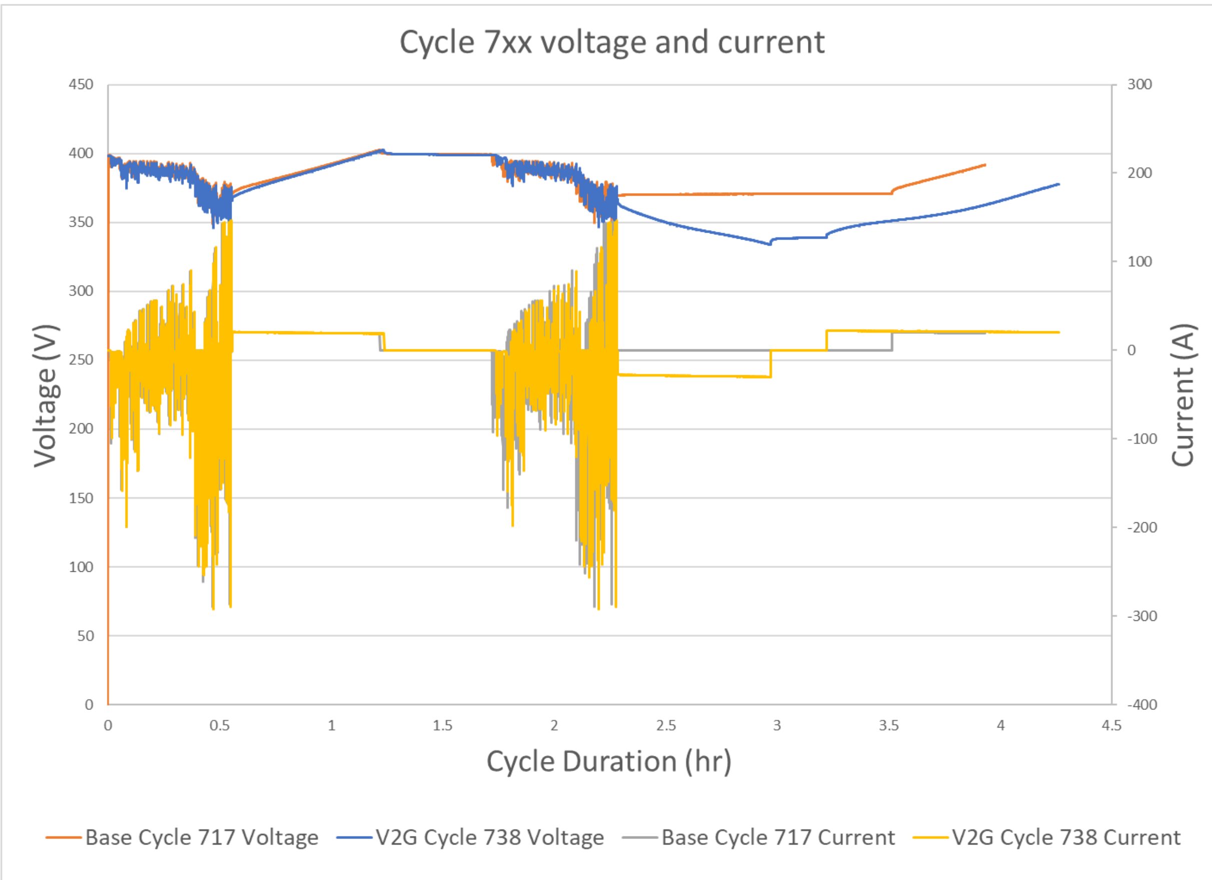



*Figure 35 Battery Current and Voltage Profiles for V2G and Baseline Packs*

The testing began in June of 2020. However, the first quarter of testing was not set up correctly as the vehicle and V2G battery packs did not perform the discharge profile correctly. So, this error was found during August 2020 review and corrected. Figure 35, and all figures going forward, show the latest data available from the May 2021 review, effectively representing three years' worth of throughput and cycle data. Significant results are discussed and shown here.

Table 3 shows the dates on which the test data were collected to assess battery health along with comments indicating any significant aspects of testing.

**Table 6 Test Data Collection Schedule**

| *RPT#* | *Date Conducted* | *Comments* |
|---|---|---|
| *0* | 06/26/2020 | First test with automated setup to validate test setup |
| *1* | 08/10/2020 | First check-in test, discovered power profile error |
| *2* | 08/21/2020 | Repeated first test at 2-month interval, verifying correct function |
| *3* | 09/21/2020 | First monthly test, equal to a quarter of throughput |
| *4* | 10/22/2020 | Month 2 |
| *5* | 12/01/2020 | Month 3 |
| *6* | 01/04/2021 | Month 4.5 |
| *7* | 02/17/2021 | Month 7 |
| *8* | 03/24/2021 | Month 8 |
| *9* | 05/13/2021 | Month 10, equal to 36-month equivalent data |

Figure 36 shows the reference performance test (RPT) data for the amp hour (Ah) capacity of the battery pack at monthly test intervals. After the initial glitch where the battery cycling was occurring at half the rate (only charging, not discharging appropriately), the slope of the Ah degradation was flatter. As soon as this error was corrected in August and September, the Ah degradation attained a steeper slope, which makes sense. Clearly, the battery loses its capacity faster if the throughput is accelerated.

| | V2G | | Baseline | |
|---|---|---|---|---|
| RPT0 | 47.76Ah | 100.00% | 47.75Ah | 100.00% |
| RPT1 | 47.39Ah | 99.23% | 47.75Ah | 100.00% |
| RPT2 | 46.93Ah | 98.26% | 47.6Ah | 99.69% |
| RPT3 | 46.61Ah | 97.59% | 47.53Ah | 99.54% |
| RPT4 | 46.09Ah | 96.50% | 47.32Ah | 99.10% |
| RPT5 | 45.5Ah | 95.27% | 47.09Ah | 99.10% |
| RPT6 | 45.02Ah | 94.26% | 46.65Ah | 97.70% |
| RPT7 | 44.63Ah | 93.45% | 46.63Ah | 97.65% |
| RPT8 | 44.15Ah | 92.44% | 46.46Ah | 97.30% |
| RPT9 | 43.48Ah | 91.03% | 46.25Ah | 96.85% |

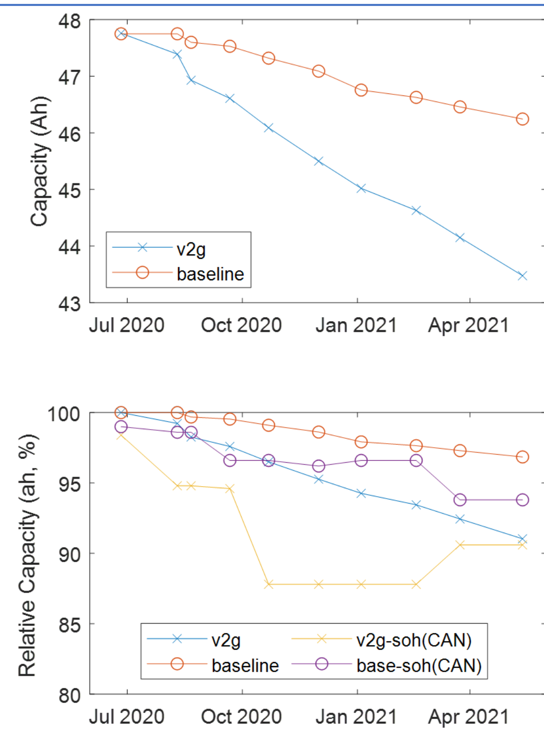



*Figure 36 Reference Performance Test Data for 3.8-Year Effective Period, Ah Capacity*

The RPT data clearly show that the V2G pack is degrading at a faster pace than the baseline (non-V2G, mobility-only) pack. This is to be expected. Such RPT data enable the battery manufacturer as well as the vehicle manufacturer to determine control setpoints for battery SOC, battery throughput, services for which the vehicle battery is made available, and when and how the battery discharge and charge cycles will occur in real-life scenarios. The basis for the setpoints are the battery prior state, battery actual use for mobility, and battery anticipated use for mobility. One interesting state of health (SOH) dataset is also plotted in Figure 37. This SOH dataset appears to indicate software variables that signify battery life. While these variables would be useful if actual test data were not available, they only loosely correlate with the actual battery SOH data for V2G application. Presumably, this is because the software for the battery SOH estimation is not written to encompass V2G condition. This situation will likely change as more test data become available for use in refining the estimation model.

Figure 38details the same RPT data for kWh capacity, which shows more uniform battery degradation with higher and higher throughput. The difference between Ah and kWh data is the internal resistance variation. As the battery pack ages, the internal resistance starts to increase slowly. This means that there is more internal voltage drop when the same current is drawn. Thus, while Ah only shows the capacity fade effect, the kWh deterioration also factors in the internal resistance increase. The internal resistance change between the baseline and the V2G packs is shown in Figure 21.

| | V2G | | Baseline | |
|---|---|---|---|---|
| RPT0 | 16.917kWh | 100.00% | 16.958kWh | 100.00% |
| RPT1 | 16.728kWh | 98.88% | 16.894kWh | 99.62% |
| RPT2 | 16.57kWh | 97.95% | 16.81kWh | 99.13% |
| RPT3 | 16.48kWh | 97.42% | 16.82kWh | 99.19% |
| RPT4 | 16.295kWh | 96.32% | 16.739kWh | 98.71% |
| RPT5 | 16.093kWh | 95.13% | 16.666kWh | 98.28% |
| RPT6 | 15.915kWh | 94.08% | 16.55kWh | 97.59% |
| RPT7 | 15.768kWh | 93.21% | 16.50kWh | 97.31% |
| RPT8 | 15.60kWh | 92.24% | 16.44kWh | 96.94% |
| RPT9 | 15.35kWh | 90.71% | 16.36kWh | 96.50% |

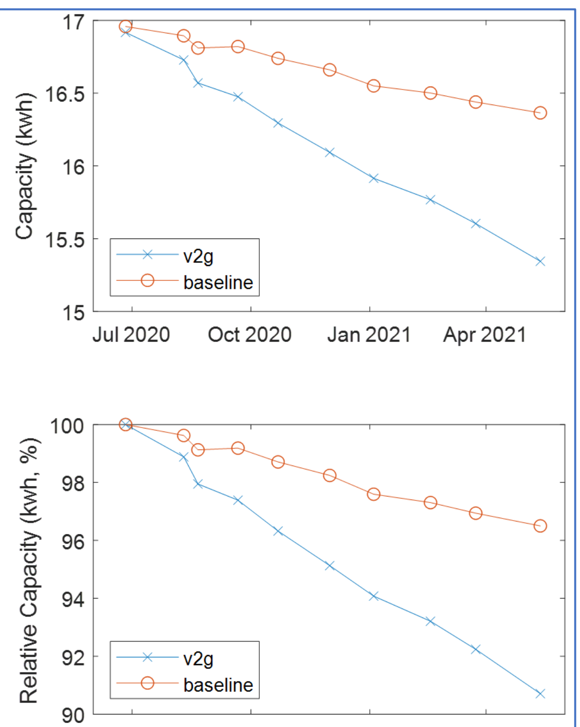



*Figure 37 Reference Performance Test Data for 3.8-year Effective Period, kWh Capacity*

Figure 24 shows the artifact of the performance degradation in terms of internal resistance that increases, thereby reducing the peak (10-second) power capability of the batteries without violating the minimum voltage requirement as well.

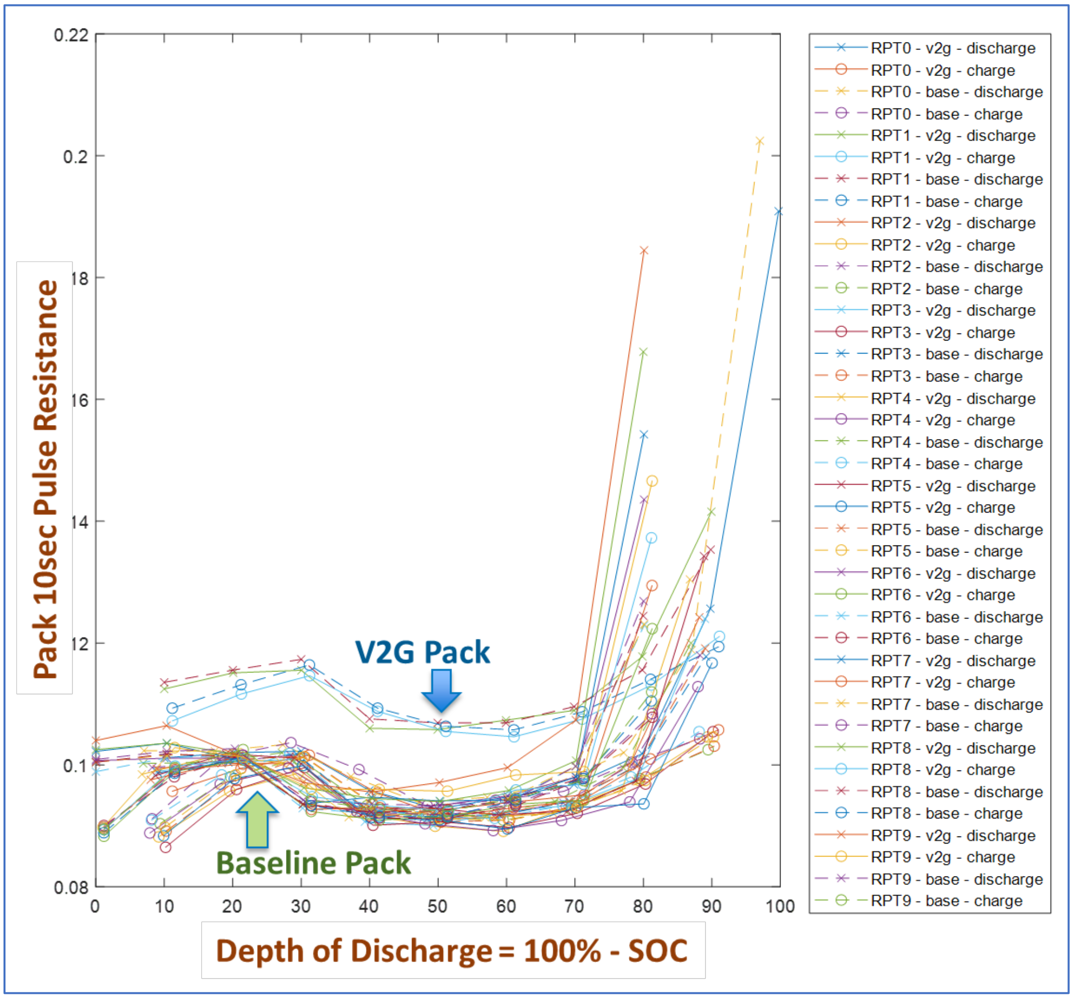



*Figure 38 High Power Performance Characterization (HPPC) Test Profiles, Baseline vs. V2G Pack*

Table 4 shows the battery cumulative throughput in kWh over the corrected test profile of seven months (about 3.7 years equivalent of data at 738 cumulative cycles, 200 cycles/year).

**Table 7 Cumulative Battery Throughput Data, V2G vs. Baseline Packs, Corrected Battery Cycle Data (RPT2 Onward)**

| | Baseline | V2G + Mobility | V2G Only | (V2G-baseline) /baseline |
|---|---|---|---|---|
| Ah throughput - total | 46,500 | 79,200 | 32,700 | 70.47% |
| Ah throughput – Charge | 23,200 | 39,800 | 16,600 | 71.25% |
| Ah throughput – Discharge | 23,200 | 39,400 | 16,200 | 69.69% |
| kWh throughput - total | 17,700 | 29,200 | 11,500 | 65.30% |
| kWh throughput – Charge | 8,990 | 14,900 | 7,500 | 65.90% |
| kWh throughput – Discharge | 8,690 | 14,300 | 7,260 | 64.69% |
| Cycle number | 717 | 738 | | |

***Battery Test Data Discussion***

The testing of this battery pack is indicative of several important and interesting findings. First, the project has so far collected about nine months of battery test data, which equates to three full years of operational data (assuming 7 days/week of driving and V2G operation). The key findings are as follows:

1. The battery test cycle for V2G includes a fairly aggressive 7260 kWh of V2G specific discharge throughput over 738 cycles. That is a 9.84 kWh charge/discharge cycle each day on a nameplate 17.6 kWh pack, representing 55% of the battery nameplate capacity. The additional charge/discharge energy represents 65% of the incremental throughput over baseline. In a previous analysis done with a Chevy Bolt battery pack of 60 kWh (utilized for the earlier on-vehicle V2G value assessment for EPC 14-086[1]), about 8000 kWh per year of discharge throughput created the baseline value available from grid services.
2. Regarding the capacity fade itself, from the embedded table of kWh capacity data in , there is a kWh decline from 100% to 90.71% (i.e., 9.29% over 3.8 years) for the V2G pack versus 100% to 96.5% for the baseline pack (3.5% over 3.8 years). That is incremental 6.15% over 3.8 years, meaning about 1.6% kWh loss every year. In all, these data show that the baseline pack will lose about 12–15% capacity, retaining 85% of the nameplate at the end of 10 years. In a V2G equipped vehicle with the same aggressive charge/discharge cycle, this capacity fade would be about 16% more, leaving about 70% of the original capacity intact even with

[1] Eric Cutter, Quantifying the Value of V2G, EPRI Infrastructure Working Council meeting, October 24, 2018, accessed 06/14/2021, https://epri.azureedge.net/documents/IWC/20181024/D1-9A_October%202018%20EPRI%20IWC_E3%20IWC%20V2G%20Slides.pdf

an aggressive schedule. This means that even the PHEV battery has significant potential to accomplish V2G services related value.

3. EV batteries carry significantly more capacity and are relatively underused between recharges *assuming the EV drivers continue to plug in their EVs each night at home*. That makes applying 55% of battery capacity for grid services much easier, resulting in 33 kWh cycled each day, or 6600 kWh per year (200 cycles). An EV battery from the same manufacturer with a similar degradation profile would retain about 70% capacity at the end of its 10-year life. Throughput of 6600 kWh from a Chevy Bolt size battery would result in a value of upwards of $400/year. For a Chrysler Pacifica PHEV sized battery at 17.6kWh nameplate capacity (roughly a third of the Bolt EV battery), this value would be about $135/year.

All of the revenue numbers ignore the costs of putting the V2G hardware outside of the vehicle. However, putting the V2G system outside of the vehicle has two advantages. The first advantage is that V2G system costs do not impact the EV costs, with only the software costs included in the EV cost increase (less than $25 at volume). The second advantage is that bringing the V2G system off-board allows synergies in hardware and software integration involving local PV, local energy management, and optional stationary storage charging management. This makes the value proposition of such a system much stronger. A PV/EV with V2G capability and energy/power management and coordination functionality can maximize renewable consumption, reduce grid renewable energy curtailment, minimize energy costs to the owner, decrease installation and hardware costs for additional inverters, and, at the same time, obviate the need for a stand-alone stationary storage system. In other words, the cost equation against the benefits may turn out to be significantly better than an on-board inverter.

The real-life situation for battery energy management is slightly more complicated. No two cars are driven the same way and in the same environment/ambient conditions. That means that each EV/PEV battery needs to be managed in a manner that prioritizes battery life followed by mobility application. Such an emphasis would then unlock the energy that would otherwise be unavailable due to a lack of visibility and control over it. Therefore, in any realistic scenario, the vehicle on-board control system will need to maintain a reasonably accurate account of the kWh throughput over the vehicle's life. A battery could be deployed for non-mobility services by the on-board control system continually weighing the costs of lost capacity vs. the value of revenue opportunity available, through a continuous algorithm both on vehicle, on SPIN and in the cloud, factoring in all the relevant parameters. Undoubtedly, this type of a control system may also require additional information exchange between the grid and the vehicle.

***Summary***

The testing of the complete system as well as battery impacts provided several important learnings. On the system testing side, for the first time ever, a CCS-equipped integrated DER system was tested for real-time energy flow balance, including deploying V2G capability of the SPIN to serve the resiliency function, in conjunction with the local PV resource, or in a standalone manner. The control and communications functionality modified to facilitate reverse power flow over DIN70121 protocol is planned to be incorporated in the next version of the SAE J2847/2 standard in the coming months, so the broader OEM and technology provider communities can implement this. The implications of this development are huge. Majority (except Tesla) of the OEMs and the global regulations are moving towards making CCS the coupler standard (and DIN70121 as the communication protocol) for Electric Vehicles. EVs are the ones with larger battery capacity on-board, and are suitable for extended resiliency services. The uniform implementation of standard by all OEMS has the potential to accelerate application of EVs toward resiliency with the help of off-board DC V2G inverters, at a large scale, and in an interoperable manner (most prevalent DC V2G systems rely on a proprietary communications link between their cloud server, their wallbox (DC V2G converter) and the EV).

In addition, a comprehensive, still ongoing, battery life impacts analysis was performed to inform the multiple stakeholders about how best to apply EV batteries for V2G services while maintaining the overall battery life requirements and not violating the warranty. While much work remains to be done toward a practical and viable implementation of the operational strategy, there is significant value potential to justify such an effort.

4. Products developed under the Award and technology transfer activities, such as: Publications

On-Board V2G part of the project resulted in the following publications:

1. [1]https://www.academia.edu/38676029/Distribution_System_Constrained_Vehicle-to-_Grid_Services_for_Improved_Grid_Stability_and_Reliability
2. [1] Open Standards-Based Vehicle-to-Grid: Technology Development, EPRI, 3002014770, 2018, https://membercenter.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002014770
3. [1] Open Standards-Based Vehicle-to-Grid: Integrated Resource Planning Considerations, EPRI, 3002014801, https://membercenter.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002014801
4. [1] Open Standards-Based Vehicle-to-Grid: Value Assessment, EPRI, 3002014771, 2019, https://membercenter.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002014771