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Energy Research and Development Division

FINAL PROJECT REPORT

Assessing Communications and Control of Smart Inverters and Consumer Devices to Enable More Residential Solar Energy

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PREFACE

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

Assessing Communications and Control of Smart Inverters and Consumer Devices to Enable More Residential Solar Energy is the final report for the Assessing the Ability of Smart Inverters and Smart Consumer Devices to Enable more Residential Solar Energy project (Contract Number: EPC-14-079) conducted by Electric Power Research Institute, Inc. The 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 CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

California's aggressive clean energy policies and deployment goals for inverter-based distributed energy resources, such as photovoltaics and battery energy storage, have led to the development of advanced functions for smart inverters. The key challenge is how multiple inverters can operate side-by-side stably and beneficially when each is performing smart-inverter functions. This issue is a primary concern at the residential level, where multiple homes share the same distribution-level transformer, feeder, or substation in which consumers are not permitted to add solar due to local over-voltage conditions already existing. To address this problem, the project focused on understanding advanced smart-inverter functions, as defined in California's Rule 21 tariff. The following two methods were used to assess smart inverter behavior using laboratory and field tests: (1) successful side-by-side operation of smart inverters, and (2) using residential smart loads to enable more solar photovoltaics on the grid. As a result, specific smart load management algorithms and communications architecture were developed. The distributed energy resource devices and systems were reviewed for the viability of mass-market adoption and benefits to California. Project results and recommendations are intended to advance the industry's knowledge of the use of smart loads and automation to effectively enable greater use of solar photovoltaics to customers and on the grid.

Keywords: solar energy, smart inverters, smart loads, controls optimization, communication technologies, open standards.

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EXECUTIVE SUMMARY

Introduction

California's aggressive clean energy policies have led to plans to determine the use of inverter-based distributed energy resources. Smart inverter based distributed energy resources are resources that are grid connected where the power output originates as direct current and is inverted to alternating current. These resources include behind-the-meter stationary storage (e.g., batteries) which have become more important for grid stability as California transitions to 100 percent renewable energy by 2045. Smart inverter-based distributed energy resources can be controlled to respond to various signals and fluctuate to meet the supply and demand of the electrical system. Under Assembly Bill 2514 (Skinner, Chapter 469, Statutes of 2010), the California Public Utilities Commission (CPUC) set a target of 1,325 megawatts of energy storage for procurement by 2030. The state's Go Solar California campaign has a goal to obtain 3,000 megawatts of customer-owned distributed solar. A sizable portion of California's policy goals applies to the utility-managed electric distribution system and to customer-managed inverter-based distributed energy resources. In 2014, the CPUC adopted revisions to the Rule 21 tariff that requires three of California's investor-owned utilities to implement advanced inverter functions and communications to address grid integration challenges posed by distributed energy resources.

One critical challenge for smart inverters has not been well studied: whether multiple inverters can operate side-by-side stably and beneficially when each is performing individual smart-inverter functions. This issue is a major concern for multiple homes sharing the same distribution transformer, feeder, or substation.

Project Purpose

This project focused on understanding advanced smart inverter functions using two methods to assess smart-inverter behavior using laboratory and field tests: (1) successful side-by-side operation of smart inverters, and (2) using residential smart loads to enable more solar photovoltaics on the grid. The project directly assessed these methods while exercising the functions called out in California's Rule 21. Testing the smart inverters in laboratory and field environments evaluated the ability of the smart loads to enable greater use of residential solar photovoltaics. The two core objectives were as follows:

Objective 1: Provide insight into whether specific function and control-loop timing parameters are necessary to enable successful side-by-side inverter operation. This includes identifying the key factors that limit the local PV hosting capacity, determining which Rule 21 functions can be configured to interoperate in a supportive way, quantifying which local hosting capacity can be increased by using the smart inverter functions, coordinating with relevant standards organizations so solutions can be standardized, and addressing these issues to enable mass deployment of solar PV and battery storage in California, to help the state meet its policy goals. The objective was to see the interaction between the inverters, and to see if multiple inverters performing smart-inverter functions operate side-by-side in a stable and beneficial fashion. The concern was there would be isolation when inverters interact when operating on the same feeder volt/volt-amps-reactive (var) curve. For example, if the inverters each pump up the vars, and the voltage goes higher, then can the two inverters operating on the same feeders follow the rules?

Objective 2: Advance the industry's knowledge regarding how consumer loads can be managed most effectively to enable more photovoltaics on the grid. This includes determining the extent to which on-site advanced loads can help mitigate impacts of distributed solar generation and enable higher penetrations and reviewing the most common and most significant (in terms of impact) smart customer loads, including EV chargers, thermostats, pool pumps, and water heaters to enable more solar energy.

For both core objectives, a comprehensive laboratory and limited field demonstration were carried out with a specific focus on answering two key questions:

- How much can the solar PV hosting capacity of California's distribution systems be increased by activating the new Rule 21 smart inverter functions across multiple or all inverters?
- How much additional solar photovoltaic hosting capacity can be achieved by managing consumer loads in a fashion that is optimized for solar photovoltaic energy use?

Project Approach

The project achieved results through four core activities: (1) assessment of requirements, (2) laboratory testing, (3) field testing, and (4) research analysis.

For better coordination from a diverse set of teams, the four core activities were divided intoeight tasks: (1) general project tasks; (2) requirements development and equipment acquisition; (3) modeling and algorithm development; (4) communications and control system development; (5) development of laboratory test plan and testing; (6) field test site identification, pre-testing analysis; and testing, (7) evaluation of project benefits, and (8) technology and knowledge transfer activities.

Data from laboratory and field tests, relative to Rule 21 advanced smart inverter functions, were analyzed to assess results, derive findings and recommendations, and evaluate benefits to California ratepayers. The team also conducted technology and market transfer activities.

Project Results

Comprehensive laboratory tests conducted by two California investor-owned utilities (Pacific Gas and Electric and Southern California Edison) were primary sources from which to derive the study's findings. The laboratory test results demonstrated that the management of smart inverters and loads did not affect electric grid performance and stability. Within the configurations tested, there was no abnormal behavior observed with the size and number of solar photovoltaic systems added to the distribution grid. Furthermore, the tests showed that the inverter can supply or absorb reactive power based on the over- and under-voltage conditions, and that advanced smart inverter functions will support the local voltage when it is needed.

The field test results demonstrated that residential smart loads could consume excess solar photovoltaic production that otherwise would feed into the grid or be curtailed. The feed-in is often at a price lower than the grid electricity price. In one instance, excess solar photovoltaic production warranted triggering the discretionary pool pump load to switch on. The resulting strategy reduced the quantity of feed-in power for the whole house. This strategy allowed the project to use excess photovoltaic production for the home rather than feeding it back to the grid at lower prices. This approach increased the solar photovoltaic value to the homeowners. It can also adhere to distribution grid requirements as an asset to the utility system.

The project showed that optimizing smart inverter functions, smart load management, and adaptation of communications architecture is key to enabling greater use of solar photovoltaics.

Advancing the Research to Market

Technology and knowledge transfer activities such as the publication of research reports and scholarly articles, presentations at industry events, and informational webcasts, disseminated project findings to market stakeholders and solicited their feedback to improve project recommendations. The activities advanced the industry's knowledge of the use of smart loads and automation to effectively enable greater use of solar photovoltaics to customers and on the grid.

Recommendations

The following are the key recommendations for enabling greater use of solar photovoltaics:

- **Smart Inverter Compliant Products:** Standardize smart inverter features and compliance to advanced Rule 21 functions and their certification to ensure that their features can be validated before the installation.
- **Standards Compliant Smart Devices:** Investor-owned utilities should work jointly to have adequate smart device manufacturers and technology integrators develop standards-compliant products and ensure that they are validated in the field.
- **Decentralized Communications and Controls Architecture:** Review modular system architecture for practical applications across the industry.
- **Widescale Testing of Rule 21 Functions:** State agencies and investor-owned utilities should conduct tests before widescale use. In addition, the manufacturers must ensure that the user manuals and features are improved and standardized to support proper programming, installation, and commissioning of the smart inverters.
- **Assessing Smart Inverters and Loads for Solar Photovoltaic Optimization:** Neighborhood field tests should be more accessible to facilitate administering further testing of solar photovoltaics.

Benefits to California

In alignment with the state's goals for ratepayers, the results and recommendations from the project could benefit California ratepayers in the following primary ways: (1) lower costs, (2) greater electricity reliability, and (3) improved safety. In addition to these three key benefits to ratepayers, the project results are practical and achievable in the immediate future. Although the field tests were limited to one home, and the results were limited, the potential scaling of the results to hundreds or thousands of homes can realize the potential for mass-market adoption. This goal of market adoption is furthered by the project’s focus on the priority needs of customers and the utilities.

The project made the most of the inverters and other loads by leveraging devices and systems that already exist in consumer homes, as opposed to adding new types of equipment that may not exist in scale or will not be adopted for some time. In this way, the results of these developments can be immediately scaled and replicated.

The distributed energy resource devices and systems were reviewed for the viability of mass-market adoption and benefits to California. This project’s results and recommendations are intended to advance the industry’s knowledge of the use of smart loads and automation to effectively enable greater use of solar photovoltaics to customers and on the grid.

CHAPTER 1: Introduction

California has plans for aggressive deployment of inverter-based distributed energy resource (DER) technologies such as energy storage and solar photovoltaics (PV). In Assembly Bill (AB) 2514 (Skinner, Chapter 469, Statutes of 2010), the California Public Utilities Commission (CPUC) set a target of 1,325 megawatts (MW) of energy storage for procurement by 2030 (AB 2514, 2010; CPUC 2020a). The CPUC has three important goals for the procurement of energy storage: (1) peak load reduction, (2) renewable energy integration, and (3) reduction of greenhouse gas emissions. Within the goal of aggressive deployment of renewable energy generation, the state's Go Solar California campaign, a joint effort between the CPUC and the California Energy Commission (CEC), has a procurement goal of 3,000 MW of customer-owned distributed solar (homes and businesses) and a budget of $3.3 billion (Go Solar 2020). When this report was published, the campaign had more than 9 MW of solar installed, with more than a million projects. A sizable portion of California's policy goal is applicable to the electric distribution system that is managed by the distribution utilities.

> In addition to these statewide policies, with emphasis on the inverter-based DER technologies, the CPUC Electric Rule 21 (Rule 21) tariff (CPUC 2020b) describes the interconnection, operating, and metering requirements for generation facilities to be connected to a utility's distribution system. The tariff provides customers wishing to install generating or storage facilities on their premises with access to the electric grid while protecting the safety and reliability of the distribution and transmission systems at the local and system levels.

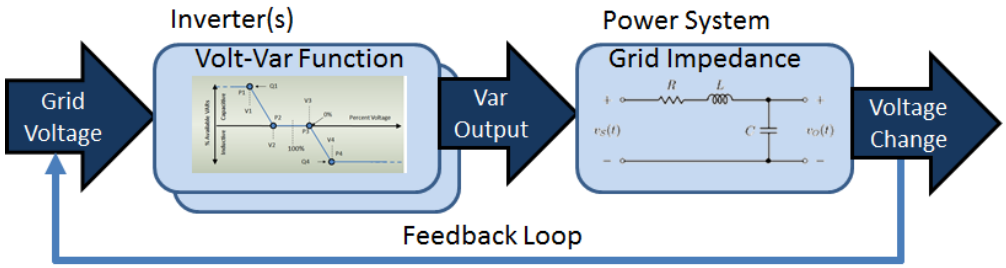
In 2014, CPUC adopted revisions to Rule 21 that required California's three investor-owned utilities (IOUs)—Pacific Gas and Electric Company (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric Company (SDG&E)—to implement the recommendations from the smart-inverter working group (SIWG) that focused on the technical requirements for inverter-based DERs (SIWG 2014; CPUC 2020c). Applications of these technical functions have led to the emergence of the term "smart inverters."

With these widespread deployment plans of smart inverters in California that support the state's policy goals, one of the key challenges originating from the smart inverters is not well studied: how multiple inverters can operate side-by-side in a stable and beneficial fashion when each is performing individual smart-inverter functions.

The lack of timing-specific requirements in the smart-inverter standards such as those in the Institute of Electrical and Electronics Engineers (IEEE) 1547-2018 edition (IEEE, 2018) creates a risk that multiple devices could interact negatively. This issue is a major concern at the residential level, where multiple homes share the same distribution-level transformer, feeder, or substation. Such limitations have occurred where consumers are not permitted to add solar, or inverters experienced shutdown due to local over-voltage conditions on the alternating current (AC) or direct current (DC) side of the inverter (NERC 2018).

As illustrated in Figure 1, other smart inverter functions also may have unintended side effects. For example, the electrical voltage and the volt-ampere reactive power (var) (or simply called the reactive power function), which has been identified in the requirements in the California Rule 21 revision process, are among several functions that have a natural negative feedback path. They could have unintended behaviors, particularly when multiple inverters are acting together. Where voltage is required to move an electrical charge (electrons), var is a measurement unit of reactive power, which exists when the electrical current and voltage are not in phase. These functions are critical for the safe and reliable operation of a power system connected to a smart inverter.

Figure 1: Feedback Effect of Smart Inverter Functions



Source: Electric Power Research Institute

Focusing on the challenges that can be posed by Rule 21 requirements, the project sought to understand the smart inverter capabilities and assess their performance using two key methods that were developed to conduct laboratory and field testing:

Successful Side-by-Side Operation of Smart Inverters

This method is used to understand how and whether multiple inverters can operate side-by-side in a stable and beneficial fashion when each is performing individual smart inverter functions. It also could be used to understand the timing-specific requirements in the standards that are used for smart inverters to address any risks from multiple devices that could interact undesirably. This method also is used to understand the links of both objectives to smart inverter certification practices, such as Underwriters Laboratory's 1741-2018 edition standard (UL 2010), to assess the potential for this kind of interaction.

Using Residential Smart Loads to Enable More Solar PV on the Grid

This method was used to understand to what extent on-site advanced or smart loads such as air-conditioning, pool pumps, electric vehicle (EV) charging, and water heaters can help mitigate impacts of solar PV distributed generation (DG) and enable higher penetrations thereof. The other objective was to understand the application of general demand management of these kinds of consumer products to enable more solar energy.

This research project was conducted under the premise that the extant research has not addressed these issues. Smart inverter manufacturers for solar PV and other DERs such as energy storage and EV are not naturally motivated to carry out research with competitors and have been reluctant to expose the critical timing and control-loop characteristics of their equipment. Most independent and funded research projects have been narrowly focused on individual inverters, leaving a gap in knowledge that puts California's statutory policy goals at risk. This project was conducted to address this issue because neither individual manufacturers nor testing agencies have an incentive to do so and are not directly affected by the negative interactions that might occur.

Purpose

The project purpose was to directly assess two methods for assessing smart inverter behavior using laboratory and field tests: (1) successful side-by-side operation of smart inverters, and (2) using residential smart loads to enable more solar photovoltaics on the grid. It exercised the functions called out in the California Rule 21 revision drafts and operated in both laboratory and field environments to assess the ability of smart inverters and smart loads to enable greater use of residential solar PV. Specific smart load management algorithms and communications architecture were developed, and the DER devices and systems were reviewed for the viability of mass-market adoption and benefits for California. This project's results and recommendations are intended to advance the industry's knowledge of the use of smart loads and automation to effectively enable greater use of solar PV to customers and on the grid.

Goals and Objectives

The project goal was to conduct a comprehensive evaluation of advanced or smart inverter functionalities and management of smart loads, to enable higher penetration levels of solar PV systems to customers and the grid. The project focused on the local hosting limitations that occur when multiple solar PV systems are installed on the same residential transformer. The project intended to mitigate the limitations by (1) smart management of residential loads, and (2) measuring and analyzing the impacts on smart inverter functionalities. The project had two core objectives, as follows:

- **Core Objective 1:** Provide insight into whether specific function and control-loop timing parameters are necessary to enable successful side-by-side inverter operation: This project provided insights into whether specific function and control-loop timing parameters are necessary to enable successful side-by-side inverter operation. This includes identifying the key factors that limit the local PV hosting capacity, determining which Rule 21 functions can be configured to interoperate in a supportive way, and quantifying which local hosting capacity can be increased by using the smart inverter functions. These findings were coordinated with relevant standards organizations so solutions can be standardized, and the issues can be addressed for California and globally. Addressing these issues at this level was necessary to enable mass deployment of solar PV and battery storage in California, to help the state meet its policy goals.
- **Core Objective 2:** Advance the industry's knowledge regarding how consumer loads can be managed most effectively to enable more PV on the grid: In addition to evaluating smart inverters, the project determined the extent to which on-site advanced loads can help mitigate impacts of distributed solar generation and enable higher penetrations. The project reviewed the most common and most significant (in terms of impact) smart customer loads, including EV chargers, thermostats, pool pumps, and water heaters. General demand response (DR) management of these kinds of consumer products is not new, but the application to enable more solar energy is an area where more research was much needed.

For both objectives, a comprehensive laboratory and limited field demonstration were carried out with a specific focus on answering two key questions:

- How much can the solar PV hosting capacity of California's distribution systems be increased by activating the new Rule 21 smart inverter functions across multiple or all inverters?
- How much additional solar PV hosting capacity can be achieved by managing consumer loads in a fashion that is optimized for solar PV energy use?

Smart management or DR application of other potential on-site DERs, such as stationary battery storage, are also possible and are being studied (DOE 2016). This research focused on consumer loads because they exist naturally and are most likely to be available to meet California's policy goals. This is a key approach to the overall economic feasibility of the methods developed in the project.

Report Organization

The report is organized as follows:

- Chapter 2 describes the technical approach taken to meet the project's goals and objectives.
- Chapter 3 reviews the laboratory and field tests for smart inverters and smart loads and presents the results from the analysis of these tests.
- Chapter 4 summarizes the technology and market transfer activities that were conducted to relevant market stakeholders.
- Chapter 5 lists project findings and recommendations based on lessons from the technology and knowledge transfer activities and the laboratory and field test results.
- Chapter 6 summarizes the benefits to California ratepayers based on project findings.

CHAPTER 2: Project Technical Approach

The project achieved the results through four core activities: (1) assessment of requirements, (2) laboratory testing, (3) field testing, and (4) research analysis.

For better coordination from a diverse set of team members and technical activities, the four core activities were split into eight tasks. Table 1 lists the tasks and their respective outcomes, which are described further in the following sections. The outcomes or deliverables that are not included in this report are listed under either the References or Appendices sections at the end of this report.

Table 1: Project Tasks and Outcomes

Task	Task Name and Outcomes	Core Activity
1	**General Project Tasks** Weekly team meetings, monthly reports, industry meetings, and regular update meetings with the CEC	N/A
2	**Requirements Development and Equipment Acquisition** Smart inverter and communications and control gateway requirements (Appendix B, EPRI 2016a; EPRI 2016b) Functional specifications for testing solar and smart consumer devices (EPRI 2016c; EPRI 2018)	Assessment of Requirements
3	**Modeling and Algorithm Development** Optimal methods and algorithms (inverters and smart loads) to enable greater use of solar energy (Appendix C)	Assessment of Requirements
4	**Communications and Control System Development** Market-ready and tested communications and monitoring system and architecture to coordinate solar PV and loads (Appendix D)	Assessment of Requirements
5	**Development of Laboratory Test Plan and Testing** Laboratory test plan (Appendix E), test procedures (Appendix F: Test Procedures: Southern California Edison), test reports (Appendix G: Test Results: Southern California Edison and Appendix H: Smart Inverter Voltage Support Functions), and data analysis	Laboratory Testing
6	**Field Test Site Identification, Pre-Testing Analysis, and Testing** Field test site description and field test plans (Appendix I: Field Test Site Description and Test Plan)	Field Testing
7	**Evaluation of Project Benefits** Results (Appendix J and Appendix K), recommendations, and assessment of benefits to California	Research Analysis
8	**Technology and Knowledge Transfer Activities** Summary of technology and knowledge transfer activities	Research Analysis

Source: Electric Power Research Institute

The following section describes each of these tasks.

Assessment of Requirements

In preparation for the laboratory and field-testing environment, the project team developed the scenarios or requirements to be tested and procured the equipment.

Requirements Development and Equipment Acquisition

The task included the development of requirements for smart inverters, smart loads, and communication and control gateways that would be used to manage smart loads (EPRI 2016a; EPRI 2016b). The functional specifications were developed for smart inverters and smart consumer loads or devices to ensure adequate procurement of equipment for testing (EPRI 2016c; EPRI 2018). Appendix B provides an overview of the control and communication requirements for a system designed to manage smart loads and smart inverters at home.

For assessment, the project used conventional (non-smart) inverters in the testing. The purpose of this inclusion was to assess the interaction and behavior of conventional inverters and smart inverters when operating side-by-side under a variety of operating conditions. Conventional inverters are presently deployed throughout California, and when new grid codes go into effect, the new products will be operating alongside the conventional inverters for some years.

Inverters with California Rule 21 Functionalities

The project reviewed designs and functions from different inverter manufacturers with the goal of testing several brands in the laboratory. The project team acquired and tested a range of residential-scale inverters presented by manufacturers as having the functionality to satisfy the revised Rule 21 requirements of advanced functions (SIWG 2014). Team members worked with inverter manufacturers who had indicated they have smart inverters relative to Rule 21 capabilities. Table 2 shows the functions that Rule 21-compliant inverters must support, as well as their due dates.

The key smart inverter functions reviewed to enable more solar energy hosting at the local, residential level are "volt-var" mode and "volt-watt" mode. As illustrated in Figure 2 and Figure 3, Rule 21 functions involve configuration "curves" that enable the inverters to independently and instantaneously react to power changes. For PG&E laboratory tests, smart inverter modes were configured to the recommended settings (or curves) according to the volt-var (Table 3, Figure 2) and volt-watt (Table 4, Figure 3) values for PG&E's service territory (PG&E 2018).

Table 2: Rule 21 Functions, Definitions, and Due Dates for Compliance

Function	Name	Definition	Due Date	Entity and Tests Performed
1	Low-/High-Frequency Ride-Through	Ability of smart inverter to ride through a certain range of frequencies before tripping off.	June 22, 2020*	Tests 6, 7 performed (SCE per inverter test plan)
2	Low/High Voltage Ride-Through	Ability of smart inverter to ride through a certain range of voltages before tripping off.	June 22, 2020*	Tested by tests 4, 5, (SCE per inverter test plan)
3	Monitor Distributed Energy Resource	Ability to monitor the state of DER technology operations.	June 22, 2020 (CPUC 2020b)**	Tested by PG&E per lab test plan
4	Anti-Islanding Protection (DER Connect/Disconnect)	Ability to detect the loss of utility/grid source and cease to energize.	June 22, 2020 (CPUC 2020b)**	Tested by PG&E per lab test plan
5	Volt-Watt and Frequency-Watt (Limit Maximum Active Power)	Ability to control real power as a function of voltage or frequency.	June 22, 2020 (CPUC 2020b)**	Test 13, 14 tests function 5 (SCE per inverter test plan)
6	Ramp Rates (Set Power Modes and Values)	Ability to have an adjustable entry service ramp-rate when a DG restores the output of active power or changes output levels over the normal course of operation.	June 22, 2020 (CPUC 2020b)**	Test 12 tested by function 6 (SCE per inverter test plan)
7	Fixed Power Factor	References power factor that is set to a fixed value. Also referred to as “specified power factor” or “adjustable constant power factor”.	12 months after the nationally recognized standard	This is part of validation testing. (SCE per inverter test plan)
8	Voltage-Reactive or Volt-Var (Dynamic Reactive Support)	In reference to control of reactive power output as a voltage function.	12 months after the nationally recognized standard	Tests 14, 15 tested by Function 8 (SCE per inverter test plan)

*** The due date was originally set for February 22, 2019, but on March 20, 2020, it was extended by the CPUC to June 22, 2020.**

**** The deadline is scheduled after the completion of the project and includes functions for Phase 2 communications requirements and Phase 3 requirements.**

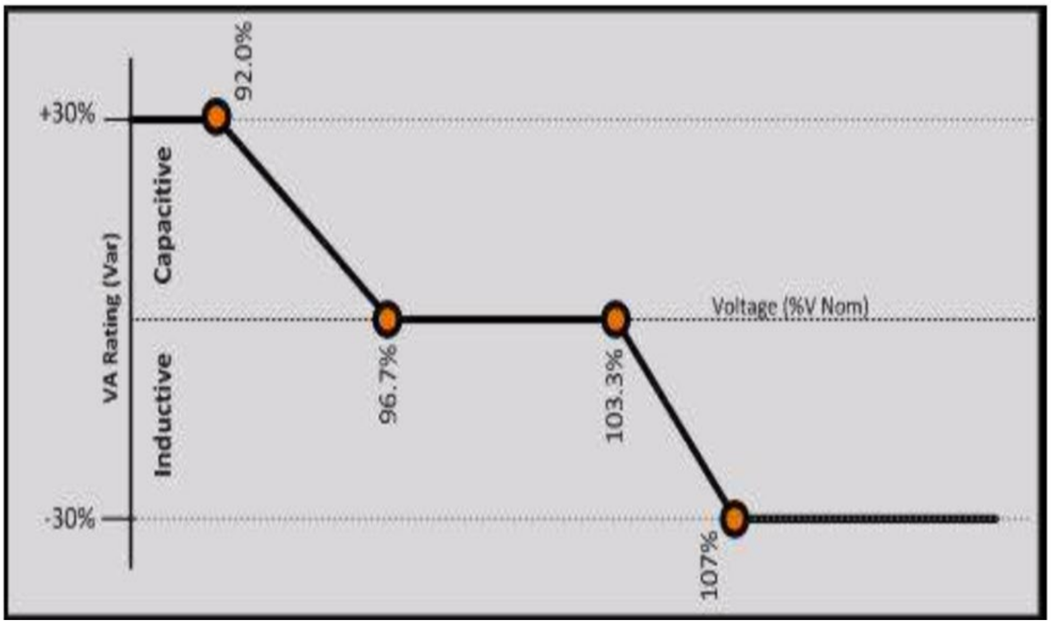
Source: Electric Power Research Institute

Table 3: Default Smart Inverter Voltage (volt) and Reactive Power (var) Settings

Voltage Setpoint	Voltage Value (%)	Reactive Setpoint	Reactive Value (%)	Operation
V1	92.0	Q1	30	Reactive power injection
V2	96.7	Q2	0	Unity power factor
V3	103.3	Q3	0	Unity power factor
V4	107.0	Q4	30	Reactive power absorption

Source: Electric Power Research Institute

Figure 2: Default Smart Inverter Voltage (volt) and Reactive Power (var) Settings



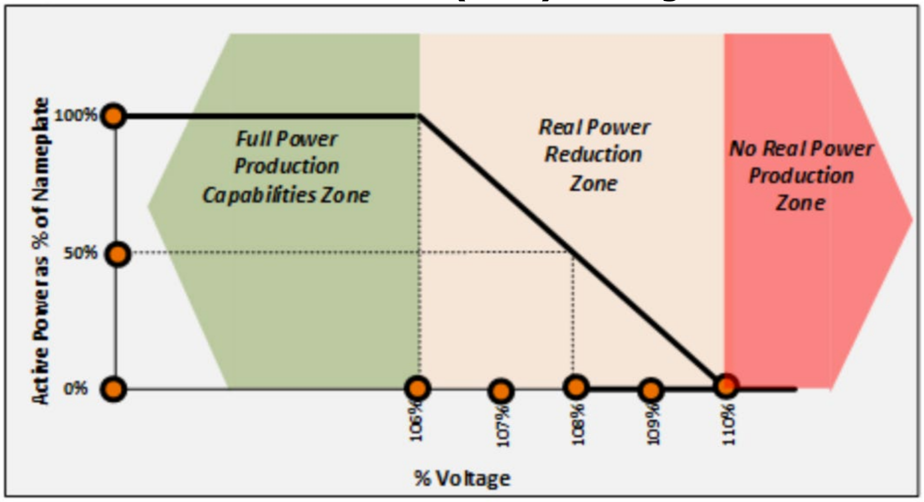
Source: Electric Power Research Institute

Table 4: Default Smart Inverter Voltage (volt) and Active Power (watt) Settings

Voltage Setpoint	Voltage Value (%)	Active Setpoint	Active Value (%)
V1	106.0	P1	100
V2	110.0	P2	0

Source: Electric Power Research Institute

Figure 3: Default Smart Inverter Voltage (volt) and Active Power (watt) Settings



Source: Electric Power Research Institute

The volt-var and volt-watt modes are voltage-driven functions due to the voltage-related nature of the issues that occur at the local level (i.e., single residential inverter or transformer). These smart inverter functions, as defined in the California Rule 21 requirements, were used for laboratory testing.

Smart Consumer Devices

In addition to multiple inverters operating side-by-side, a range of advanced consumer products were evaluated, as they operate alongside and support the solar PV systems. The specific products investigated for laboratory tests are those that represent the largest consumer loads and have been successfully used in DR programs in the past--for example, water heaters and EV chargers. Traditional DR programs, and the majority of the industry's knowledge, are centered on uses that help manage wide-area system peak demand, including aggregation and participation energy markets (EPRI 2017).

As solar energy becomes more abundant, the application of DR must advance and evaluate the optimal way in which smart consumer loads should be managed locally or within a sub-system or a system to directly support greater use of solar energy. Besides the integration issues, the first order limiting factor for solar PV is at a local level and its connected distribution system, where voltage regulation, variability, and asset loading stand to limit the increase in hosting capacity. Here, localized DR could play a useful role.

The project considered this advanced application of DR principles and developed specific control schemes by which these naturally available products (things people buy and use today) can best work alongside smart inverters. While extant research is determining the best ways for inverters to support grid reliability and flexibility, similar emphasis for supported smart devices does not exist (EPRI 2016a). The project considered the following types of smart consumer devices:

Electric Vehicles and Chargers: Intelligent EV charging is playing a prominent role with utilities, automotive, and standards organizations relative to emerging systems for DR. When EVs are connected, a significant opportunity exists to mitigate the impacts of solar generation.

EVs store energy and can potentially charge at variable levels. Some of the EV chargers support standards-based communications such as Open Charge Point Protocol, Consumer Technology Application, or CTA-2045 standards to manage EV charging (van Amstel et al. 2020; CTA 2018). The project evaluated how such factors could support avoiding undesirable curtailment of solar PV systems.

Advanced or Smart Loads: The industry is producing products to manage residential and commercial loads that are compatible with California's grid codes (Ghatikar et al. 2015). These include devices with two-way communications and DR capabilities. The project re-evaluated thermostat capabilities (EPRI 2014), focusing on the uses relative to PV generation. Heating or cooling systems with thermostatic controls may be able to align operation with periods of peak solar output, reducing over-voltage and other limiting factors. Manufacturing of grid- and standards-supportive water heaters is mainstreamed, as well. The project identified how water heaters could offset solar impacts and implemented these capabilities to support laboratory testing. Similarly, pool pumps, including advanced variable-speed types that are more efficient, can be used for DR programs. The project investigated and implemented the variable up or down and ON or OFF optimized control capabilities of the pool pumps in relation to the solar variability. Other types of DER, such as stationary battery storage at the home or community level, also have the potential to address solar variability. Such devices would notionally have great ability to enable more solar energy depending on availability and cost constraints.

Modeling and Algorithm Development

The project developed advanced load management methods to provide a mechanism to improve distribution system performance, such as voltage, to accommodate higher levels of solar PV. The project identified the specific algorithms and optimal means by which smart inverter functions can be used to enable more solar PV to be connected at the residential level distribution system. These advanced methods and algorithms were used to test smart inverters that included control gateways with cellular communications and control modules that supported the CTA-2045 standard.

The controls strategy for each home was used to solve the local optimization problem for the greater use of solar energy. These optimization schemes included:

- Which loads should be ON to consume predicted solar energy.
- Remaining solar energy that can be offered to neighbors.
- Solar PV prediction that is based on the hourly weather forecast.
- Prioritization of loads based on the evaluation of grid impact and consumer comfort.

Consumers had the option to modify these priorities; for example, they could opt out. Within the optimization problem with the objective to use more solar energy, the use of smart loads was prioritized based on impact on the homeowner's comfort. Homeowners had the option to prioritize the use of smart loads via a graphical user interface (GUI), and they had an option to initiate opt-out or override from the optimization. The DER optimization evaluated the smart inverter controls: power factor, volt-var, and volt-watt. The laboratory testing leveraged these optimization scenarios. The related research outcome was summarized in a technical report (EPRI 2016d). In this report, computer modeling and simulation tools and methods were used to make determinations to maximize the use of solar PV. The Open Distribution System Simulator (OpenDSS) tool was used for power system modeling (EPRI No Date).

Communications and Control System Development

The project performed different forms of analysis that significantly advanced the state of the art. These analyses included the following:

- Modeling the California Rule 21 functions and adding the inverter control loop characteristics into the models to discern potential negative interactions between inverters.
- Studying the issues on the customer secondary, and developing secondary, models according to the real California distribution systems in which the laboratory and/or field testing were conducted.
- Modeling the behaviors of the other DER and the consumer devices to enable simulation of the smart inverter functions and other DERs acting together. This analysis was used to determine optimal settings for all the equipment used in the laboratory and field testing.

For each inverter acting alone, and together with other DERs, an analysis was performed, and optimal behaviors were identified for each of the top three solar PV-limiting conditions:

- Local over-voltage (stemming from higher levels of PV generation).
- Voltage variability (stemming from natural solar variability).
- Asset loading and reverse power limitations.

Connectivity and Communication Architecture

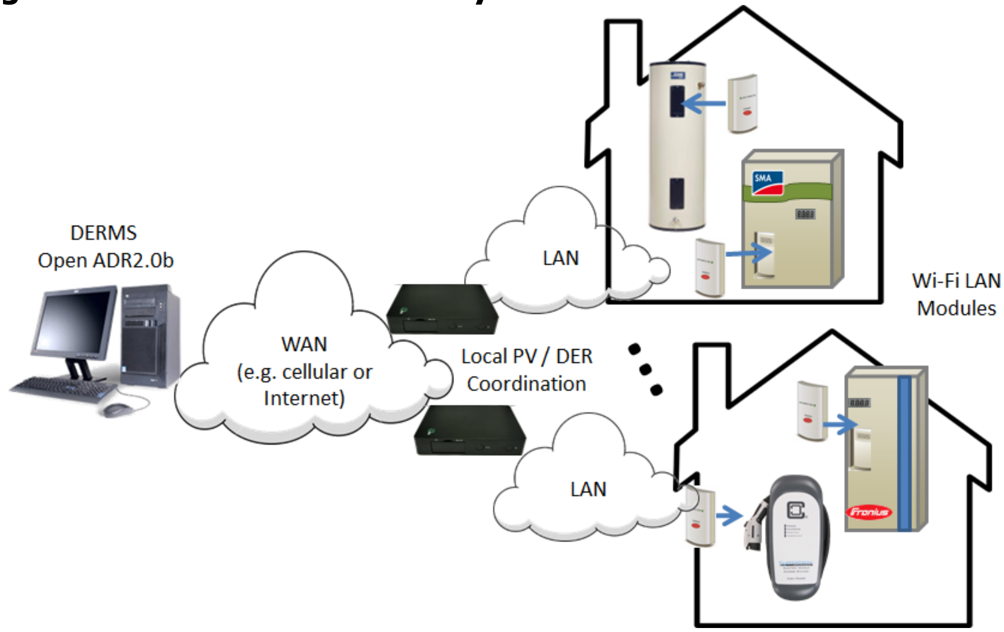
One key objective of the project was to use connectivity and communications for automation that are critical for the practical application of research outcomes. The project used an open standards-based approach wherever circumstances permitted. This was a critical element to further the goals of the Rule 21 Phase 2 process of controls and communication functions that will set the stage for real market production.

Figure 4 shows the connectivity and communications architecture for the field tests. The key components included the following:

- **Local Area Networks (LANs):** All the smart devices, including the smart inverters, were connected via Wi-Fi or LAN.
- **Solar Inverter Interfaces:** Solar PV inverters communicate using standardized communications. Wherever available, the CTA-2045 standard with Wi-Fi was used.
- **Other Smart Devices:** All smart devices communicate using standardized communications. Wherever available, the CTA-2045 standard with Wi-Fi was used.
- **Energy Management Systems:** Each home had an energy management system (EMS) or a local controller that managed smart devices within that home. These EMSs had an upstream communication interface to the head-end system and downstream communication to the individual devices. The capability and algorithms were developed within the EMSs or on the cloud to perform the logic desired for each test step. The architecture was developed to enable testing modes that require fast and frequent communication as well as slower communication.

- **Decentralized System:** A local and head-end software was developed to enable remote monitoring and management of the field testing with decentralized or peer-to-peer principles. The system can coordinate at the "local or community" level — across the group of controllers at homes or a home.

Figure 4: Field Test Connectivity and Communications Architecture



Source: Electric Power Research Institute

The Rule 21 activity to assess the requirements formed the bases for application within the laboratory and field testing, as applicable. Even in instances where the requirements were not tested in either/or the laboratory or field tests, the outcomes from the project will help the industry with activities outside the scope of the project. Appendix D describes a multi-agent system to coordinate solar PV and smart loads at home.

Laboratory and Field Testing

The laboratory testing allowed power quality functions (for example, voltage, frequency), solar variability, and consumer activity to be varied in a controlled fashion, thereby evaluating the full range of conditions. Field tests from the project highlighted the real-world conditions, including power quality changes and other factors that were induced by load changes. Another key aspect of the testing was the communication and controls architecture that reflected the real-world conditions. The project measured the total solar generated at home, net load at each home during the test and non-test days, energy profiles, and power quality measurements at the smart inverter. The tests primarily focused on the application and communication of smart load management algorithms developed in the project. The results enabled comparison of the net load at each home and the ability to observe the impact of the tests on the smart inverter's power quality and the use of solar energy. The power quality data were used to review any deleterious impacts of the treatment and to determine the impacts on the solar hosting capacity.

In the testing environment, the equipment was provisioned, and experiments were carried out to attain the project objectives, as outlined in Chapter 1.

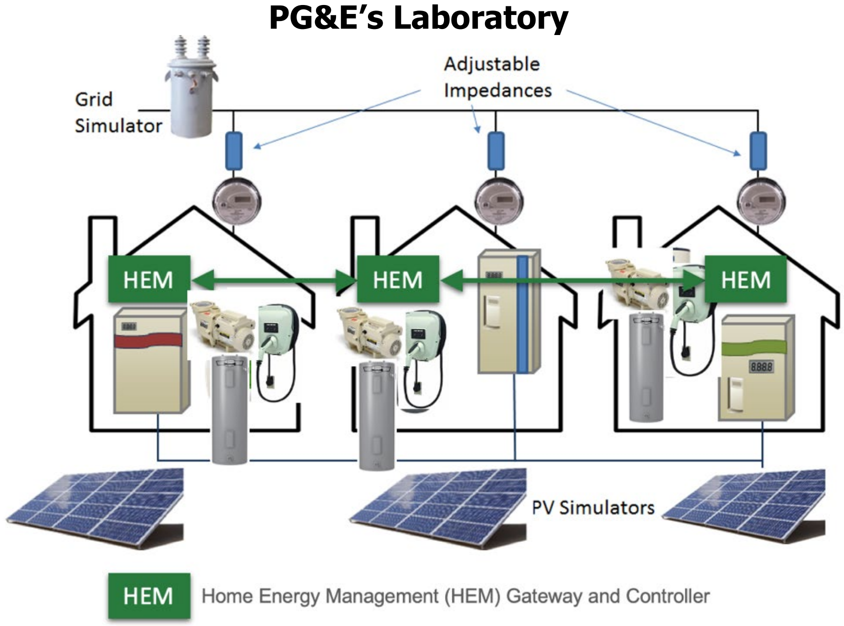
Development of the Laboratory Test Plan and Testing

The laboratory phase of testing was conducted at PG&E's Applied Technology Services (ATS) Laboratory and at SCE. Both laboratories were well equipped with advanced technology testing and evaluations of technologies, including those such as DG and battery energy storage, emerging technologies and DR, solar PV inverters, and smart grid applications on the distribution system. The project procured the following four smart consumer devices for testing at PG&E Laboratory, which were compatible with the CTA-2045 standard and communicated using Wi-Fi:

- Programmable thermostat.
- Heat-pump water heater (50-, 66-, and 80-gallon sizes).
- Variable-speed pool pump with DR controller.
- EV charger with CTA-2045 module and wireless communications.

The ATS Laboratory was designed, built, and configured as illustrated in Figure 5. This arrangement simulated a set of three homes on a shared distribution transformer. Each home was set up with a solar inverter and smart devices. The homes tested water heaters, pool pumps, and EV chargers with smart inverters. Although the thermostat was not part of the tests, it was used for control loop testing with the site controller, to obtain temperature settings, and to identify demand-management strategies.

Figure 5: Configuration of Homes, Inverters, and Smart Devices at PG&E's Laboratory



Source: Electric Power Research Institute

Bulk impedances were inserted between the homes and the common tie point at the transformer to simulate the various secondary line lengths that would be found in California's residential communities. This was a key step to accurately evaluate multi-inverter interactions and to assess the stability of the Rule 21 functions.

The laboratory testing was carried out in two steps: (1) multi-inverter testing and inverters, and (2) other DERs or smart devices. Each step assessed the stability of operation and then determined the possible increase in solar PV hosting capacity.

The expectation was that Rule 21 would become effective as soon as the project started. However, everything took longer than expected and Rule 21 standards were delayed. As the functionality compliant due dates for inverters came in, the project team felt the need to run these tests to make sure no impact to the grid incurred or better understand the impacts. Note that Rule 21 inverters were smart enough to adjust their behaviors due to environmental factors. The lab tests helped to see the behaviors to validate the inverters against Rule 21. The PG&E lab tests show interaction with DERs turned ON and OFF to determine the effects.

The planned test sequence summarized in Table 5 leveraged the detailed test plans that were developed to support testing. Table 5 shows a summary of the 17 tests from the detailed test plan, which is included in Appendix E.

Table 5: Summary of Tests from Detailed Test Plan

Test No.	Test Description
2.1	Harmonics from all three smart inverters under resistive load and steady-state conditions
2.2	Harmonics generated by all three smart inverters with all smart loads
3.1	Autonomous under-voltage and over-voltage support (var priority)
3.2	Autonomous under-voltage and over-voltage support (Watts [W] priority)
4.1	Smart load (measurement and power) characterization
5.1	Fixed reactive loads (var priority)
5.2	Fixed reactive loads (W priority)
6.1	Varied PV (var priority)
6.2	Varied PV (W priority)
7.1	Continuous electronic load and smart loads (var priority)
7.2	Continuous electronic load and smart loads (W priority)
8.1	Varying smart loads (var priority)
8.2	Varying smart loads (W priority)
9.1	Additional conventional inverter with varying smart loads (var priority)
9.2	Additional conventional inverter with varying smart loads (W priority)
10.1	Additional conventional inverter with varying smart loads with varying grid voltage (var priority)
10.2	Additional conventional inverter with varying smart loads with varying grid voltage (W priority)

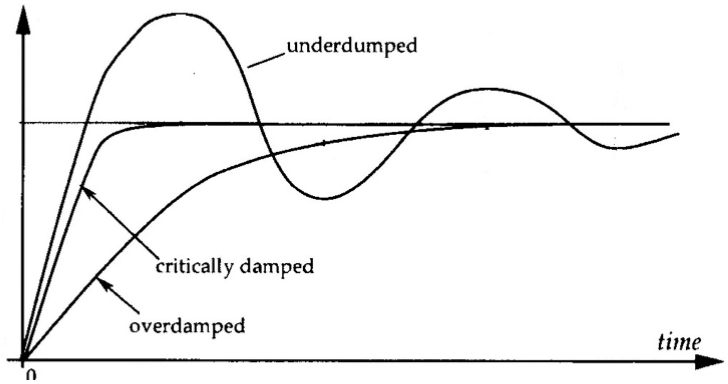
Source: Electric Power Research Institute

The following parameters were captured for the PG&E laboratory tests:

- **Secondary voltage power quality:** This measurement looked for harmonics and indicators of instability, such as low-frequency oscillatory behavior.
- **Inverter power ON or OFF:** This test assessed the response of the group of inverters upon recovery when one or more started up or shut down due to command or grid outage. The tests required the smart inverters to be at steady-state and characterized if the inverter was inadvertently powering off.

- **Response to step change in grid voltage:** This test involved generating a step increase and a step decrease in the primary side grid voltage. This test simulated changes that may occur during normal operation when capacitor banks are switched or when taps change on transformers or regulators. The captured data included the secondary voltage and the current output from each of the PV inverters under test. As illustrated in Figure 6, the aggregate inverter responses indicated some degree of stability or instability in reaching their new setpoint. The oscillatory behavior, as shown by the "underdamped" curve, indicates near instability. If near-oscillatory results are seen in any of the tests, that condition will be exacerbated to fully understand the situation. Here, three voltage ramp levels—0.4 volts (V)/sec, 0.8 V/sec, and 1.6 V/sec—were tested, along with areas of instability.

Figure 6: Example Response Types to System Disturbances



Source: Electric Power Research Institute

Response to step change in load: This test assessed the group of inverters' responses to a step change in local load in the test homes. This test simulated the start-up of a pool pump, water heater, or EV charger.

Response to a step change in solar PV output: This test was to simulate conditions when the solar PV output of all systems changed rapidly. However, it was not conducted because the inverters were all operating at about 60 percent nameplate rating due to solar simulator limitations.

For each test that involved smart inverters, the inverters were reconfigured with the following function combinations for each test:

- Volt-var function (watts precedence).
- Volt-watt function (in conjunction with volt-var).
- Fixed power factor.

Table 6 shows the six test sequences and a description of the tests conducted at the ATS Laboratory. These tests were a subset of the 17 tests in the detailed test plan and were selected to be essential to meet the project goals and objectives. The additional test cases included in the test plan serve as a reference for the industry.

Table 6 describes Harmonics tests, even though Rule 21 may not include Harmonics requirement testing. It is good to qualify the inverter functionality operable and satisfactory. Quality inverters should not have Harmonics; this allows testing to be done for basic operations of inverters for any interferences. An older Rule 21 may have included Harmonics as a testing requirement.

Table 6: Laboratory Test Sequence and Test Description

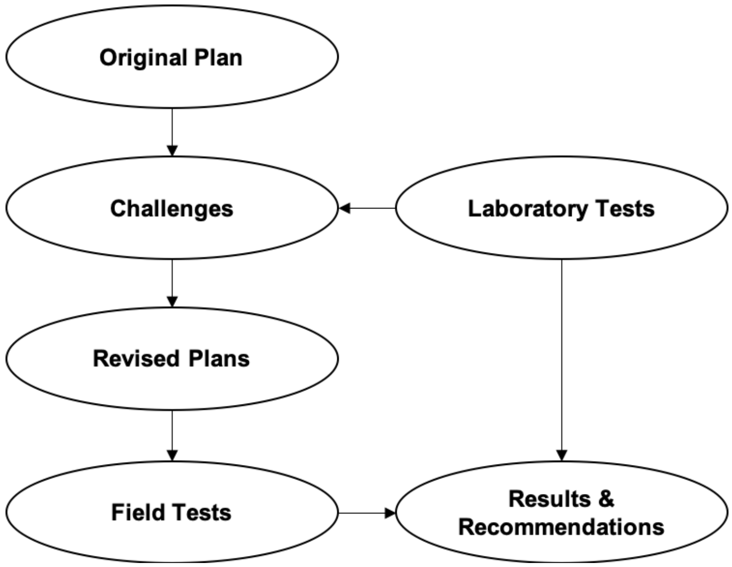
Test No.	Description
2.1	Harmonics from all three smart inverters under resistive load and steady-state conditions
2.2	Harmonics generated by all three smart inverters with all smart loads
7.1	Continuous electronic load and smart Loads (var priority)
8.1	Varying smart loads (var priority)
9.1	Additional conventional inverter with varying smart loads (var priority)
10.1	Additional conventional inverter with varying smart loads with varying grid voltage (var priority)

Source: Electric Power Research Institute

The original plan proposed field tests at multiple utility territories. One of the tests was to be carried out at a site in SCE service territory with solar PV systems. The other field-testing site was planned to be within the Sacramento Municipal Utility District (SMUD) service territory. Due to the constraints and challenges revealed by laboratory testing, the field testing was limited to one home in the SCE service territory.

This project also planned to have all homes outfitted with PV systems and smart inverters that provide the functionality identified in Rule 21. The inverters from the laboratory testing that perform the best and/or offer the greatest opportunity to learn about interactions in the field were intended for this test phase. Due to the constraints and challenges posed by the smart inverters and compliance to standards by the smart loads in laboratory testing, the testing of smart inverters installed at home was not conducted. Figure 7 illustrates the strategy used by the project to derive results and propose recommendations.

Figure 7: Project Strategy to Derive Results and Propose Recommendations



Source: Electric Power Research Institute

The details for the actual laboratory and field tests and results are provided in Chapter 3.

Field Test Site Description and Test Plan

By design, the equipment configuration in the field was intended to be similar to that used in the laboratory tests. The field testing was not planned to allow certain parameters (such as the grid voltage and frequency) to be directly manipulated. Instead, they provided an opportunity to gain several key insights:

- Operation and interaction of a greater number of inverter units.
- Real-world noise and variability conditions.
- Real-world communication integration.

In contrast to the laboratory environment, the field tests required local communication interfacing and remote management and monitoring of smart consumer devices. A detailed field test site description was prepared to identify and recruit the homes. This field test site description is shown in Appendix I.

Following the selection of the site, a detailed field test plan was prepared to conduct the tests. This field test site plan is also shown in Appendix I.

Field Instrumentation and Measured Parameters

During the field testing, an assessment of the measured parameters was carried out, as described in Table 7.

Table 7: Field Test Sequence and Indicators

Parameter	Description	Source
Watt-hours, total	Whole-home real energy	Smart meter (net load)
Watts, total	Whole-home real power (instantaneous)	Smart meter (net load)
Volt-Amps, total	Whole-home apparent power	Smart inverter
Var, total	Whole-home reactive power (instantaneous)	Smart inverter
Watts, per device	Whole-home, active power	Smart inverter
Volts	Direct-current-alternating-current (AC-DC) voltage	Smart inverter
Watts, pool pump	Pool pump real power (instantaneous)	Pool pump sub-meter
Temperature, thermostat	Whole-home heating-cooling setpoints	Thermostat sub-meter
Watts, rated capacity	Pool pump, solar PV, and energy storage	Homeowners

Source: Electric Power Research Institute

As is true with any research project, the actual tests may not always go as planned. Several factors were identified with the potential to impede the research process and/or limit the success and effectiveness of the project. This project considered a list of key factors and identified the associated mitigation strategies shown in Table 8.

Table 8: Success and Risk Factors, Mitigation Strategies

Success and Risk Factors	Project Mitigation Strategies
Residential inverter makers and owners must be willing to make the product available for testing that supports the needed functions.	Leverage project results from a prior project to engage inverter makers and secure their commitment to support the project. Work with homeowners and any existing solar PV inverters to conduct a limited set of tests. Although not ideal, carry elaborate laboratory testing that can support project objectives.
Manufacturers of EV chargers and other smart devices must be willing to make the product available with the capabilities and interfaces needed for the tests.	Partner with companies already involved in advancing these technologies. Leverage ongoing research and development funding from the project team to motivate the industry to build advanced products. Use adapter devices to enable testing using other (nonstandard) products if required.
Consumers at the field test sites must be willing to participate.	Maximize options to identify field test sites. Incentivize customers to participate. Use utility employees, existing CEC project field test sites, friends, and family homes as a backup.
Communication interfaces must interoperate to enable the mix of products to perform together.	Use all end devices with a modular communication port (CTA-2045) that can interoperate with a diversity of technology. Develop communication modules for integration of the devices, as needed.

Success and Risk Factors	Project Mitigation Strategies
	Although not ideal, use non standardized communications to achieve project objectives.
Manufacturers must be able to translate the methods and learnings of this project into retail products to realize practical benefits.	Use an incremental design approach, building the new functionality of products on existing designs. Use a standardized communication interface so products are valid/compatible in the mass market. Engage market-leading companies in the project. Align partners with a fundamental commitment in seeing these results come to the marketplace.
Interconnection rules, at a minimum, allow for the identified functionality, and, at best, require them to realize the benefits.	Recruit project partners, effective educators in the energy industry, to inform the industry of the benefits identified. Recruit project partners who are active members of relevant standards organizations to inform those bodies of the results and approaches taken.
Test results may not yield the expected level of benefits.	Support limited or lack of result as an equally valuable finding. Alternately, recognize that support for investments in other or better grid infrastructure, such as distributed storage or higher capacity feeders, may be of value.

Source: Electric Power Research Institute

Research Analysis

The laboratory and field test data were analyzed to assess results, derive findings, make recommendations, and evaluate benefits to California ratepayers. In addition, the project conducted technology and market transfer activities. The four core activities and each of the eight tasks listed in this chapter were used as a baseline for conducting laboratory and field testing.

The results from laboratory and field tests and the challenges encountered are highlighted in Chapter 3.

CHAPTER 3: Project Results

This chapter discusses the laboratory and field-testing details and results. The details include lab and field test setup, system architecture, communication technologies, measurements, and results from data analysis. Key outcomes are presented wherever relevant.

Overview

The laboratory tests were conducted within the laboratories of the electric utilities, PG&E and SCE. The field test for one home was conducted in the service territory of SCE in close coordination with the project team and the customers. The laboratory testing evaluated advanced inverter functionality and the load characteristics with the goal of enabling higher penetration levels of solar PV systems in California's distribution systems. The project tests were specifically focused on the local PV hosting limitations that occur when multiple PV systems are installed in a residential environment.

The tests investigated the dynamic performance of smart inverters with various test scenarios relevant to Rule 21 and interaction with smart loads. The laboratory test results were used to determine the plans for field tests. The test results helped the project understand the behavior of smart inverter features and system stability and determine whether they are grid-friendly under load switching and voltage events. The laboratory and field-testing details and results from an extensive data analysis are included in the following sections.

Laboratory Tests

Electric utilities PG&E and SCE conducted the laboratory tests in their respective laboratories. PG&E focused on six tests—2.1, 2.2, 7.1, 8.1, 9.1, and 10.1. SCE tests focused on tests 3.1 and 3.2 for under-voltage and over-voltage operating conditions and var and watt priorities. The laboratory tests focused on the following:

- Evaluate the extent to which Rule 21 smart inverter functions might affect total PV hosting capacity on individual residential transformers.

Rule 21 inverters operating autonomously may experience unanticipated and undesirable interactions. UL raised this as a concern since it is not under their inverter test procedures. Any autonomous functions like volt-var could lead to over correction, under correction, and isolation. That is why it is important to test all the autonomous functions. PG&E did not see any bad experience per this project. It would not be necessary to limit PV hosting capacity if it can be determined that there are no undesirable interactions between neighboring inverters acting autonomously. It eliminates one argument to limit PV hosting capacity that was previously unknown. Inverters will not behave badly, so this proves that point.

- Review Rule 21 curves that were tested as relevant to the project scope, which is included in the equipment provisioning section in Chapter 2.
- Evaluate the extent to which other DERs, including EV chargers and other smart consumer devices, can (or cannot) further increase PV hosting capacity, and test the

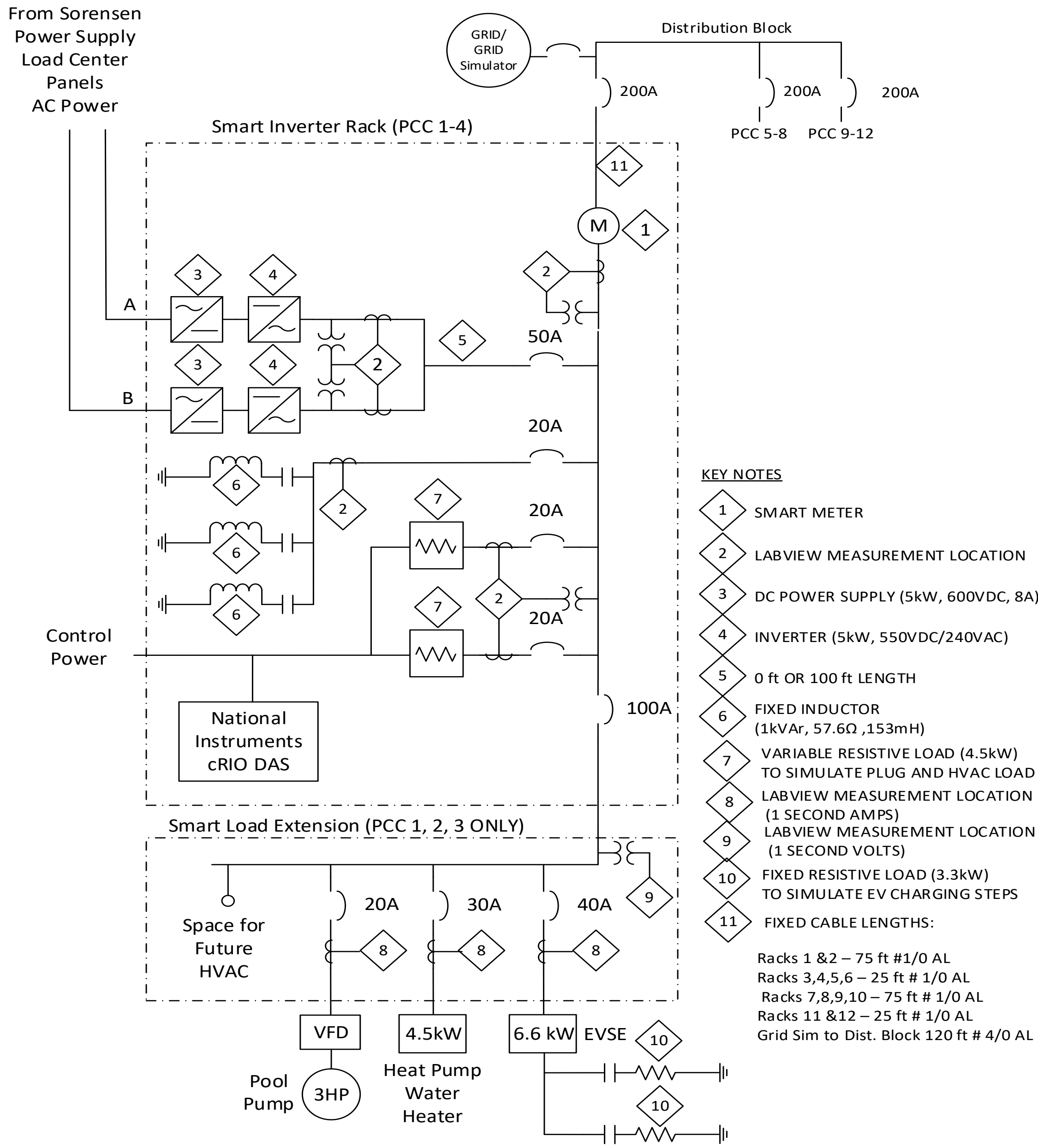
specific algorithms and methods required to achieve the indicated increases in PV production.

- Evaluate any effects on basic grid quality when operating multiple smart devices in a simulated multi-home residential environment, along with the ability to control smart devices in a field setting.

Testing at Pacific Gas and Electric Company

The test setup at the PG&E laboratory is shown as a single line diagram in Figure 8. Figure 9 shows the physical setup of the smart loads. The test setup consisted of three smart loads—pool pump, heat pump water heater, and EV charger (Smart Load Extension in Figure 8)—as well as four inverters: three smart inverters and a conventional inverter (the Smart Inverter Rack in Figure 9). A load bank with a capacity of 3.8 kilowatts (kW) represented a home. All the smart loads and inverters were equipped with meters that recorded data. The equipment was connected to a grid simulator (Grid Simulator in Figure 8) to represent a distribution grid block. LabView software was used to acquire data for analysis.

Figure 8: Single Line Diagram of the Setup for Laboratory Testing at PG&E



Source: Electric Power Research Institute

Figure 9: Smart Loads and Smart Inverter Test Setup at PG&E Laboratory

Source: Electric Power Research Institute

The test setup was used to conduct the testing of equipment individually and in a coordinated fashion. Data were recorded and analyzed for performance.

Inverters and Solar PV Simulator Equipment Under Test

Four inverters were tested. They had nameplate power ratings in the range of 3.8 kW to 5 kW. Table 9 identifies all the inverters under test. The description lists unique test cases for inverters. The vendor names are excluded to avoid any perception of product bias.

Table 9: Inverters Under Test at the PG&E Laboratory

Inverters Under Test	Make and Model	Description
Vendor 1 Nameplate Rating 3.8 kVA	SW: 2.23 running Rule 21 USA34 Grid settings SN: SJ0118-11720882E-ED	Rule 21-compliant inverter with unit software modified to allow operation without power optimizers
Vendor 2 Nameplate Rating 3.8 kW	SW: V1.1.12.1 and Rule 21 grid settings CAL 1 SN: 29043071	Rule 21-compliant inverter
Vendor 3 Nameplate Rating 3.8 kW	SW: 1.8.12 USA (Rule21)-240VSplit SN:1724118084	Rule 21-compliant inverter
Vendor 4 Nameplate Rating 5.0 kW	SW: C2.0.0.0 SN: 431635	Not Rule 21-compliant (conventional inverter)

Source: Electric Power Research Institute

Smart Loads Under Test

The smart loads in the tests included a pool pump, heat pump water heater, and EV charger, which is also technically termed "EV supply equipment" (EVSE). These smart loads, along with a smart inverter and simulated solar PV, represented each home, for a total of three homes. Table 10 identifies all the smart loads under test with loads. The description highlights any unique test cases for smart loads. The vendor names are excluded to avoid any perception of product bias.

Table 10: Smart Loads Under Test, Make and Model, and Description at PG&E Laboratory

Equipment Under Test	Make and Model	Description
Vendor 5 Pool Pump	PN#: 350035	One for each home
Vendor 6 Water Heater	PN#s: HPTU-60N-120 HPTU-66N-120 HPTU-80N-120	One for each home
Vendor 7 EV charger or EVSE	1ACACAC026 1ACACAC166 1ACACAC075	One for each home, with simulated car sensor circuitry to dispense power

Source: Electric Power Research Institute

With the inverters and smart loads under test and setup, several tests were conducted for the six test cases, as described in the test plan. The following sections describe the results from each of these tests. The test plan details are described in Appendix E.

Summary of Laboratory Test Results

Table 11 show results for the tests on multiple inverters and the Rule 21 functions tested. The results demonstrate that there were no undesirable effects on the grid of running multiple autonomous Rule 21 inverters attached to the same residential transformer, making it possible to employ the Rule 21 communication features of the inverters to balance additional local PV generation with local controllable loads.

Table 11: Summary of Tests from Detailed Test Plan

Test No.	Test Description	Results	Rule 21 Function Tested[1]
2.1	Harmonics from all three smart inverters under resistive load and steady-state conditions	No undesirable behavior observed	Hh.2.g: Harmonics
2.2	Harmonics generated by all three smart inverters with all smart loads	No undesirable behavior observed	Hh.2.g: Harmonics
3.1	Autonomous under-voltage and over-voltage support (var priority)	Inverters behaved per Rule 21. No undesirable interactions between inverters were observed.	Hh.2.b.ii: Voltage Disturbances
3.2	Autonomous under-voltage and over-voltage support (Watts [W] priority)	Inverters behaved per Rule 21. No undesirable interactions between inverters were observed.	Hh.2.b.ii: Voltage Disturbances
4.1	Smart load (measurement and power) characterization	Loads were characterized	N/A
5.1	Fixed reactive loads (var priority).	Inverters behaved per Rule 21	Hh.2.i: Fixed Power Factor
5.2	Fixed reactive loads (W priority)	Inverters behaved per Rule 21	Hh.2.i: Fixed Power Factor
6.1	Varied PV (var priority)	Inverters behaved per Rule 21	Hh.2.j: Dynamic Volt/VAR Operations
6.2	Varied PV (W priority)	Inverters behaved per Rule 21	Hh.2.m: Voltage-Watt Default Setting Requirements
7.1	Continuous electronic load and smart loads (var priority)	Inverters behaved per Rule 21	Hh.2.j: Dynamic Volt/VAR Operations
7.2	Continuous electronic load and smart loads (W priority)	Inverters behaved per Rule 21	Hh.2.m: Voltage-Watt Default Setting Requirements
8.1	Varying smart loads (var priority)	Inverters behaved per Rule 21. Transients introduced by load switching were acceptable. Inverter and load communications functioned as expected.	Hh.2.j: Dynamic Volt/VAR Operations
8.2	Varying smart loads (W priority)	Inverters behaved per Rule 21. Transients introduced by load switching were acceptable.	Hh.2.m: Voltage-Watt Default Setting Requirements
9.1	Additional conventional inverter with varying smart loads (var priority)	Inverters behaved per Rule 21. Transients introduced by load switching were handled acceptably.	Hh.2.j: Dynamic Volt/VAR Operations

[1] https://www.pge.com/tariffs/assets/pdf/tariffbook/ELEC_RULES_21.pdf

Test No.	Test Description	Results	Rule 21 Function Tested[1]
9.2	Additional conventional inverter with varying smart loads (W priority)	Inverters behaved per Rule 21. Transients introduced by load switching were handled acceptably.	Hh.2.m: Voltage-Watt Default Setting Requirements
10.1	Additional conventional inverter with varying smart loads with varying grid voltage (var priority)	Inverters behaved per Rule 21. Transients introduced by load switching were handled acceptably.	Hh.2.j: Dynamic Volt/VAR Operations
10.2	Additional conventional inverter with varying smart loads with varying grid voltage (W priority)	Inverters behaved per Rule 21. Transients introduced by load switching were handled acceptably.	Hh.2.m: Voltage-Watt Default Setting Requirements

Source: Electric Power Research Institute

The following sections show the results from the laboratory tests by PG&E.

Test 2.1 and 2.2 Harmonics and Test 10.1 in Coordination with Smart Loads

Smart inverter current harmonics can affect the grid's voltage total harmonic distortion. High harmonic generation can produce unintended negative impacts on utility field equipment such as capacitors, transformers, and switching equipment by overloading them. This test assessed the current harmonics generated by all four smart inverters under resistive load and steady-state conditions. The Test 2.1 use case evaluated the equipment under test or the smart inverter harmonics generation envelope to assess their potential impact. Test 2.2 assessed the current harmonics generated by all four smart inverters with all smart loads in an operational state. Test 10.1 evaluated the entire system operation with an additional home with a conventional inverter and with varying (increasing or decreasing) smart loads at each home.

The grid simulator was set to a nominal 240 V ±10 percent and a 60 hertz (Hz) frequency.

Test 2.1 showed harmonics levels without loads to establish a baseline. Test 2.1 with a 3.8 kW load and all inverters on converting power showed harmonics thresholds, a voltage total harmonic distortion (THD) of 0.39 percent, and a current THD of 2.50 percent.

Test 2.2, which ensured inverters were configured for autonomous Rule 21 voltage support and with all three home loads active, collected up to the 50th harmonic, showing a voltage THD of 0.21 percent and a current THD of 0.46 percent.

Test 10.1, where a conventional inverter (not supporting Rule 21) was added to the test bed, resulted in a voltage THD of 0.2 percent and a current THD of 1.11 percent.

Tests 2.1, 2.2, and 10.1 of voltage and current harmonics generated showed no potential impact to the grid and were found to be compliant with IEEE standard 1547, even with multiple inverters and smart loads.

The inverters and smart loads, operating together, did not add any additional power quality issues. Additional harmonics data from the results of tests 2.1, 2.2, and 10.1 are included in Appendix J.

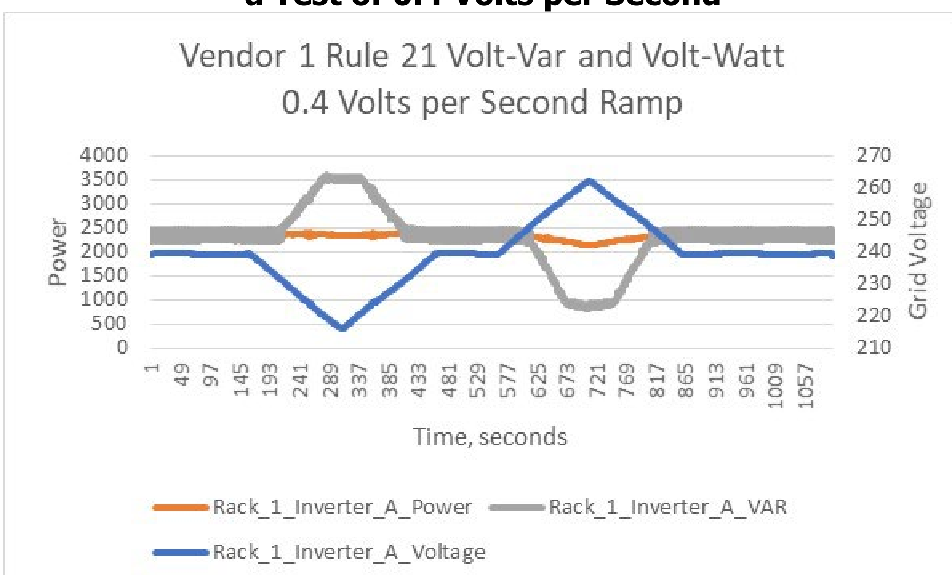
Test 7.1 Smart Loads in the ON State and Smart Inverters in Volt-Var and Var Priority

The test demonstrated the stability, quality, and load sharing of smart load operations for all three homes and an inverter under the autonomous Rule 21 operational state. This test evaluated the entire system operation with a continuous basic home load and smart loads operating at all homes to determine performance, stability, and voltage support provided by inverters under normal operating loads. In this test, no abnormal inverter behavior was detected with all three home inverters and smart loads active.

Inverters were subject to three different ramp rates: 0.4, 0.8, and 1.6 per second. The 0.8 and 1.6 per second ramp rates demonstrated similar behavior to the inverter 0.4 ramp rate shown in Figure 10, Figure 11, and Figure 12. No instability was exhibited during under-voltage conditions. However, under-voltage conditions did demonstrate that the inverter did not fully curtail active power to zero during a high-voltage ramp. This is due to the nature of inverter electronics not reacting fast enough to change during high grid voltages. The examples in Figure 10, Figure 11, and Figure 12 for volt/watt demonstrate some manufacturers' equipment exhibited a faster response. Please note that it is not a presumed failure because the inverters were still in a stable operating condition.

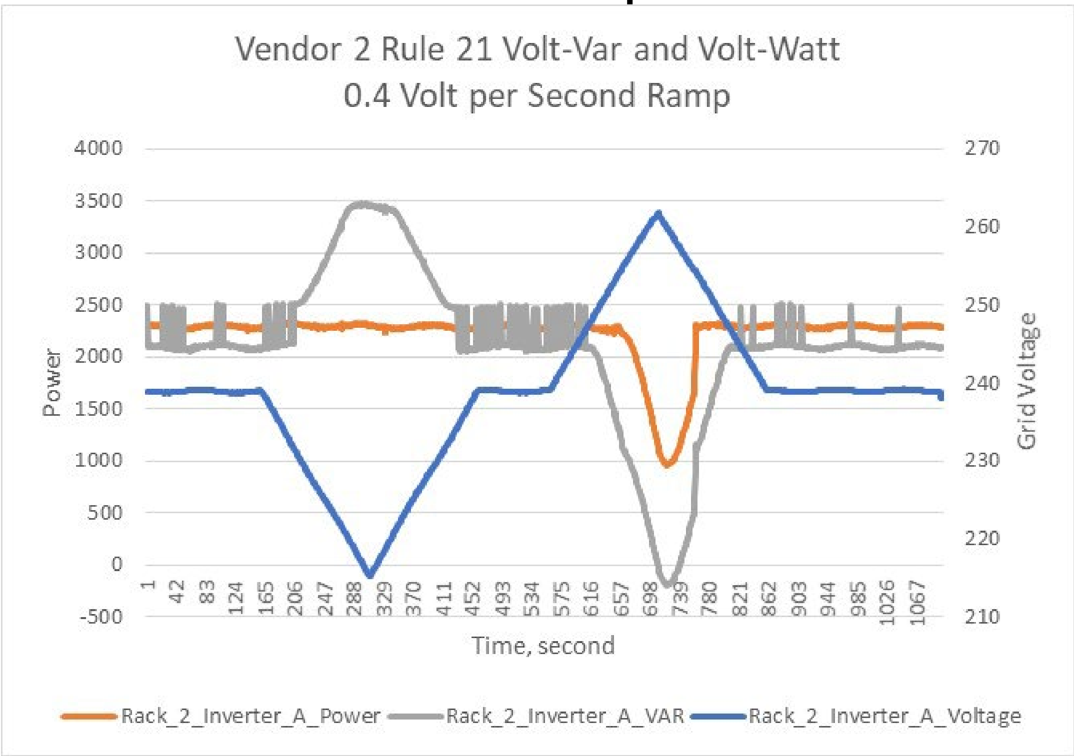
Figure 10, Figure 11, and Figure 12 show the typical graph for 0.4 volts per second.

Figure 10: Vendor 1, Home 1 Test Voltage Ramp Rate for a Test of 0.4 Volts per Second



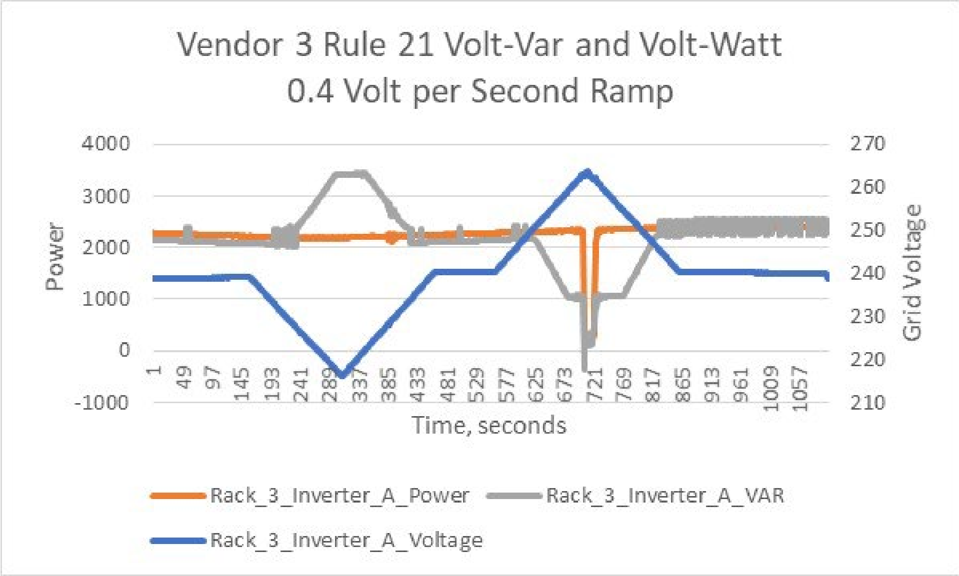
Source: Electric Power Research Institute

Figure 11: Vendor 2, Home 2 Test Voltage Ramp Rate for a Test of 0.4 Volts per Second



Source: Electric Power Research Institute

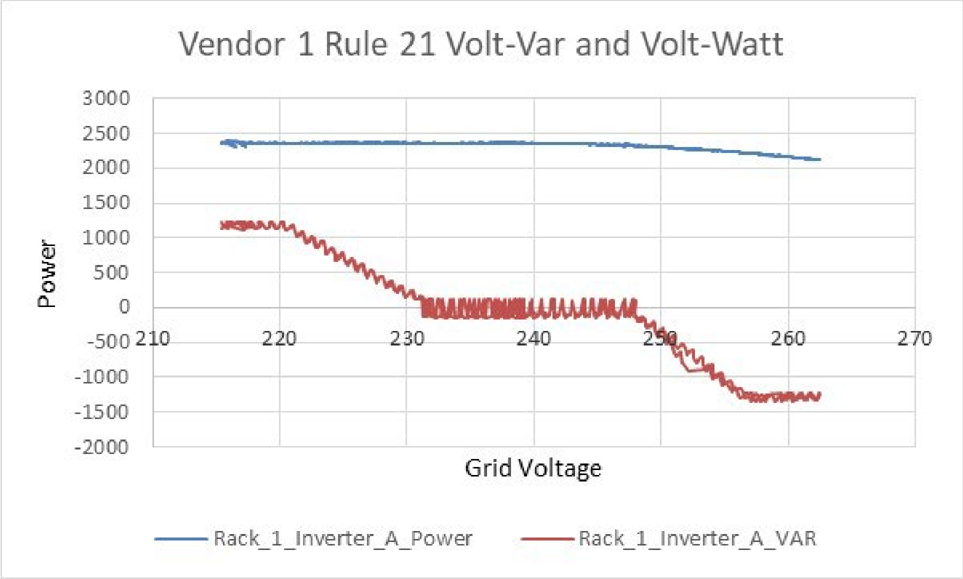
Figure 12: Vendor 3, Home 3 Test Voltage Ramp Rate for a Test of 0.4 Volts per Second



Source: Electric Power Research Institute

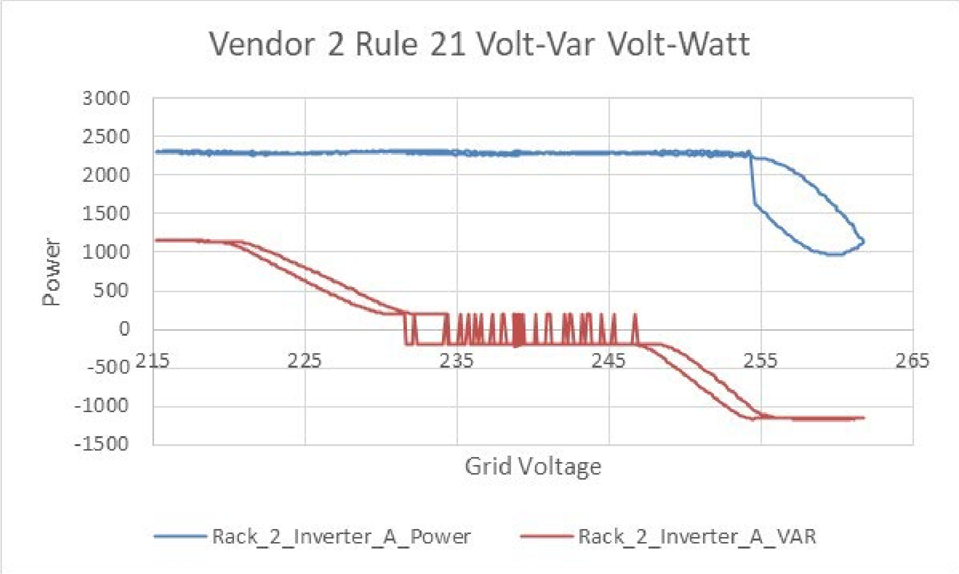
Figure 13, Figure 14, and Figure 15 demonstrate the inverter characterization settings that resulted in slightly different data for each of the manufacturers. The behavior of inverters from three vendors (1, 2, and 3) at high voltages did not follow the Rule 21 results exactly at high AC grid voltage (110 percent per unit).The response to varying grid voltage ramp rates was similar for all three inverter manufacturers.

Figure 13: Vendor 1, Home 1 Typical Response of the Inverter with Loads



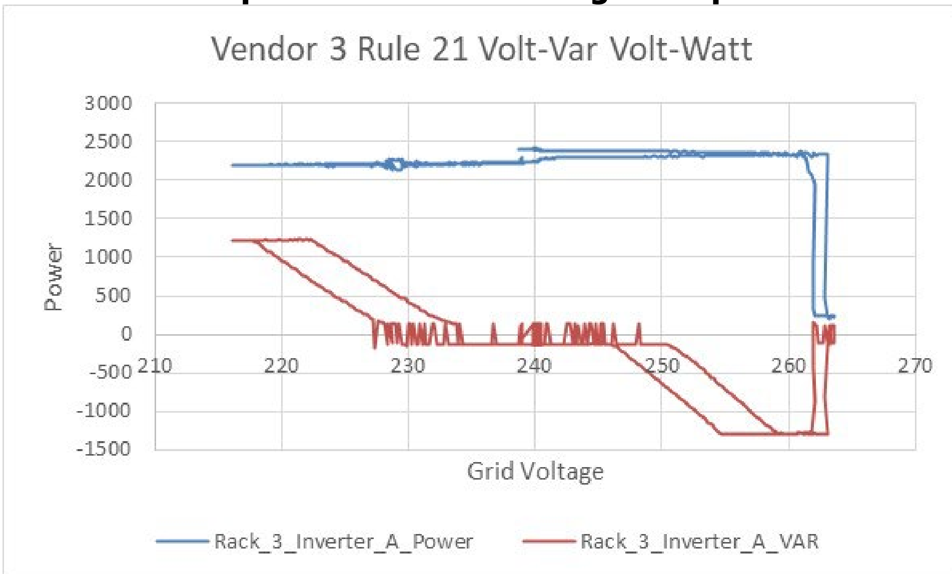
Source: Electric Power Research Institute

Figure 14: Vendor 2, Home 2 Typical Response of the Inverter with Loads and 0.4 Volts per Second Grid Voltage Ramp Rate



Source: Electric Power Research Institute

Figure 15: Vendor 3, Home 3 Typical Response of the Inverter with Loads and 0.4 Volts per Second Grid Voltage Ramp Rate



Source: Electric Power Research Institute

Additional information on the test setup and power levels is included in Appendix E.

Test 8.1 Smart Load ON-OFF States and Smart Inverter Volt-Var and Var Priority

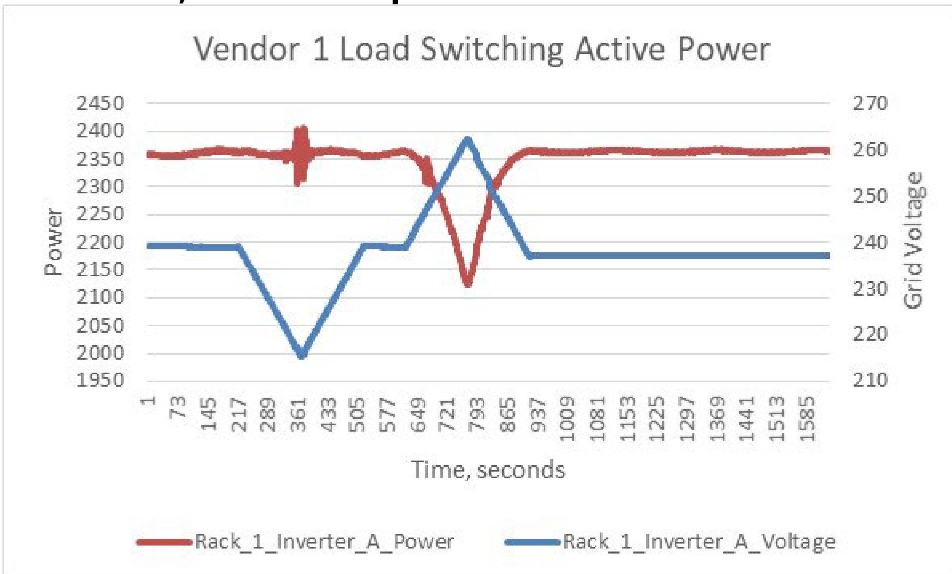
This test evaluated the performance of smart loads in ON and OFF states in each home and observed the loads and the behavior of the inverter. The test identified if the inverters had any power interruptions and if there was a violation of Rule 21 autonomous and ride-through rules (Functions 1 and 2), when the loads were switched ON and OFF. Test 8.1 included all smart loads, volt-var, and var priority. Home 1, 2, and 3 loads were cycled.

In this test, no abnormal inverter behavior was detected with all three home inverters and with smart loads cycled.

All loads followed the volt-var and volt-watt curves. It should be noted that the second and third test runs for the pool pump load showed a ripple and negative power. The ripple behavior occurs when the pool pump is sitting idle; therefore, one could conclude that it was a ripple from the inverter power conversion. The water heater load also showed a ripple once the load was active. However, the second and third tests showed that the load was functional, and inverter behavior was picking up the load settings. This behavior did not have any adverse effect on the overall operation of the system. It allowed solar PV hosting capacity to be added to the home with controllable loads. However, the field setup should review the National Electrical Code (NEC) to consider the typical wiring limitations (NEIC 2020).

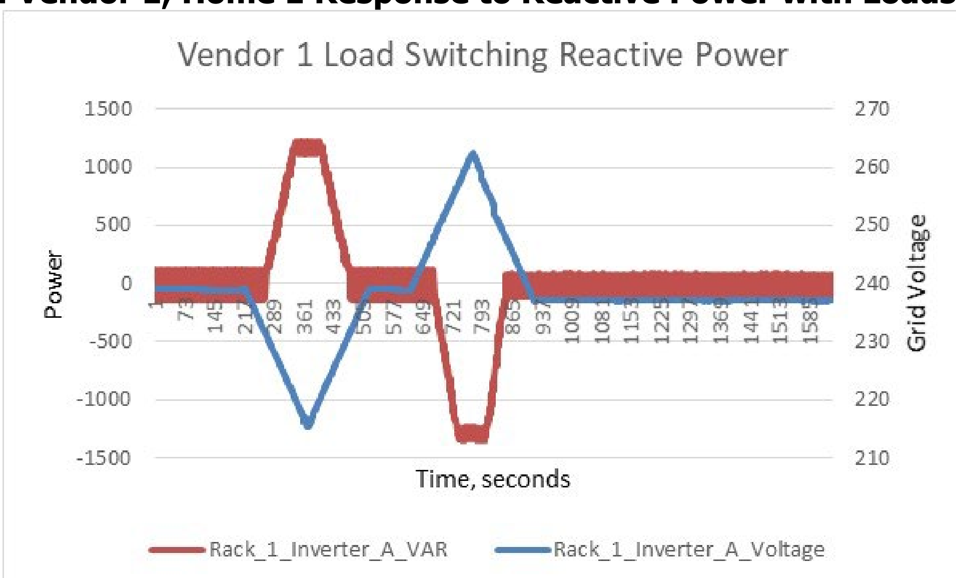
Figure 16, Figure 17, Figure 18, Figure 19, and Figure 20 show the smart load ON-OFF states and smart inverter volt-var and var priority.

Figure 16: Vendor 1, Home 1 Response to Active Power with Loads Switching



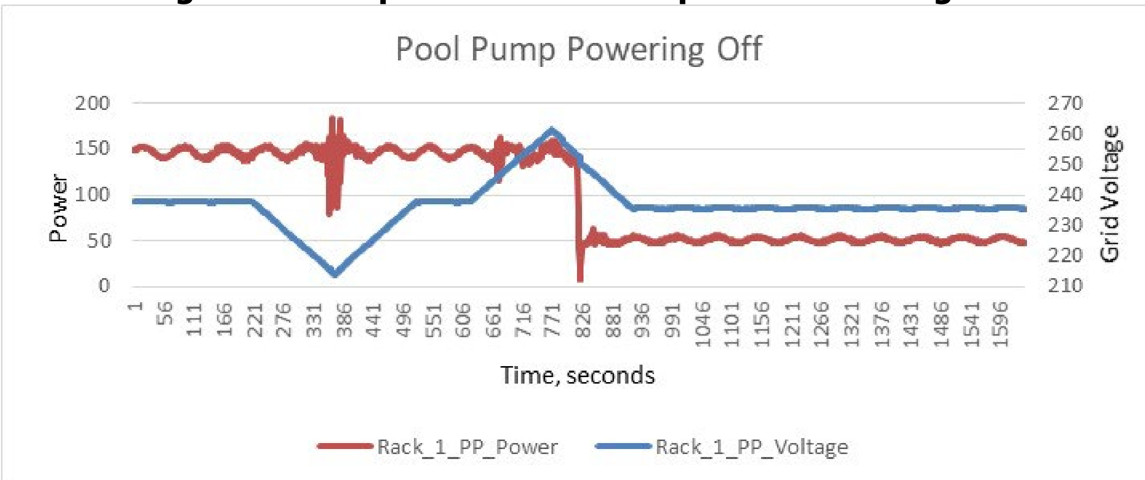
Source: Electric Power Research Institute

Figure 17: Vendor 1, Home 1 Response to Reactive Power with Loads Switching



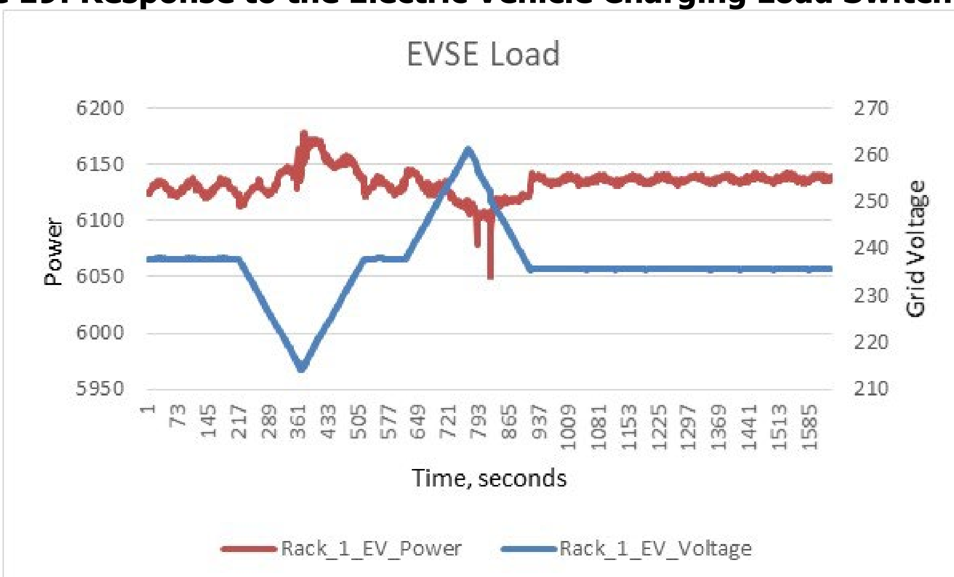
Source: Electric Power Research Institute

Figure 18: Response to Pool Pump Load Switching Off



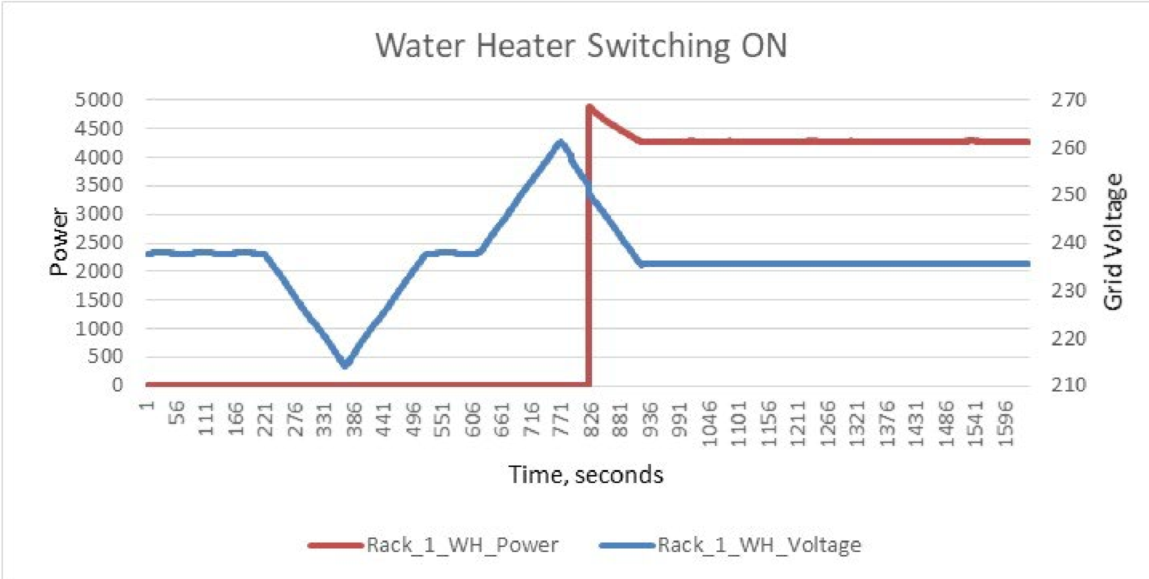
Source: Electric Power Research Institute

Figure 19: Response to the Electric Vehicle Charging Load Switching ON



Source: Electric Power Research Institute

Figure 20: Response to Water Heater Load Switching ON



Source: Electric Power Research Institute

Additional information on the test setup and power levels is shown in Appendix E.

Test 9.1 Smart Load ON-OFF States and Smart Inverters Volt-Var and Var Priority

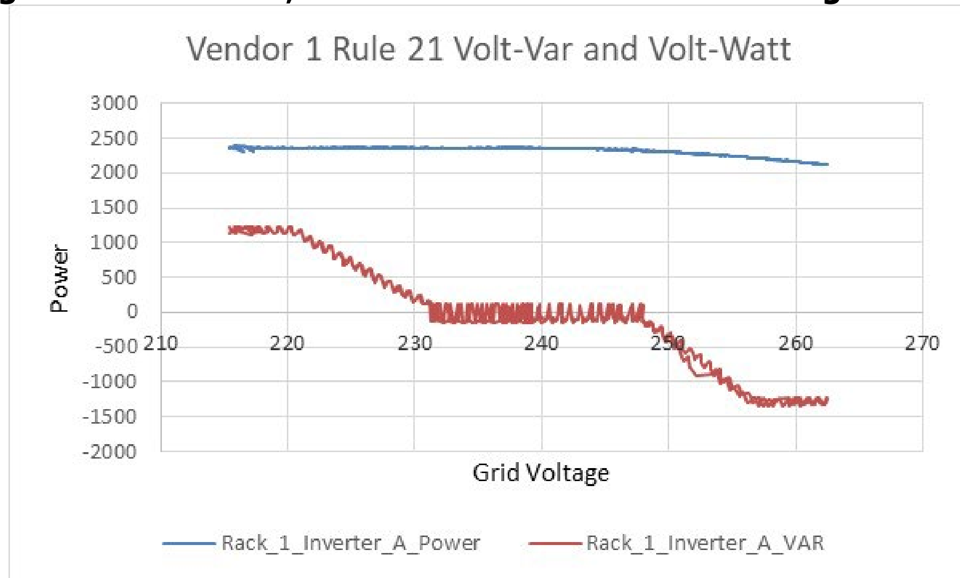
The test demonstrated one conventional inverter and three smart inverters—all smart loads with volt-var and var priority. The test evaluated the whole home system operation with a conventional inverter and with varying (increase or decrease) home smart loads at each home at selected times during the control test voltage profile run. This was done to determine performance, stability, and support during load changes and various voltage rates.

No abnormal inverter behavior was detected with the one conventional inverter or with varying, adding, or losing the three smart loads.

The test showed that solar PV hosting capacity could be added to the home with controllable loads.

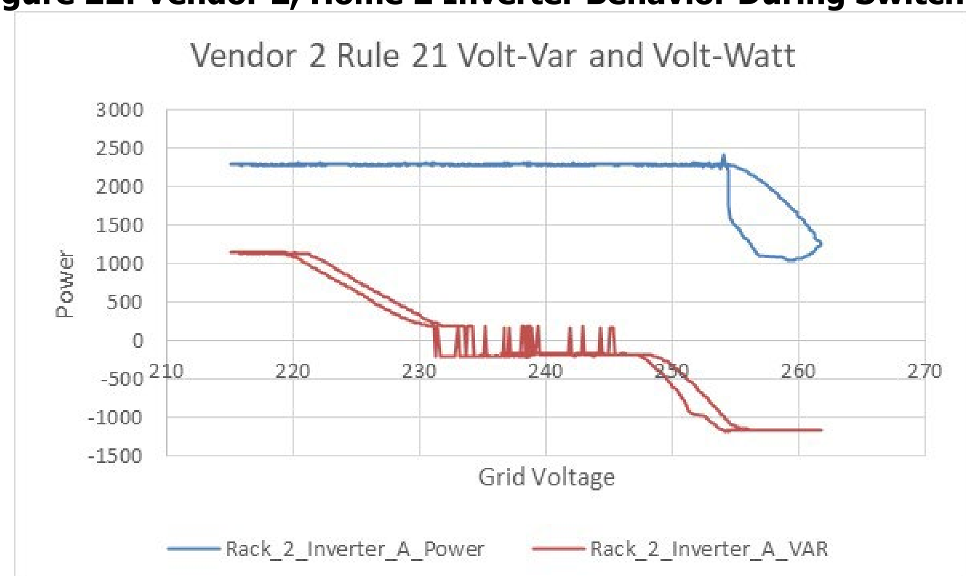
Figure 21, Figure 22, Figure 23, Figure 24, Figure 25, Figure 26, and Figure 27 show smart load ON-OFF states and smart inverters volt-var and var priority, demonstrating one conventional inverter and three smart inverters—all smart loads with volt-var and var priority.

Figure 21: Vendor 1, Home 1 Inverter Behavior During Switching



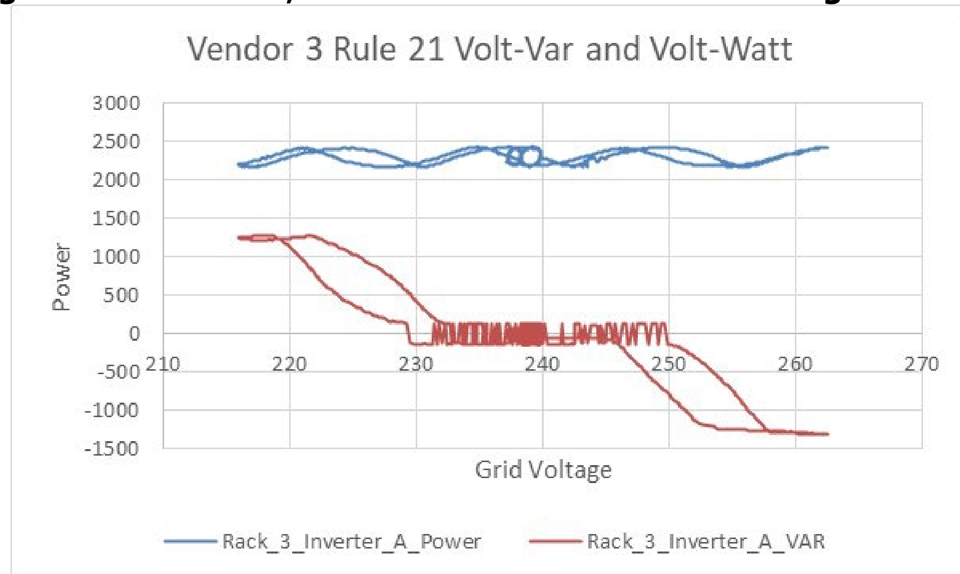
Source: Electric Power Research Institute

Figure 22: Vendor 2, Home 2 Inverter Behavior During Switching



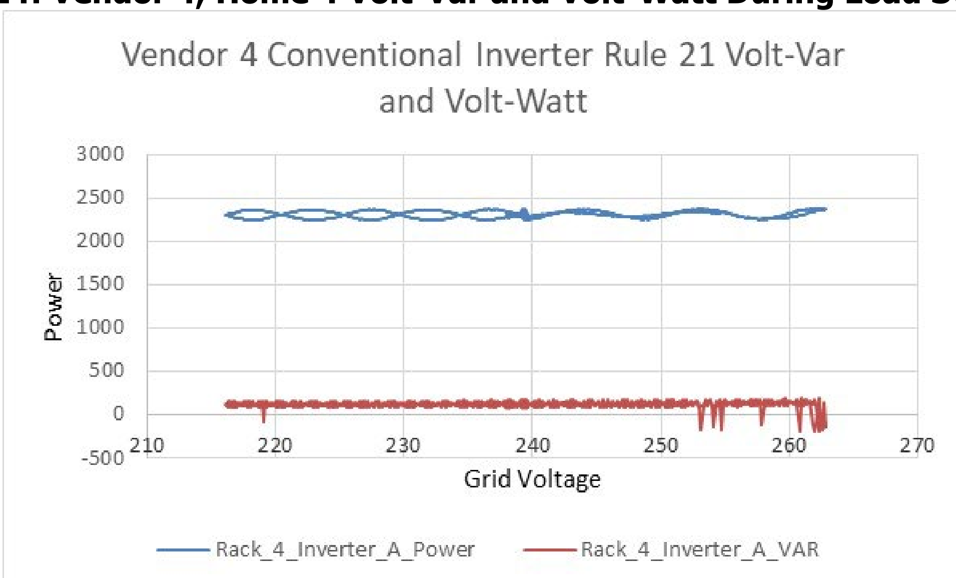
Source: Electric Power Research Institute

Figure 23: Vendor 3, Home 3 Inverter Behavior During Switching



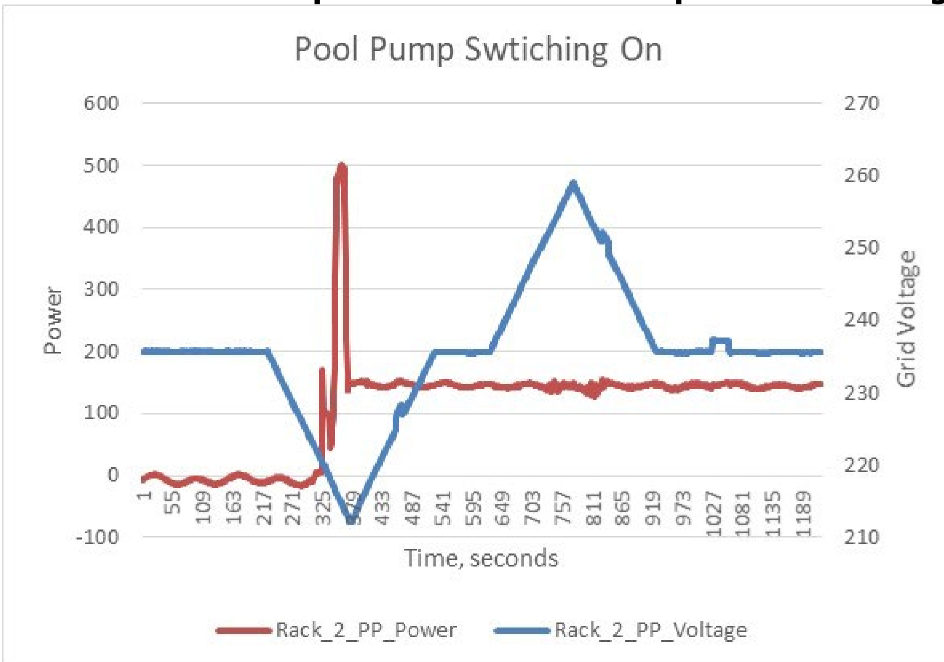
Source: Electric Power Research Institute

Figure 24: Vendor 4, Home 4 Volt-Var and Volt-Watt During Load Switching



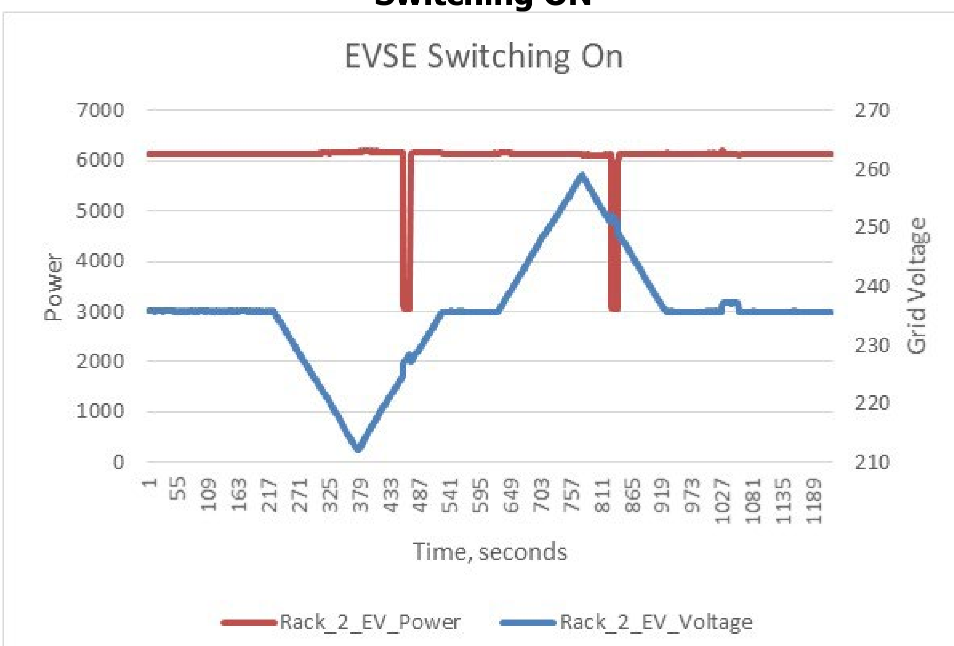
Source: Electric Power Research Institute

Figure 25: Home 2 Response to the Pool Pump Load Switching ON



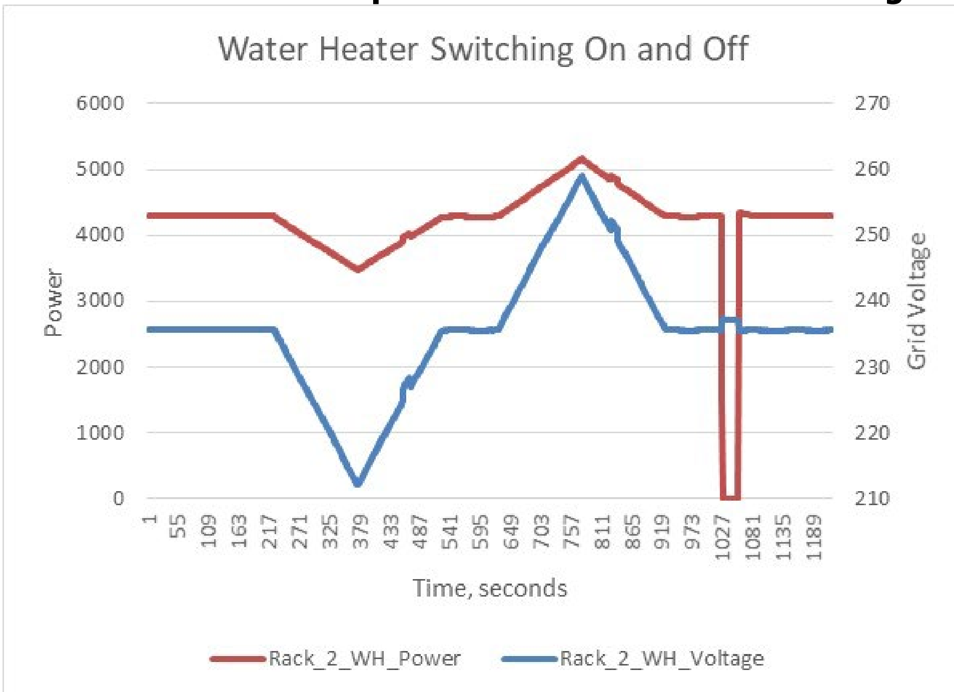
Source: Electric Power Research Institute

Figure 26: Home 2 Response to the Electric Vehicle Supply Equipment Switching ON



Source: Electric Power Research Institute

Figure 27: Home 2 Inverter Response to Water Heater Switching ON and OFF



Source: Electric Power Research Institute

Additional information on the test setup and power levels is shown in Appendix E.

Test 10.1 Smart Loads ON-OFF States and Smart Inverters Volt-Var and Var Priority, and Varying Voltage—

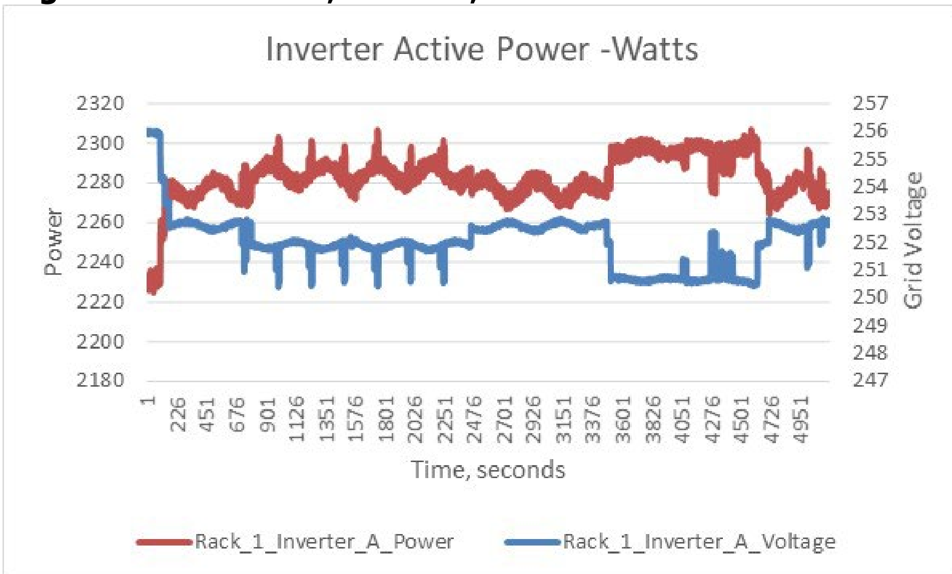
The test demonstrated a conventional inverter, three smart inverters, and smart loads (pool pump, water heater, and EV charger) with volt-var and var priority. The test measured the quality, stability, and load sharing of all the homes, including a home with a conventional inverter, during load changes and nominal, high, and low grid voltage levels.

No abnormal inverter behavior was detected with the three smart inverters, a conventional inverter, or the three smart loads switching ON-OFF during volt-var and var priority testing. Inverter behavior was assessed when high load changes occurred and when all smart loads were active. Here, the voltage dropped at the power control center, and this effect was due to I^2R losses in the cable, I^2R being the power (in watts) lost in electrical circuits, where I is current (in amperes) and R is resistance (in ohms).

This test allows solar PV hosting capacity to be added to the home with controllable loads.

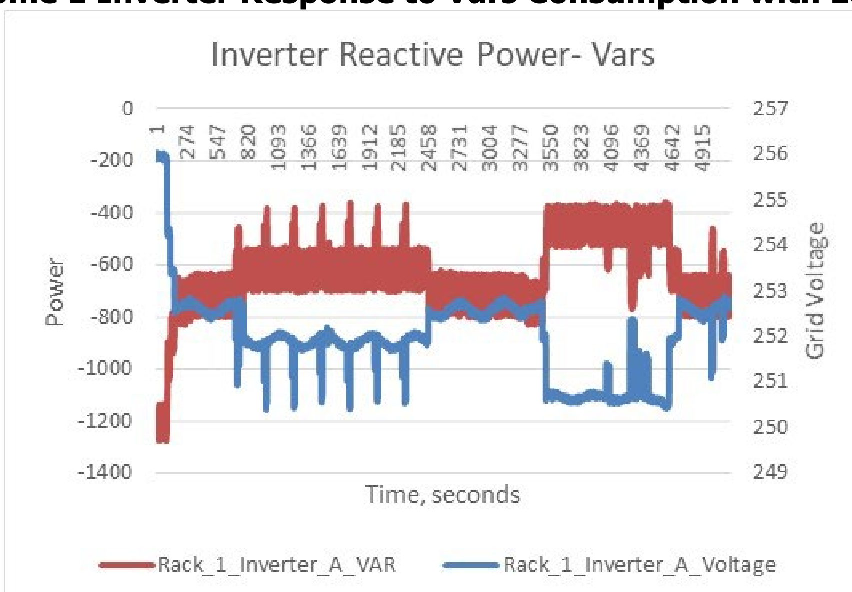
Figure 28, Figure 29, Figure 30, Figure 31, and Figure 32 show smart load ON-OFF states and smart inverters volt-var and var priority, and varying voltage, demonstrating a conventional inverter, three smart inverters, and smart loads (pool pump, water heater, and EV charger) with volt-var and var priority.

Figure 28: Vendor 1, Home 1, Inverter Active Power Levels



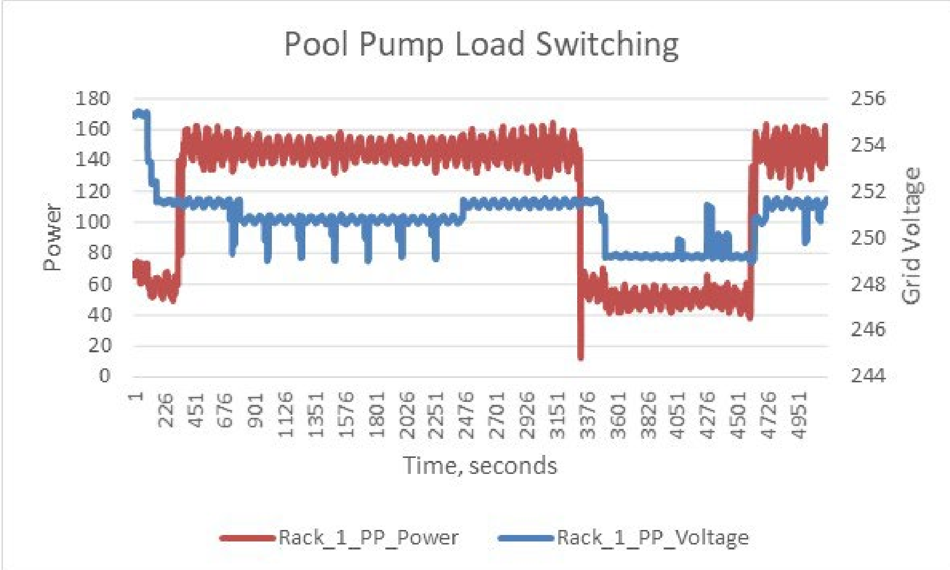
Source: Electric Power Research Institute

Figure 29: Home 1 Inverter Response to Vars Consumption with Load Switching



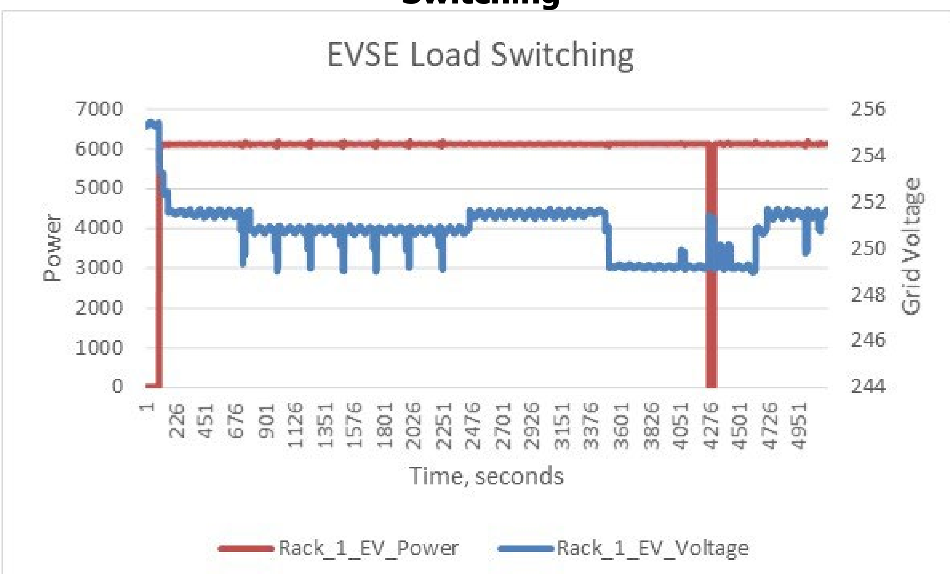
Source: Electric Power Research Institute

Figure 30: Home 1 Voltage Excursions with Pool Pump Load Switching



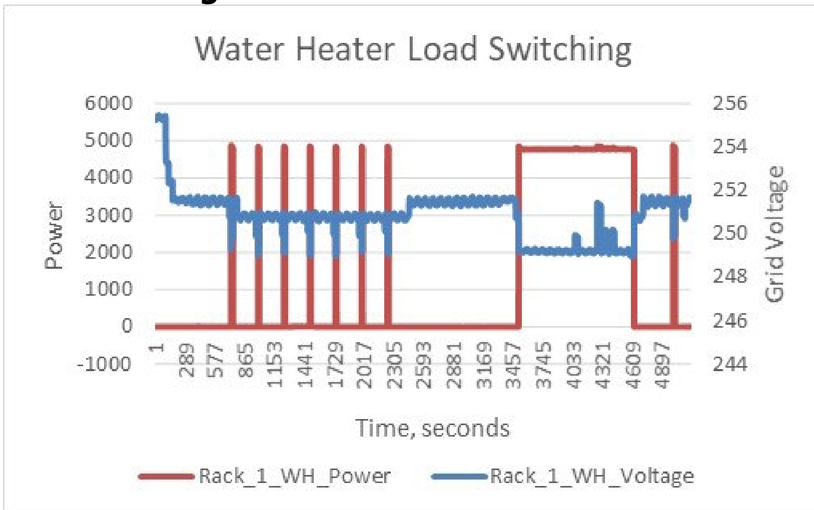
Source: Electric Power Research Institute

Figure 31: Home 1 Voltage Excursions with Electric Vehicle Charging Load Switching



Source: Electric Power Research Institute

Figure 32: Home 1 Voltage Excursions Due to Water Heater Load Switching



Source: Electric Power Research Institute

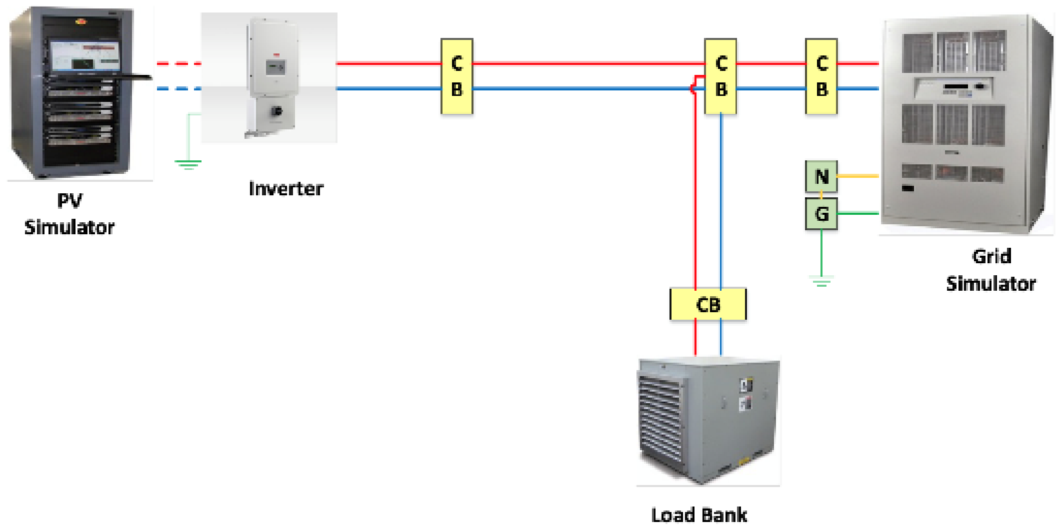
Additional information on the test setup and power levels is shown in Appendix E.

A comprehensive set of tests for smart inverters and loads was conducted at PG&E's laboratory and simulated under different scenarios. The tests that spanned a couple of years show that inverter functions closely reflect the Rule 21 requirements. However, the behavior is not consistent. The results from the comprehensiveness of these tests have become the basis for project findings and recommendations, which are included in Chapter 5, Findings and Recommendations.

Testing at Southern California Edison

The test setup at SCE primarily consisted of an inverter and a solar PV simulator to conduct testing for under- and over-voltage conditions. This tested the volt/var and volt/watt functions, which are over and under voltage Rule 21 ride-through functions. The test setup was comprised of: (1) a grid simulator that performs actual voltage and frequency deviations typically seen in the grid; (2) a solar PV simulator that simulates the solar PV array; (3) a load bank that dissipates active and inductive power; (4) equipment under test that is Rule 21 supporting a residential smart solar PV inverter; and (5) a data acquisition system that records voltages, real power, and reactive power. The inverter was connected to a load bank and a grid simulator to reflect grid conditions. Figure 33 illustrates this setup of the inverter or the equipment where the grid simulator was programmed to perform various under- and over-voltage events needed for the test.

Figure 33: Inverter and Solar Photovoltaic Simulator Setup for Testing at SCE



Source: Electric Power Research Institute

Inverters and Solar Photovoltaic Simulator Equipment Under Test

The SCE tests focused on var and watt priority for under- and over-voltage conditions. Table 12 identifies the inverter under test. The inverter name, make, and model information has been removed for privacy. The description highlights any unique test cases for inverters. The inverter was tested in SCE's Distributed Energy Resources Laboratory.

Table 12: Inverters Under Test, Ratings, and Description at SCE Laboratory

Inverters Under Test	Make and Model	Description
Vendor 1	Model	Rule 21-compliant inverter

Source: Electric Power Research Institute

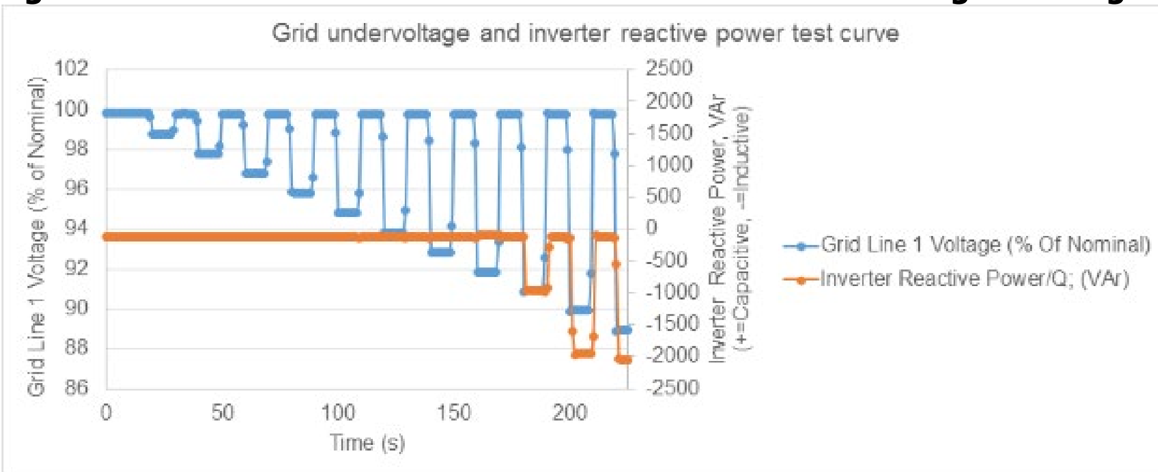
The detailed SCE test report is shown in Appendix G.

Test 3.1 Smart Inverter Under-Voltage to Var Priority and Testing of Rule 21 Function 2, volt/var and volt/watt functions—

The objective of the test was to ensure that the inverter is capable of performing the reactive power absorption or injection, as suggested by the inverter manufacturer. The test evaluated the smart inverter's performance during typical under-voltage grid events. The tested nominal voltage had a duration equal to 10 seconds (t_1) and a delay equal to 10 seconds (t_2) between voltage changes to let the smart inverter settle into a steady state.

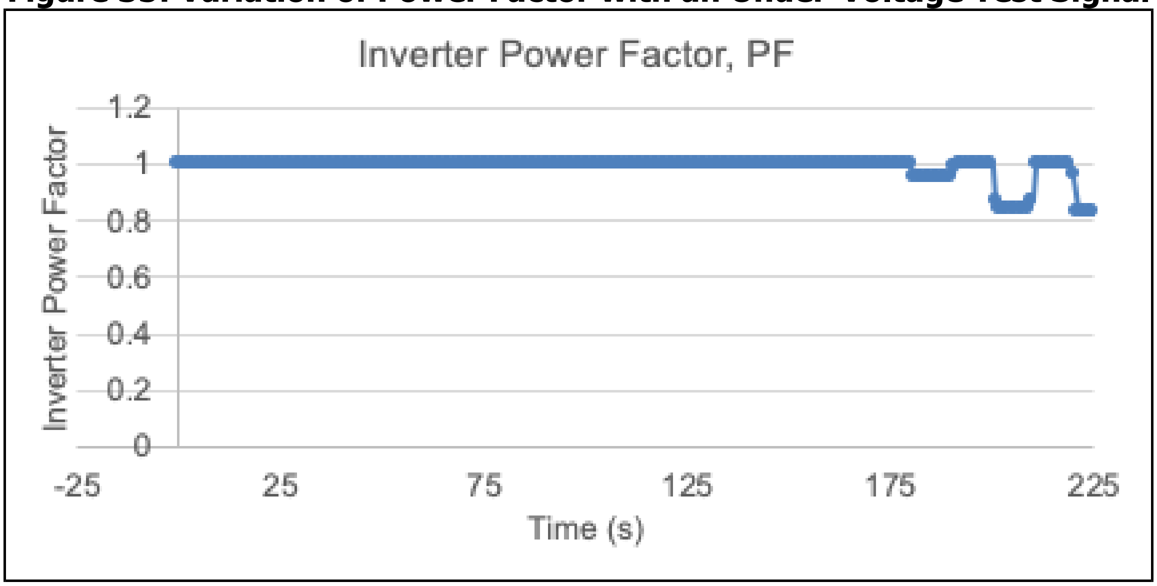
Figure 34 shows the test results: the inverter increased its var output after the voltage dropped below 91 percent. Figure 35 shows the test results, where the inverter started to operate at the needed power factor value of 0.82.

Figure 34: Variation of Reactive Power with an Under-Voltage Test Signal



Source: Electric Power Research Institute

Figure 35: Variation of Power Factor with an Under-Voltage Test Signal



Source: Electric Power Research Institute

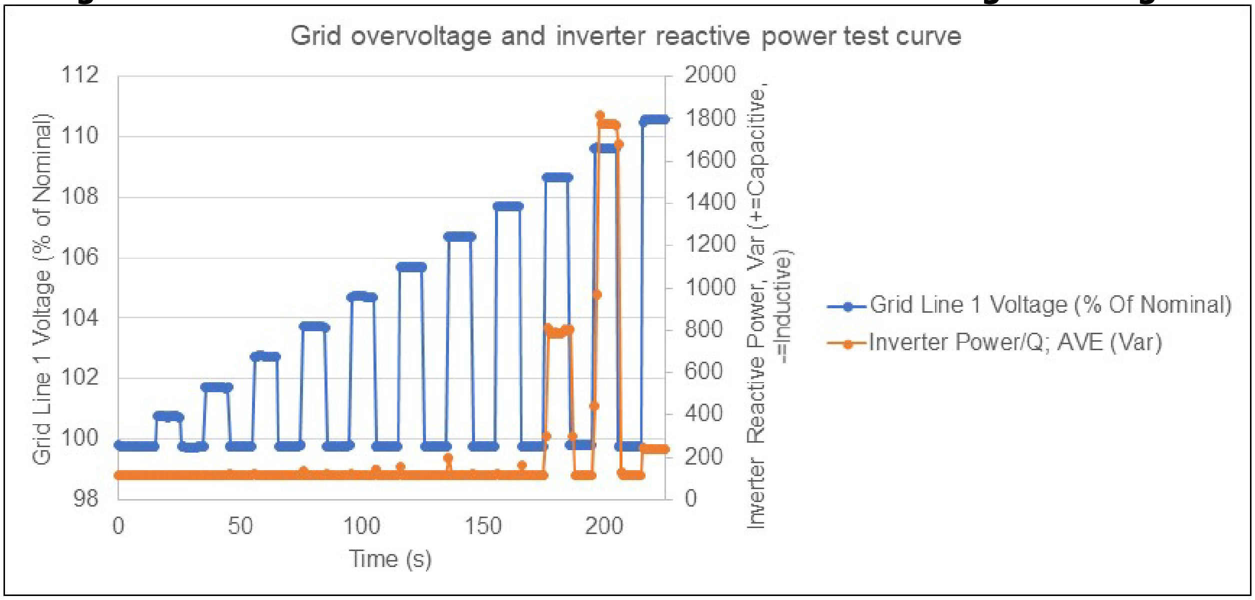
The test validated the manufacturer's claim, thus meeting the test's core objectives.

Test 3.2 Smart Inverter Over-Voltage to Var Priority and Steady-State Power Factor

The objective of the over-voltage test was to evaluate the smart inverter's performance during typical over-voltage grid conditions. The tested nominal voltage duration was equal to 10 seconds (t_1) and the delay was equal to 10 seconds (t_2) between voltage changes to let the smart inverter settle into a steady state.

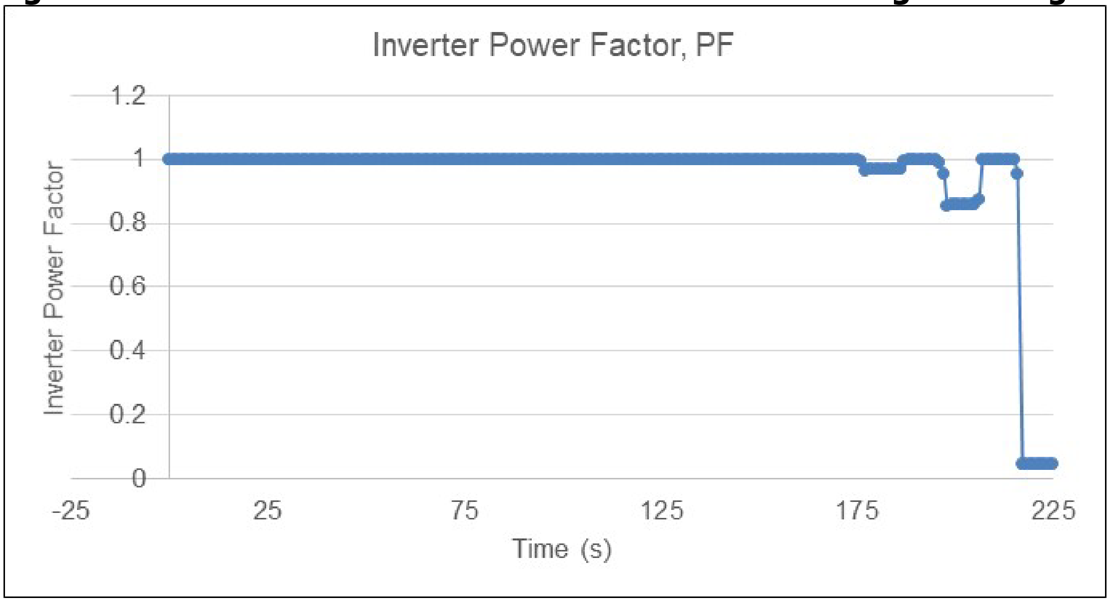
Figure 36 shows that the inverter increased its var output shortly after the voltage dropped below 108 percent of nominal. Figure 37 shows the inverter started to operate at the needed power factor with a value of 0.85 to accommodate the var requirement.

Figure 36: Variation of Reactive Power with an Over-Voltage Test Signal



Source: Electric Power Research Institute

Figure 37: Variation of Power Factor with an Over-Voltage Test Signal



Source: Electric Power Research Institute

Additionally, leveraging the same test setup, SCE conducted laboratory tests for two voltage functions—volt-var and volt-watt—for inverters from one manufacturer The volt-var and volt-watt functions are key smart inverter functions that are applicable to solar PV under the revised Rule 21 and IEEE1547-2018, as of September 2017. The results show that volt-var and volt-watt advanced functions could provide grid benefits if they are incorporated and enabled for grid-connected smart inverters.

A detailed report with results is shown in Appendix G.

Field Tests

The objective of the field tests was to use the Home Energy Management System (HEMS) for a scalable solution to mitigate the impact of solar PV on the distribution system. The HEMS control gateway coordinated the smart load management of a pool pump relative to the solar PV generation within a home. The field tests were conducted in the service territory of SCE. Due to the challenges faced by the project team related to inverter performance against the Rule 21 requirements, and the additional efforts needed to complete comprehensive laboratory tests, the field test focused on one home that had an existing smart inverter, solar PV, and controllable pool pump smart load. Due to the limitations (time, remote operations due to COVID-19), the project did not install any new equipment. The extant equipment, measurement, and communications infrastructure were leveraged to apply developed algorithms. A new smart load management architecture was developed to enable the testing.

The field tests focused on test cases 7.2, 9.2, and 10.2, with the focus on controlling smart loads.

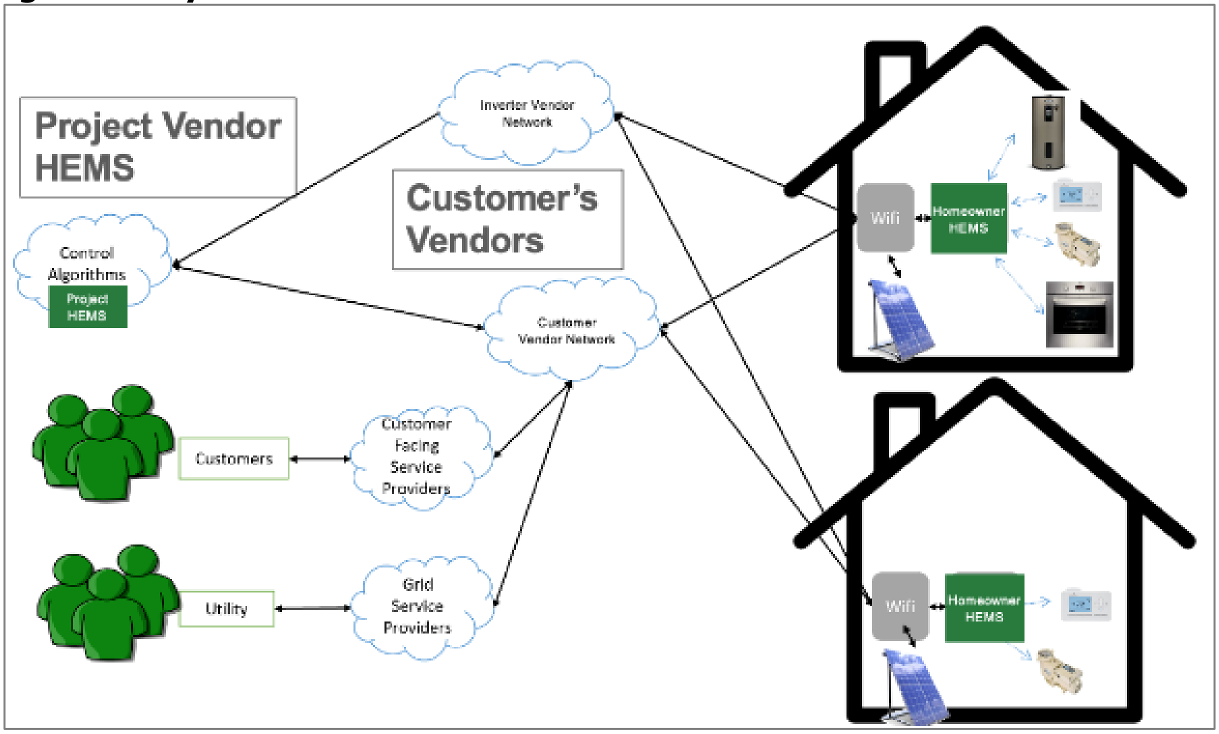
Residential Test Setup

Considering that the project had to use the existing residential infrastructure, the test plan and the tasks related to assessing project requirements had to be adapted. The original test plan was to let each home controller or HEMS make all control allocation decisions locally. Additionally, transactive "sharing" (peer-to-peer exchange) of excess generation or demand between HEMS was to be tested.

With the adaptation, the test focused on using the HEMS controls developed in the project that was situated in one of the vendor's networks and outside the residential network. Another HEMS, operated by another vendor and preferred by the customer, was situated locally in the home. Both HEMS were integrated by application programming interfaces that enabled diverse vendor technologies to communicate with each other. This architecture was determined based on the best possible scenarios of site availability and customer preferences. This adaptation supported the project's objectives, particularly to test the communications and control sequences and to manage smart loads remotely.

Figure 38 illustrates the new systems and communications architecture. The HEMS making control decisions developed in the project was a relay device in the project vendor network, and the home Wi-Fi network was used to communicate with the homeowner's HEMS. The homeowner interacted with vendors and utilities using existing relationships. Table 13 shows the existing equipment infrastructure that included electric smart loads and inverter based DERs that included solar PV and battery energy storage. The heating and cooling end use was excluded since it was not an electric load; heating and cooling used gas as the energy source. The pool pump was the only smart load leveraged for the tests to provide 1.8 kW of controllable power.

Figure 38: System and Communications Architecture for Smart Load Controls



Source: Electric Power Research Institute

Table 13: Smart Load or Equipment Under Test

Loads and DER	Rated Capacity (kW)	Equipment Make and Model
Water Heater	N/A	Not electrical load (gas source)
Pool Pump	1.8	(Vendor 1)
Solar PV	6.6	(Vendor 2)
Energy Storage	10.0	(Vendor 3)

Source: Electric Power Research Institute

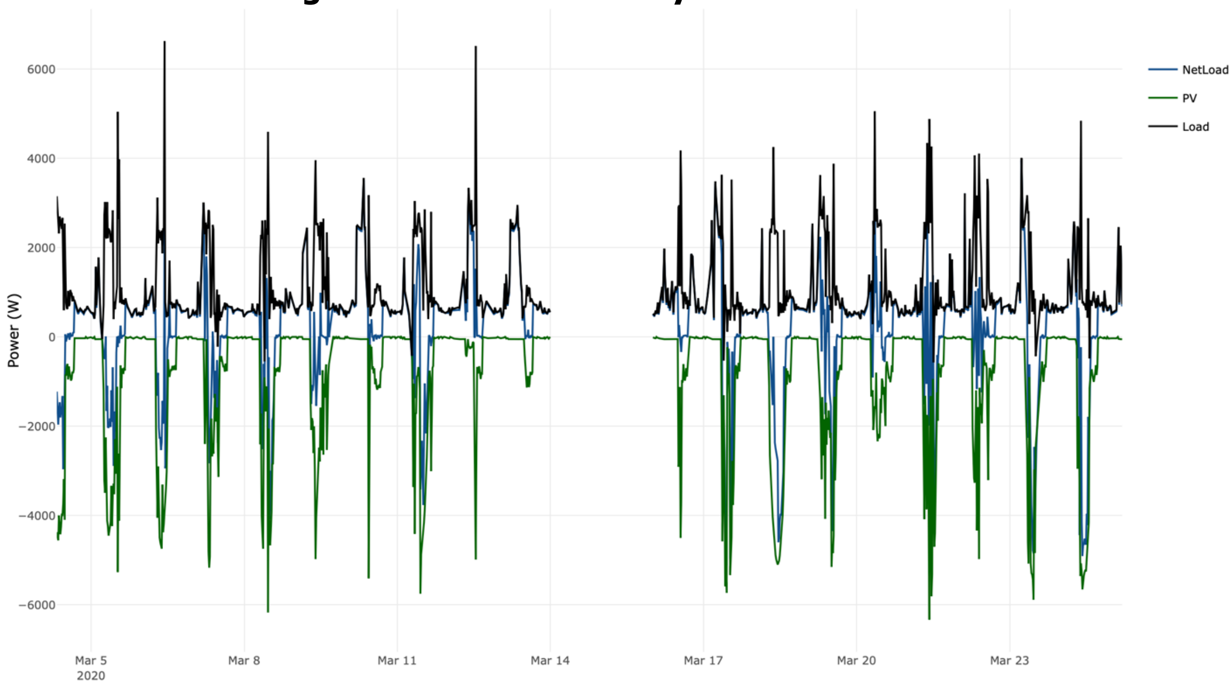
Smart loads under test included the following, with respective power data needed for analysis: solar PV (power generated in watts [W]); smart meter (W); smart thermostat (temperature, cooling, and heating setpoints in Fahrenheit [°F]); cooling; and pool pump (power used in W and pool state of ON-OFF).

The detailed Intwine technology descriptions are provided in Appendices C, D, and L.

Energy Analysis

The home electricity is serviced by the electric grid and local solar PV generation. The smart meter records the net load, not the overall home energy use, which can include local generation by solar PV (the net load analysis did not consider battery energy storage discharge as a local generation source). The net load data is the *total home power use* minus *on-site power generation*. A net load analysis was done to identify total home energy use. The available time-series data were recorded at different intervals and had missing values when data were matched (smart meter data at 5-minute intervals and solar PV production data at 20-minute intervals). A method of linear extrapolation was used to fill in the missing data except for March 14 and March 15, where data were missing for most of the day and were removed from the dataset to reduce the bias and improve the accuracy of the analysis. The load for the home was calculated using the smart meter net load data and the solar PV production data (*net load data* plus *on-site power generation*). Figure 39 shows the results of these analyses.

Figure 39: Net Load Analysis for the Home



Source: Electric Power Research Institute

The net load analysis led to the identification of the following information for most of the days in March, as shown in Table 14.

- ***ExcessEnergy (kWh):*** Energy exported from the home to the grid. This is excess local solar energy generation not used by the home.
- ***EnergyWithoutPV (kWh):*** Energy the home would have used from the grid if no PV were installed.
- ***EnergyWithPV (kWh):*** Energy the house used from the grid with the PV installed.
- ***EnergySaved (kWh):*** The difference between EnergyWithoutPV and EnergyWithPV. This is the energy that the house did not have to import from the grid due to the local PV generation.

Table 14: Home Energy Analysis with and without Solar PV Generation

Date	ExcessEnergy (kWh)	EnergyWithoutPV (kWh)	EnergyWithPV (kWh)	EnergySaved (kWh)
3/4/20	7.2056257	17.8921417	4.9609341	12.9312076
3/5/20	9.46192697	27.3394578	8.39405143	18.9454064
3/6/20	9.6462842	25.2003132	10.7390974	14.4612158
3/7/20	7.80087687	24.1921797	12.0727233	12.1194565
3/8/20	10.1932233	22.2858535	10.2420767	12.0437767
3/9/20	3.88796923	29.2925697	13.3428723	15.9496974
3/10/20	0.8135243	26.6817884	20.1243127	6.5574757
3/11/20	9.87920827	26.508871	12.3634126	14.1454584
3/12/20	0.01968153	27.4355078	19.7285227	7.70698513
3/13/20	0.0285928	26.3668097	22.3620692	4.00474053
3/14/20	NA	NA	NA	NA
3/15/20	NA	NA	NA	NA
3/16/20	0.23026643	24.9181402	16.9689066	7.94923357
3/17/20	13.4049474	26.7909697	18.1987504	8.5922193
3/18/20	18.0668238	25.4579999	9.31299043	16.1450095
3/19/20	7.9350161	29.4237918	13.8294746	15.5943172
3/20/20	1.0081273	25.5965785	12.4400391	13.1565394
3/21/20	9.24227129	28.0071618	13.0347664	14.9723954
3/22/20	1.66930515	28.7733911	12.8088629	15.9645282
3/23/20	15.3271003	25.2342669	15.5053672	9.72889975

Source: Electric Power Research Institute

This analysis helped the project identify the times when the excess energy from solar PV can be used locally by smart management of pool pumps and extrapolate the results to California homes to show overall energy-saving opportunities.

Field Tests and Results

The tests, which were planned to coincide with solar PV generation, were conducted in one home on March 24, 2020. Table 15 summarizes 5-minute net load data from a smart meter on the field test day (test start times are highlighted), pool pump power use and states, and heating-cooling temperature setpoints. The temperature setpoints for heating and cooling are shown for reference because the water heater is not an electric load (it uses gas as an energy source). The battery storage was not used, and its state of charge remained between 88 percent to 100 percent.

The results demonstrate that smart loads in Home 3 (H3) can use additional solar PV generation that otherwise would be fed to the grid. Leveraging local smart loads, enabled by communicating inverters, may allow an increase in PV hosting capacity without increasing back feed to the distribution grid.

The data show that the highest power fed to the grid was about 5 kW, possibly when the *home power use* was low and/or *on-site power generation* was high. Here, the discretionary pool pump load was switched ON to use the excess solar PV generation. Advanced algorithms were not tested due to the use of existing devices and controls.

Table 15: Data from the Intwine Connect Field Test for Home 3 (H3)

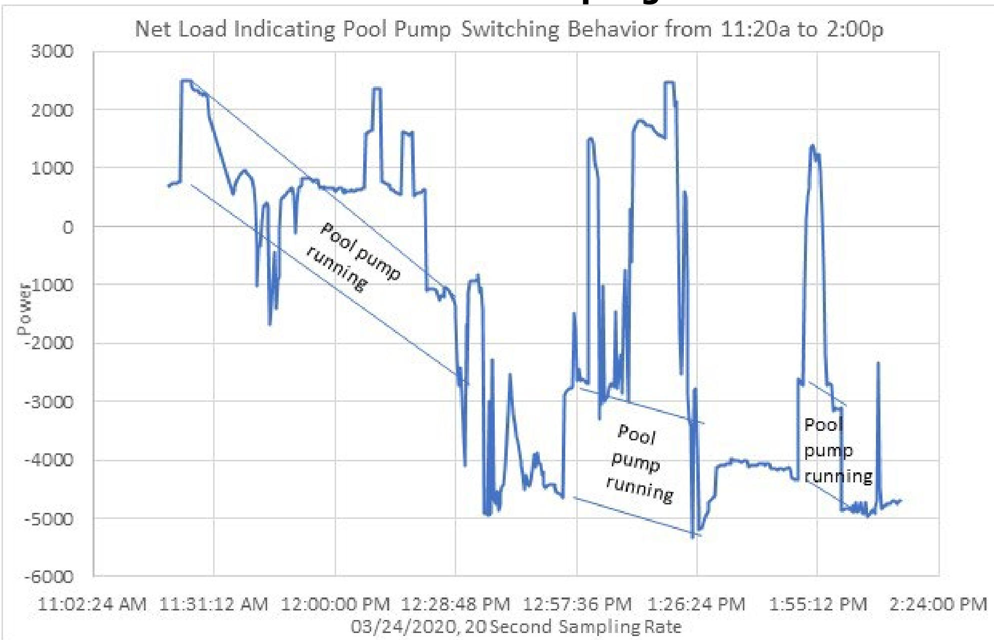
Date—Time (U.S. Eastern Time)	Pool Pump Power (W)	Net Power at Meter (W)	Interior Temp. (degF)	Cooling Setpoint (degF)	Heating Setpoint (degF)	H3 Pool Pump State
Test 1						
3/24/20 14:24	1,782	2,507	67.9	74	68	ON
3/24/20 14:30	1,785	1,881	67.9	74	68	ON
3/24/20 14:35	1,782	1,269	67.9	74	68	ON
3/24/20 14:40	1,783	851	67.9	74	68	ON
3/24/20 14:45	1,783	-1,336	67.9	74	68	ON
3/24/20 14:50	1,782	509	68	74	68	ON
3/24/20 14:55	1,782	789	68	74	68	ON
3/24/20 15:00	1,785	614	68	74	68	ON
3/24/20 15:05	1,783	623	68.1	74	68	ON
3/24/20 15:10	1,785	2,352	68.1	74	68	ON
3/24/20 15:15	1,781	549	68.2	74	68	ON
3/24/20 15:20	1,783	607	68.3	74	68	ON
3/24/20 15:25	0	-1,173	68.3	74	68	OFF
Test 2						
3/24/20 15:56	1,791	-2,787	68.3	74	68	ON
3/24/20 16:01	1,792	1,510	68.2	74	68	ON
3/24/20 16:06	1,793	-2,686	68.4	74	68	ON
3/24/20 16:11	1,792	1,617	68.3	74	68	ON
3/24/20 16:16	1,788	1,639	68.5	74	68	ON
3/24/20 16:21	1,784	2,149	68.4	74	68	ON
3/24/20 16:26	0	-4,957	68.1	74	68	OFF
Test 3						
3/24/20 16:52	1,789	-1,025	68.4	74	68	ON
3/24/20 16:57	1,788	-2,208	68.5	74	68	ON
3/24/20 17:02	0	-4,848	68.4	74	68	OFF

Source: Electric Power Research Institute

Appendix K shows additional data before and after the field tests were conducted.

Figure 40 shows the net load graph with smart management of the pool pump using a 20-second sampling rate. Here, H3 solar PV feed-in reduction was demonstrated using the optimized controls. The pool pump was turned ON during excess solar PV generation. The first interval shows the pool pump switched ON from 11:24 a.m. to 12:24 p.m. or 1 hour (United States Pacific Time). The second interval shows the pool pump switched ON from 12:55 p.m. to 1:25 p.m., or 30 minutes, and the last interval, the 10-minute interval test, is shown from 1:52 p.m. to 2:02 p.m. During the time when the pool pump was switched ON, the feed-in of power from the whole house was reduced.

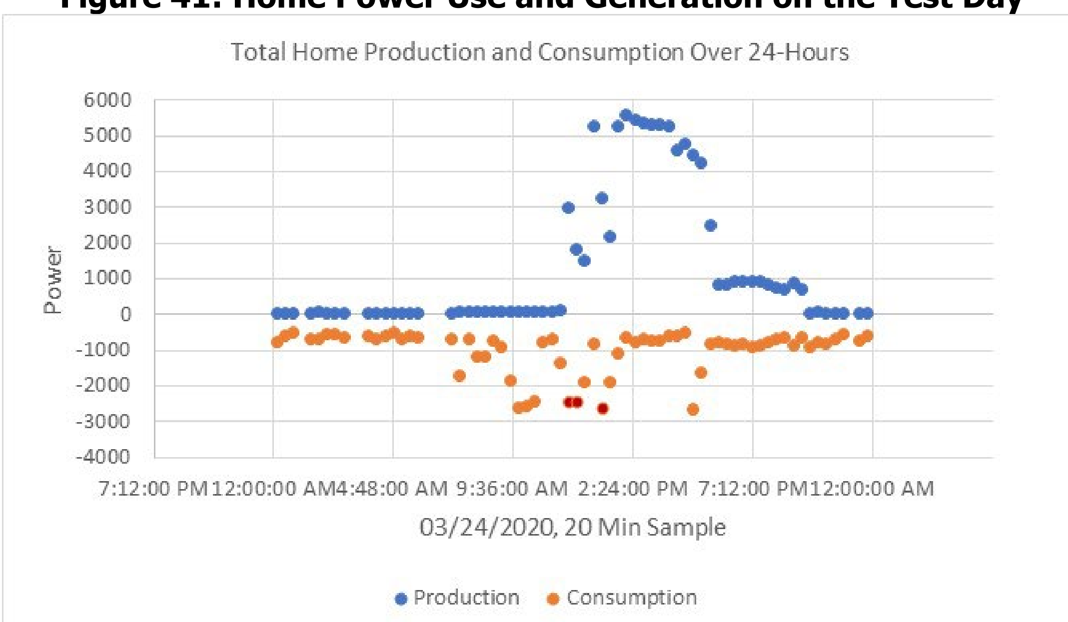
Figure 40: Net Load Indicating Pool Pump Switching Behavior in a 20-Second Sampling Rate



Source: Electric Power Research Institute

Figure 41 shows the total home production and consumption over a 24-hour period with a 20-minute sampling rate on the test day. The test shows variations in the net load that can result in switching the pool pump load ON and OFF. The test illustrates that there was no solar PV production in the night hours. The production was mostly seen during the day, with some load following in the evening hours. The test demonstrated the balancing of local supply and demand over a 24-hour day.

Figure 41: Home Power Use and Generation on the Test Day



Source: Electric Power Research Institute

It should be noted that a simple method was used for the energy and demand saving analysis where other smart loads (thermostats, EVSEs, lighting) are excluded. The actual savings depend on the application of technology and customer adoption rates. It also should be noted that not all California pool pumps are single speed. California's Title 20 Appliance Efficiency Regulations specify that residential pool pump motors with a motor capacity of 1 horsepower or greater, which were manufactured on or after January 1, 2010, shall have the capability of operating at two or more speeds with a low speed having a rotation rate that is no more than one-half of the motor's maximum rotation rate (CEC 2020). As a result, the methods and algorithms developed in this project also can be applied for varying the speed of the pool pumps and other smart loads to achieve the objective of enabling more residential solar energy.

CHAPTER 4: Technology, Knowledge, and Market Transfer Activities

Numerous technology and knowledge transfer activities were conducted and leveraged during this project to disseminate findings to members of stakeholder organizations to whom the research is relevant and to obtain feedback to improve the project recommendations. Publication of research reports and scholarly articles, presentations at industry events, and informational webcasts provided a broad and effective mechanism for disseminating the project findings and for emphasizing the findings' significance in determining the direction of the industry. These activities directly aligned with the project's objective to advance the industry's knowledge regarding how consumer loads can be managed most effectively to enable more PV on the grid.

Technical Advisory Committee Support

The project activities were improved through collaborative engagement with a technical advisory committee (TAC) whose members included leading practitioners and subject matter experts from various facets of the industry. Meetings and presentations with the committee helped to identify salient characteristics of the needs of smart inverters and loads to enable greater use of solar energy, alignment with California's policy objectives, and improvement of the technical work for laboratory and field tests.

Technical advisory committee members were instrumental in:

- Providing guidance in project direction. The guidance included scope and methodologies, timing, technical outcomes, and coordination with other projects.
- Reviewing products and providing recommendations for needed product adjustments, refinements, or enhancements.
- Evaluating the tangible benefits of the project to the State of California and providing recommendations as needed to enhance the benefits.
- Providing recommendations regarding information dissemination, market pathways, or commercialization strategies relevant to the project products.

Appendix A lists the committee members and the organizations they represent.

Knowledge Transfer Activities

The project focused on the technology readiness levels (TRL) 3, which included the development of analytical models, algorithms, and test cases, and 6 for the pilot-scale validation of technology and systems within a relevant environment (DOE 2013). Technical advisory committee members were instrumental in conveying knowledge to the relevant markets, as were industry events. Specific additional knowledge transfer engagements included a presentation of the research objectives and early-stage findings in industry forums, as shown in Table 16.

Table 16: Knowledge Transfer Through Forums and Publications

Forum or Publication	Description
The CEC's Electric Program Investment Charge (EPIC) Innovation Symposium 2015	EPIC Innovation Symposium presentation, "Assessing the Ability of Smart Inverters and Smart Consumer Devices to Enable More Residential Solar Energy," in the session titled "Distributed Energy Future" (EPIC 2015)
DistribuTECH 2019 and 2020 International Conferences	The laboratory testing, smart load controls, and early-stage findings were presented in the following two panels at the DistribuTECH 2019 and 2020 International Conferences, respectively (DistribuTECH 2019; DistribuTECH 2020) 1. "Virtual Metering Enabled Through Use of Smart Inverters and Smart Consumer Devices" 2. "Smart Inverter Experience from Coast-to-Coast: Disruptive Emerging and Innovative Technologies"
EPRI Grid Analytics and Power Quality Conference and Exhibition 2019	Presentation, "Testing, Results, and Grid Benefits to California Rule 21 Smart Solar PV Inverters" (EPRI 2019)
Technical Report	Technical report defining the specifications for variable-speed pool pumps with built-in DR capabilities and standardized communication interfaces (EPRI 2016d)
Technical Report	Compilation of four previously issued reports that detailed the functional and communication interface requirements that demand-responsive smart loads must support to communicate using standards (EPRI 2018)

Source: Electric Power Research Institute

The related research for the project is referenced in EPRI's "Technology Assessment and Delivery (TA&D)." The research can be used to assess the potential of the CEC-funded projects for use in utility DR programs (EPRI 2020). This is a good example of the project's technology applications.

The collective information disseminated, and the feedback received from these technology and knowledge transfer activities, provide a platform for market facilitation. Some of the market transfer activities can help to inform public agency policies, address regulatory barriers, and encourage markets to use the advanced smart inverter and smart load technologies to enable greater use of solar PV energy.

CHAPTER 5: Findings and Recommendations

This chapter describes the essential findings and recommendations, primarily from the laboratory and field tests. The challenges experienced by the project during laboratory testing are discussed. Both these findings and challenges should help the regulators and the grid operators evaluate the regulatory changes needed to scale deployment of Rule 21-compliant inverters and assess the outcomes that are relevant to their DR programs and reliable grid operations. Both lab and field tests showed that allowing more installation and operation of PV with smart loads increases hosting capacity without causing grid operational problems.

Laboratory Tests

The PG&E laboratory tests focused on smart inverters and loads in coordination with multiple solar PVs sited in residential homes. The management of smart inverters and loads did not affect electric grid performance and stability. Within the configurations tested, there was no abnormal behavior observed with the size and numbers of solar PV systems added to the distribution grid. Based on the project goals, the hosting capacity of the electric grid suggests that Rule 21 recommendations are enough. It appeared that Rule 21 default settings could be safely maintained even with increased PV generation. Some additional findings were:

- Inverters do not use standardized displays of programmable features, including the feature names in the graphical user interfaces (GUIs), which makes it challenging to understand the features and customize them.
- The inverter manuals had limited or nonexistent information on smart features, which made it difficult to understand such features and required customization.
- There is no certainty that the inverters are preprogrammed with Rule 21 as the default functions. The process for configuring and enabling the Rule 21 functions may require complex procedures that are time-consuming for an installer.

Smart consumer devices or loads, which supported CTA-2045, lacked interoperability due to the nonexistence of standardized compliance testing and certification requirements. Some additional findings were:

- Full commissioning of all the smart loads could not be completed due to a lack of default interoperability with the standard.
- The EVSEs were found to be noncompliant and required factory upgrades due to failures with an on-site upgrade. The final verification of desired operations with the CTA-2045 module was completed after the software upgrades.

The SCE laboratory tests focused on a Rule 21-supporting smart inverter. The inverter under-voltage and over-voltage functions worked as expected. The communications gateway, as provided by the manufacturer, needed an evaluation from a cybersecurity standpoint, albeit this was not the focus of the project. The measurement accuracy of the inverter and grid simulator should be as close as possible to activate the inverter reactive power functionality. It is envisioned in Rule 21 that inverters should be able to supply or absorb reactive power from the grid or feed reactive power to the grid to maintain a stable grid voltage. The tests found that the inverter can supply or absorb reactive power based on the over- and under-voltage conditions. The detailed under- and over-voltage tests proved that advanced smart inverter functions will support the local voltage when it is needed, that is, when the voltage should remain within the volt-var and volt-watt setpoints.

Rule 21 functions include:

1. **Autonomous functions–***The harmonic testing, under- and over-voltage tests, and ride-through tests could be considered Phase "0" since these were done as part of the initial testing. Volt-var testing at PG&E showed that multiple inverters using standard Rule 21 settings behaved as expected. The Rule 21 settings adopted by the IOU did not result in undesirable inverter behaviors when connected to the same residential transformer.*
2. **Communications–**Phase/Function 2. *Inverters successfully communicated operational information, including hosting capacity. This was tested by Intwine, the project's communication and control subcontractor, at the PG&E site.*

In one of the project's serendipitous moments, an inverter's voltage measurement was not accurate when it started injecting reactive power into the grid prematurely. This issue could have been due to an inaccurate inverter meter. This anomaly has led to a finding that it may not be desirable for inverters from all manufacturers to react at the same time in an event. One may consider a natural staggering of the responses from the smart inverters to avoid grid power quality and reliability issues.

Field Tests

While the architecture of controls and communications required adaptation to meet the field-testing requirements, it represented no change in the end state of the tests and managing of the smart loads. The automation architecture can manage smart loads and inverters to avoid curtailment of solar PV during periods of high generation. The outcome was a new architecture that interoperates with two vendor technologies. This outcome has the potential to engage a diverse set of technologies among vendors with new business opportunities. A transformer can operate within preset capacity limits using the same strategy. This strategy allows a higher return on the solar PV investment while mitigating any wider-area disruption of the electrical grid.

The solar PV generation capacity and the availability of "flexible" or demand-responsive loads play a pivotal role in determining the amount of increase in the hosting capacity. Other flexible loads such as energy storage could not be field tested but can provide further flexibility to optimize management for solar PV. For this project, the storage market was immature when the project started. Locating a storage vendor or partners for this project was difficult. EV service equipment (EVSE) was part of the project lab tests. Following the field tests, the homeowner was asked the following questions to understand the automation features and evaluate the value proposition to participate in a market-based program:

- How important are the opt-out features if you are willing to allow the project to control these devices to balance loads with PV production?

- If it would not impact your normal day-to-day operations and enough incentive is provided, what would motivate you to allow control of smart devices and energy storage?

Active customer-engagement is more relevant in the initial stages of participation. The homeowner gains more confidence with progress in the program participation. The opt-out feature becomes vital during the initial stages of program engagement and a tool for use in case it is needed during continued operations. For example, the homeowner's family should be able to use the pool even on a low solar PV generation day.

Design and deployment of proper control strategies that are suited to the homeowner and adequate functioning of automation are vital to recruiting and retaining customers in market-based programs. For example, although this project did not manage battery energy storage, the homeowner was concerned about how battery charging and discharging could potentially shorten the battery life.

Technical Challenges Identified in Laboratory and Field Testing

The project faced challenges with Rule 21 supporting inverters and smart loads that led to project delays and additional use of resources beyond those anticipated. The project had to adapt to these changes to meet the goals and objectives.

The major unexpected challenges were related to the market availability of the full function communicating Rule 21 solar PV inverters. The original project goals relied on inverters with an out-of-the-box readiness to Rule 21 settings. The slower delivery of solar PV inverters delayed the acquisition time. This delay resulted in an inability to analyze the inverter characteristics and identify the field tests in time. The early batches of the Rule 21 Phase I-supporting inverters experienced multiple failures during the setup, and the configuration was not ready for testing. Some of the inverters required manual input of parameters, leading to errors. The manufacturer documentation to upgrade the software was difficult to locate, as products were still in development. A lot of time and resources were expended to ensure the smart inverters took the changes and exhibited the desired behavior. These challenges were likely due to manufacturers' lack of a Rule 21-compliant inverter since the procedures to test and certify compliance are in development. The new CPUC compliance deadline of July 22, 2020, (three months after project completion) made it challenging to identify a Rule 21-compliant inverter for field testing. It was evident from the laboratory tests that Rule 21 settings are only checked by the manufacturer (self-certification) with no neutral third-party verification. In the process of overcoming these technical challenges, the project had to conduct more detailed laboratory testing of the inverters with the issues that were not anticipated earlier in the project scope.

Due to the smart inverter challenges, SCE and SMUD expressed apprehension about using the smart inverters in the field tests. As SMUD appropriately indicated, the updates to smart inverter standards were delayed multiple times, and certified products were not available for testing at customers' homes. As a result, SMUD was unable to agree to interconnect noncertified inverters to the project's distribution grid. Field-testing such inverters in homes can potentially lead to equipment failures and homeowners declining to participate in the tests.

Even smart loads experienced these technical issues, including the smart loads (for example, EVSE) with standardized communications with CTA-2045. The project, again, had to expend more time to commission the EV chargers for their stated behavior, as required by the CTA-2045 standard. Smart load manufacturers that use CTA-2045 do not have compliant equipment since the test procedures to assess and certify compliance do not exist.

The project, however, overcame these challenges to recruit a home for field tests within the SCE service territory. The home had an existing inverter, solar PV, energy storage, and smart loads with communications and controls infrastructure that were leveraged for the field tests to provide early insights in support of the project objectives.

Findings Relative to Project Objectives

Relative to two core project objectives, as outlined in Chapter 1, the PG&E laboratory tests were leveraged to support Objective 1: Provide insight into whether specific function and control-loop timing parameters are necessary to enable successful side-by-side inverter operation. The smart inverters and load tests 8.1, 9.1, and 10.1 demonstrated the potential of increasing the solar PV capacity at homes with smart management of loads. The laboratory and field tests were leveraged to support Objective 2: Advance the industry's knowledge regarding how consumer loads can be managed most effectively to enable more PV on the grid. The same PG&E laboratory tests and field tests focused on test cases 7.2, 9.2, and 10.2, demonstrating that smart loads can be managed to use excess solar PV generation and, thus, increase hosting capacity.

These tests also provided early insights into answering the project's two key questions:

- How much can the solar PV hosting capacity of California's distribution systems be increased by activating the new Rule 21 smart inverter functions across multiple or all inverters?
- How much additional solar PV hosting capacity can be achieved by managing consumer loads in a fashion that is optimized for solar PV energy use?

The laboratory tests answered the questions relative to increasing the solar PV hosting capacity by activating the Rule 21 smart inverter functions across multiple inverters. The lab tests of the Rule 21 autonomous functions were done to ensure proper operation of multiple inverters when connected to a single residential transformer. Increasing PV hosting capacity was enabled by availability of the Rule 21 Phase 2 communications. The combined laboratory and field tests answered the questions relative to increasing the solar PV hosting capacity by managing the smart consumer loads.

Recommendations

The project showed that the optimization of smart inverter functions, smart load management, and adaptation of communications architecture is key to enabling greater use of solar PV. The type of load and customer engagement plays a key role in making this successful. Moving forward, the following are the key recommendations:

Smart Inverter-Compliant Products: The standardization of smart inverter features and compliance to advanced Rule 21 functions and their certification, specific to utility service territories, are essential to ensure that their features can be validated before the installation.

The lack of Rule 21 compliance testing and certification programs during the laboratory testing challenged the project's resources to validate compliance to Rule 21. State agencies and the IOUs should work jointly to have adequate smart inverter manufacturers and technology integrators develop Rule 21 compliant products and ensure that they are verified in the field.

Standards-Compliant Smart Devices: A similar challenge was experienced with compliance with standard CTA-2045. Due to the lack of market-based compliance testing and a certification program, off-the-shelf vendor products did not meet the specified guidelines. Before recommending any standards-based requirements, the state agencies and the IOUs should work jointly to have adequate smart device manufacturers and technology integrators develop standards-compliant products and ensure that they are validated in the field.

Decentralized Communications and Controls Architecture: The project's communications and controls architecture, where local controls optimize smart loads and inverter based DERs to increase solar PV use, had to be modified to suit the field conditions. A resultant and successful modular system architecture should be reviewed for practical applications across the industry. The architecture can provide utilities and consumers with a choice of the smart inverter and smart loads vendor. These products could be enrolled in different market-based programs to benefit the electric grid and the consumer—both eventually driving the goal of greater use of solar PV.

Widescale Testing of Rule 21 Functions: The challenges with the inability of smart inverters to support Rule 21 functions led to an unwillingness by the IOUs to deploy them in the field. This response is valid since any deviation from the expected performance can affect the grid operations and a consumer's lifestyle. For scaled deployments of Rule 21-compliant smart inverters, the state agencies and IOUs should conduct widescale tests. The findings can suggest improvements to the standards and products before widescale deployment. For efficient smart inverter testing, the manufacturers must ensure that the user manuals are improved, and features and GUI are standardized, to support proper programming, installation, and commissioning of the smart inverters. It can be envisioned that Rule 21 standard settings will be developed, and all inverters would have identical default settings with options for customization.

Assessing Smart Inverters and Loads for Solar PV Optimization: The project's laboratory and field tests showed the potential to manage the smart inverters and loads to understand what loads should be switched ON to consume solar energy and evaluate consumer preferences. Even with a successful optimization of controls and adaptation of communications architecture, due to the lack of field tests, the project was unable to test how solar energy can be offered (transacted) to neighbors. Having more accessibility to neighborhood field tests would facilitate further testing of how solar PV can be administered. The project's advanced optimization schemes can be potentially applied across a range of smart loads and consumers.

CHAPTER 6: Benefits to Ratepayers

The results and recommendations from the project will likely benefit the ratepayers of the three California IOUs—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—in three primary ways: (1) lower costs, (2) greater electricity reliability, and (3) improved safety. These three benefits are aligned with California's goals for the ratepayers (CPUC 2012).

Lower Costs

Consumers can reduce the energy costs from the PV systems they own and use them to self-generate their own energy. This ownership model is becoming mainstream with declining solar PV system costs. However, these consumer savings can be limited due to:

- A lack of permits to deploy a solar PV system due to distribution system constraints, which is an increasingly common situation.
- System limitations that act, as a restraint, to deploy and scale solar PV systems, limiting the savings.
- Consumer generation that is excessively curtailed or is not used to prevent the distribution system constraints.

The results from the laboratory and field tests can directly benefit consumers by minimizing, or eliminating altogether, these issues. The project approach stands to further benefit consumers by enabling them to take advantage of extant infrastructure. The smart-inverter functions, together with smart (PV-optimized) use of their loads, can enable more solar PV capacity and more PV total production in the distribution grid. The limited field tests showed a 36 percent potential increase in solar PV hosting capacity. This was higher than the assumed 30 percent improvement in the solar PV capacity originally expected. Simple analysis from the field test results showed 1,700 gigawatt-hours of excess solar could be used annually, resulting in an optimized cost and use of solar PV energy. The field test also shows no significant variability in frequency at the home level.

Greater Electricity Reliability

Optimal management of smart-inverter functions and smart consumer loads that can be aligned with distribution system constraints can minimize stress on electric grid infrastructure and improve grid reliability. Smart management of a single-speed pool pump can lower the systemwide demand by 1.5 GW over a three-hour period.

In addition, there is an inherent potential for greater reliability with local energy generation. With proper communications and controls, consumers may be able to have independent backup power and manage their energy use to improve local and grid power reliability. Enabling consumers to have and operate larger PV systems that are aligned with distribution system capabilities can add to electricity reliability.

Some of the primary smart-inverter functions identified in the California Rule 21 are to review performance during over- and under-voltage conditions. As the quantity of distributed generation grows, it is increasingly important to prevent outages that might otherwise occur due to minor voltage changes. The testing performed in this project evaluated these functions for proper behavior in multi-inverter environments. The results and recommendations from the project have the potential to further improve local and grid reliability.

Improved Safety

High levels of distribution-connected solar PV can stress distribution grid assets such as transformers, and increased stress can lead to outages and equipment failures if left unchecked. Therefore, the safety of local customer systems and grid systems can be improved.

The testing of smart-inverter functions that consider voltage and active and reactive power operational behaviors will help DER systems and smart loads operate at their optimal ratings and thus prevent them from failures. Like reliability benefits, the results and recommendations from the project have the potential to further improve local and grid safety.

Bottom Line

In addition to these three key benefits to the California ratepayers, the project results are practical and achievable in the immediate future. Although the field tests were limited to one home, and the results were limited, the potential scaling of the results to hundreds or thousands of homes can realize the potential for mass-market adoption. This goal of market adoption is furthered by the project's focus on the priority needs of consumers and the utilities.

The project made the most of the inverters and other loads by leveraging devices and systems that already exist in consumer homes, as opposed to adding new types of equipment that may not exist in scale or will not be adopted for some time. In this way, the results of these developments can be immediately scaled and replicated.

LIST OF ACRONYMS

Term	Definition
AC	alternating current
ATS	PG&E’s Applied Technology Services Laboratory
CEC	California Energy Commission
CPUC	California Public Utilities Commission
DC	direct current
DER	distributed energy resources
DERMS	distributed energy resources management system
DG	distributed generation
DOE	U.S. Department of Energy
DR	demand response
EE	energy efficiency
EMS	energy management system
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
EV	electric vehicle
EVSE	electric vehicle supply equipment
GUI	graphical user interface
GW	Gigawatt
H3	Home 3
HEMS	home energy management system
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
IOU	investor-owned utility
kVA	kilovolt-ampere
kW	Kilowatt
kWh	kilowatt-hour
LAN	local area network

Term	Definition
MW	Megawatt
NEC	National Electric Code
OpenDSS	Open Distribution System Simulator
PG&E	Pacific Gas and Electric
PQ	power quality
PV	Photovoltaic
SCE	Southern California Edison Company
SI	system of units
SIWG	Smart-Inverter Working Group
SMUD	Sacramento Municipal Utility District
ST	status temperature
THD	total harmonic distortion
TRL	technology readiness level
UL	Underwriters Laboratory
V	Volt
var	volt-ampere reactive
W	Watt
Wh	watt-hour

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APPENDICES

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