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Renewable Systems Interconnection Study:

Test and Demonstration Program Definition

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Abstract

To facilitate more extensive adoption of renewable distributed electric generation, the U.S. Department of Energy launched the Renewable Systems Interconnection (RSI) study during the spring of 2007. The study addressed the technical and analytical challenges that must be addressed to enable high penetration levels of distributed renewable energy technologies. This RSI report discusses the tests and demonstrations needed to better understand the issues and solutions associated with the high penetration levels of photovoltaics (PV) expected in future utility distribution systems. It identifies areas in which testing needs to be conducted and recommends specific tests needed to understand high-penetration PV scenarios and promote effective solutions. These tests will be conducted in both controlled laboratory settings and field demonstrations.

Preface

Now is the time to plan for the integration of significant quantities of distributed renewable energy into the electricity grid. Concerns about climate change, the adoption of state-level renewable portfolio standards and incentives, and accelerated cost reductions are driving steep growth in U.S. renewable energy technologies. The number of distributed solar photovoltaic (PV) installations, in particular, is growing rapidly. As distributed PV and other renewable energy technologies mature, they can provide a significant share of our nation's electricity demand. However, as their market share grows, concerns about potential impacts on the stability and operation of the electricity grid may create barriers to their future expansion.

To facilitate more extensive adoption of renewable distributed electric generation, the U.S. Department of Energy launched the Renewable Systems Interconnection (RSI) study during the spring of 2007. This study addresses the technical and analytical challenges that must be addressed to enable high penetration levels of distributed renewable energy technologies. Because integration-related issues at the distribution system are likely to emerge first for PV technology, the RSI study focuses on this area. A key goal of the RSI study is to identify the research and development needed to build the foundation for a high-penetration renewable energy future while enhancing the operation of the electricity grid.

The RSI study consists of 15 reports that address a variety of issues related to distributed systems technology development; advanced distribution systems integration; system-level tests and demonstrations; technical and market analysis; resource assessment; and codes, standards, and regulatory implementation. The RSI reports are:

- *Renewable Systems Interconnection: Executive Summary*
- *Distributed Photovoltaic Systems Design and Technology Requirements*
- *Advanced Grid Planning and Operation*
- *Utility Models, Analysis, and Simulation Tools*
- *Cyber Security Analysis*
- *Power System Planning: Emerging Practices Suitable for Evaluating the Impact of High-Penetration Photovoltaics*
- *Distribution System Voltage Performance Analysis for High-Penetration Photovoltaics*
- *Enhanced Reliability of Photovoltaic Systems with Energy Storage and Controls*
- *Transmission System Performance Analysis for High-Penetration Photovoltaics*
- *Solar Resource Assessment*
- *Test and Demonstration Program Definition*
- *Photovoltaics Value Analysis*
- *Photovoltaics Business Models*

- *Production Cost Modeling for High Levels of Photovoltaic Penetration*
- *Rooftop Photovoltaics Market Penetration Scenarios*.

Addressing grid-integration issues is a necessary prerequisite for the long-term viability of the distributed renewable energy industry, in general, and the distributed PV industry, in particular. The RSI study is one step on this path. The Department of Energy is also working with stakeholders to develop a research and development plan aimed at making this vision a reality.

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Executive Summary

A robust testing and demonstration program is the cornerstone of any development project, and this is certainly true for the Renewable Systems Interconnection activities of the U.S. Department of Energy (DOE). This report discusses the tests and demonstrations needed to better understand the issues and solutions associated with the high penetration levels of photovoltaics (PV) expected in future utility distribution systems. It identifies areas in which testing needs to be conducted and recommends specific tests needed to understand high-penetration PV scenarios and promote effective solutions. These tests will be conducted in both controlled laboratory settings and field demonstrations.

Significant testing and demonstration are needed if PV systems are to achieve high penetration levels in utility grids. Some tests are needed to determine that a problem exists and characterize its extent. Other tests can validate solutions to problems; still others can identify system benefits that would promote high penetration of PV.

Controlled-environment laboratory testing allows specific parameters to be characterized accurately and provides repeatable test conditions that would be difficult to find in the field without extensive long-term monitoring. Field tests can verify that a problem exists or a that solution is effective, and they can point out unexpected issues.

Computer modeling can be particularly important in these investigations, because a properly vetted model can guide researchers and narrow the range of experiments that need to be performed in a specific scenario. Although modeling cannot replace experiments, it can speed up testing significantly and reduce associated costs.

Laboratory-Based Testing

Broadly, a successful laboratory-based testing program will involve the development of requirements, evaluations of solutions, and verification and certification of products.

- Develop and validate information for models of specific PV system equipment, especially inverter performance models as they relate to the simulation of distribution system impacts.
- Develop laboratory capabilities for testing a variety of high-penetration scenarios under conditions that are as close to real-world ones as possible. Specific tests would include the evaluation of voltage regulation schemes, prevention of unintentional islanding, intentional operation of an island or microgrid, false inverter trips due to utility line transients, reverse power flow in secondary network distribution systems, and system stability issues, such as those related to variable cloud cover.
- Test a variety of communication methods between distributed PV systems, utility grid operations, storage systems, and energy management systems. As part of work involving energy management systems (EMS), storage, and PV testing, this effort would look at fault tolerance, speed, reliability, and system bandwidth, including limitations of routers, servers, and other similar elements. These tests could establish the requirements for advanced communication protocols.

- Evaluate different control schemes for autonomous distributed control in a system containing multiple inverters. Candidate control schemes include voltage or frequency "droop" controls, output impedance synthesis, and communications-based approaches that may be distributed ("agent-based" control) or centralized.

Field Testing and Demonstrations

Field tests will require identifying candidate locations with high PV system penetration. These could include new residential subdivisions with a large number of the homes having PV systems, commercial systems in which PV is a significant part of the load, and utility-interconnected systems that feed back a significant amount of PV power at the distribution level. The field testing and demonstration effort should include one or more locations with the following characteristics:

- A demonstration site with relatively high feeder-level PV penetration (>30%) on a legacy distribution system with feeder (medium voltage) and service (presumably, low voltage) voltage and current monitoring. This site would provide the means to investigate PV impacts on voltage regulation, the effectiveness of various solutions (especially inverters with volt-ampere reactive [VAR] capability), fault contribution, and fuse coordination or desensitization; the latter two would probably be studied using modeling).
- Fielded samples of an undersized or overloaded primary or secondary distribution line in which the substation voltage has been raised to deal with the voltage drop (e.g., an old, rural feeder for new, large homes).
- Fielded systems that can be used to test a variety of nontraditional benefits, which might include items such as voltage and frequency regulation support, PV as spinning reserve, customer load management, peak load reduction, utility reliability enhancement, and upgrade deferral.
- Testing of the integration of EMS with PV systems and storage to optimally manage power for commercial facilities. This can include the development of predictive algorithms for loads and PV output to optimize the sizing and use of storage.
- A demonstration site that includes integrated EMS with defined interruptible and critical loads; defined load usage profiles (either time-based or weather-based); possibly, storage with its own communications and control system; and PV with its own communications and control system. Testing would evaluate control strategies, especially any predictive capabilities each unit might employ, e.g., to predict solar output at some time in the future and to similarly predict loads, as well as when a load should be turned on or off, now or in the future, in anticipation of an expected future need or opportunity.
- A single commercial building that integrates PV and possibly storage with a comprehensive EMS.
- A high feeder-level PV penetration (>30%) commercial building application incorporating relatively large PV systems (e.g., 50 kW and up) on multiple buildings sharing a common feeder.

- A microgrid test site that incorporates many of the features listed above, as well as other generators and loads, with a centralized command and control capability.

Conclusions and Recommendations

These testing needs are critical to understanding issues, developing solutions, and engendering utility confidence. Several major test facilities are set up to support the kinds of testing envisioned here, but they will undoubtedly need funding and coordination for specific testing and equipment. Therefore, a DOE-sponsored High-Penetration PV program could include provisions for funding and coordinating an array of laboratory testing. Some of this funding would directly support testing and reporting, such as evaluating specific grid impact issues. Other funding could be used to help enhance general testing capabilities in anticipation of industry needs for product development, verification of capabilities, and certification.

Our interactions with utilities in researching this report showed their significant interest in better understanding the issues related to high-penetration PV. Therefore, the DOE program could identify and coordinate those utilities so they work toward a common goal; help them locate candidate test sites; identify appropriate developers of solutions and their products; develop specific test plans; support the installation of monitoring equipment; and lead data collection, evaluation, and reporting activities.

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1.0 Introduction

No matter what perspective we take, when it comes to achieving high-penetration photovoltaics (PV) in utilities, getting there will require solutions that provide the desired benefits, address anticipated impacts, and do both in a cost effective manner. Therefore, the U.S. Department of Energy (DOE) established the Renewable Systems Integration (RSI) project to focus on the many issues that the PV and utility industries face. The RSI project brings together a team of experts charged with systematically identifying, evaluating, and presenting the current status of a broad spectrum of technical, financial, and regulatory issues.

This report discusses the testing and demonstration needs associated with RSI activities. Tests are needed to determine whether a problem exists and to characterize its extent. Other tests are required to validate solutions to the problem. Controlled-environment laboratory testing allows specific parameters to be characterized accurately. It also provides repeatable test conditions that would be difficult to find in the field without extensive long-term monitoring. Field tests can not only verify that a problem exists or a solution is effective, they can also point to issues that had not been expected. Decisions must often be made based on a combination of field-test and laboratory results, which are sometimes contradictory. For example, if we have not measured a certain condition in the field, that does not necessarily mean it is not occurring in another place or at another time. Also, being able to imagine a problem and create the necessary conditions for it in the laboratory does not always mean that it is a legitimate real-world concern.

This report looks at the range of issues raised in the RSI project companion reports and suggests the laboratory and field testing needed to evaluate an issue and propose appropriate test requirements. The report also looks at where testing can be performed, listing a number of controlled environment test facilities. And it suggests some existing and upcoming applications that offer unique, high-penetration environments for investigating issues and testing possible solutions.

2.0 Current Status of the Research

Significant research on the interaction between PV and the utility grid has been conducted over the past 30 years. This section provides a historical sampling of projects that dealt with—and in most cases, continue to deal with—utility interconnection as at least one of the key issues.

2.1 DOE Regional Experiment Stations (1979–Present)

Beginning in 1979, three Residential Experiment Stations (RES) were established. One of them—the Northeast RES, which opened in 1980—was installed at the Massachusetts Institute of Technology (MIT). One—the Southwest RES—was established at New Mexico State University in 1981. And one—the Southeast RES—was established at the Florida Solar Energy Center (FSEC) in 1983. These were later renamed *Region* Experiment Stations to reflect the program's broader perspective. Each installed a number of prototype grid-tied residential PV systems, which included full-size PV arrays and programmable loads, to evaluate all aspects of PV performance.

The inverters used in the systems were designed and built with few of the interconnection requirements placed on today's units. Utility interconnection testing included harmonics; the output of at least one inverter was euphemistically called "modified sine wave," which meant a somewhat filtered square wave. Also included was islanding testing, which was difficult but possible to achieve in the days before anti-islanding functions were incorporated.

Although the NERES ceased operation in the mid-1980s, both the SWRES and the SERES continue operating under DOE contracts, and their staff members provide valuable engineering and evaluation services to the PV community (Figure 2-1 and Figure 2-2).

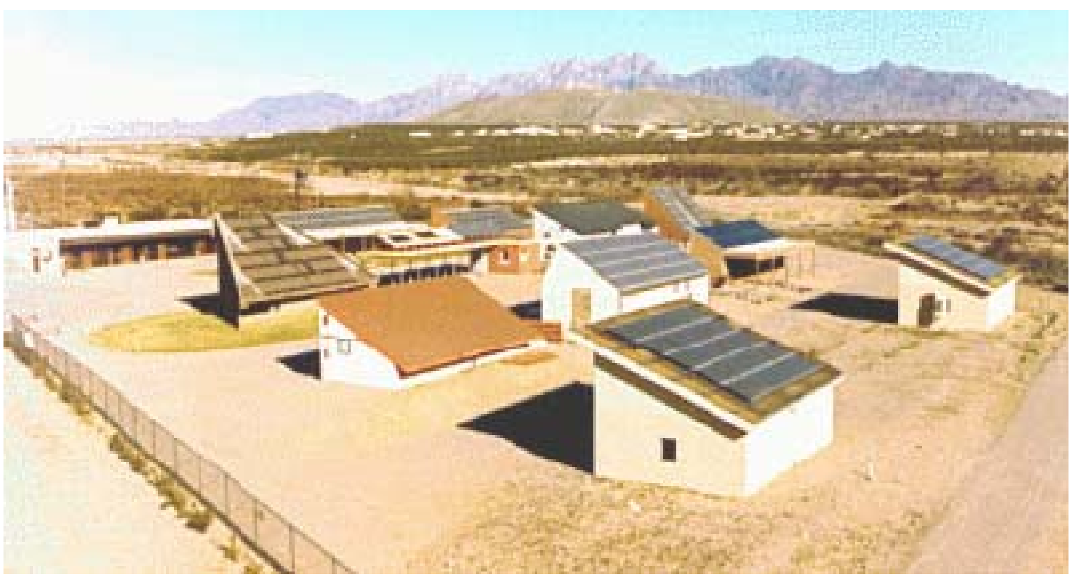

Figure 2-1. SWRES, Las Cruces, New Mexico

Figure 2-2. SERES, Cocoa, Florida

2.2 Sandia Distributed Energy Technologies Laboratory (1982–Present)

Sandia National Laboratories operate the Distributed Energy Technologies Laboratory (DETL) for DOE (Figure 2-3). The laboratory is an extension of the inverter test facility developed to support DOE Photovoltaics R&D activities. This facility has helped advance the state of commercial inverter design and operation for many years. It has accomplished this by performing product development tests with inverter manufacturers, subjecting commercial products to standardized tests to benchmark their performance, and evaluating their operation as system components. This activity has resulted in significant improvements in product reliability and capabilities.

Figure 2-3. Sandia DETL, Albuquerque, New Mexico

Engineers at DETL measure the performance of power-conditioning equipment ranging in size from a few watts to hundreds of kilowatts. Sources are tested in either grid-connected or stand-alone operating modes. Voltages and currents are acquired on both AC and DC sides of the equipment and are analyzed to evaluate key parameters such as efficiency, distortion, output regulation, and load compatibility. And to evaluate generation sources in addition to PV, other measurement capabilities have been added. These include Coriolis-effect mass flow meters for gas flow measurements and ultrasonic flow meters for liquid flow measurements of sources capable of combined heat and power (CHP) operation.

At present, seven different data-acquisition systems are in place using 16-bit, 333-kHz digitizers controlled by National Instruments LabView programs. Microsoft Excel charts are created from the reduced data representing both averages and high-speed waveforms. Instruments independent of the LabView systems include oscilloscopes, spectrum analyzers, digital multimeters, dynamic signal analyzers, and audio analyzers. Specialized test equipment is used to measure additional quantities such as conducted and radiated radio-frequency emissions, audible noise, response to high-voltage surges, and variations in AC grid voltage and frequency. DETL calls upon a local consultant to measure exhaust emissions of sources such as microturbines and fuel cell reformers.

A 480-V, 3-phase reconfigurable microgrid has been constructed at DETL to facilitate testing of interconnected sources and control methodologies. This microgrid permits testing of sources either individually or in combination with other distributed energy resources (DER). The current configuration of the DETL microgrid incorporates one 200-A, two 100-A, and two 30-A populated equipment compartments and four empty compartments for future expansion. Details of the configuration change as testing is performed for a variety of customers and applications.

2.3 NREL Outdoor Test Facility (1983–Present)

The Outdoor Test Facility at the DOE National Renewable Energy Laboratory (NREL) is an integral part of the National Center for Photovoltaics (NCPV), where researchers use advanced, state-of-the-art laboratories and outdoor test beds to characterize the performance and reliability of PV cells, modules and small (1- to 5-kW) systems (Figure 2-4). Researchers at the OTF study and evaluate advanced or emerging PV technologies under simulated, accelerated indoor and outdoor conditions (e.g., using thermal chambers) and prevailing outdoor conditions.

The research conducted in the 10,000-ft^2 facility provides verification, characterization, or modeling of technology performance; quantitative assessments of reliability; identification of failure and degradation mechanisms; and strategies to improve reliability and performance. This improved understanding of photovoltaic technologies is also used to aid industry in developing new and/or improved standards and codes.

Figure 2-4. NREL Outdoor Test Facility

2.3.1 Indoor Laboratory Testing

Specialized chambers in the high-bay area test the performance of modules when exposed to varying weather conditions, such as heat, cold, humidity, moisture, and ultraviolet (UV) light. Modules are tested in high-voltage and wet conditions to evaluate electrical insulation and moisture intrusion that can cause corrosion or ground faults or pose an electrical safety hazard. Mechanical tests include module flexing, static loading and simulated 1-in.-diameter hail strikes. Accelerated testing is conducted on PV modules, electrochromic windows and solar mirrors.

Researchers in the laboratory perform destructive and nondestructive analysis to determine failure mechanisms in cells and modules. New measurement techniques and tests are developed to help identify future problems. Indoor cell and module characterization is performed with four different simulators. Current versus voltage (I-V) measurements are made using continuous, pulsed and concentrated light. Measurements can be made at Standard Test Conditions (STC) or at various temperature and irradiance levels.

2.3.2 Outdoor Testing

Calibrations of primary reference cells are conducted at the OTF. These calibrated cells provide the photovoltaic community with a path of traceability to standards. Outdoor module characterization is conducted with the Standard Outdoor Measurement System. This system takes current-voltage (I-V) curve measurements at conditions as close as possible to Standard Test Conditions. Long-term module performance testing is conducted on the Performance and Energy Rating Testbed and in the array field. More than 30 modules of various technologies are monitored continuously for performance under various weather conditions.

Outdoor exposure and stability tests are conducted on more than 50 PV modules in the array field. Two testbeds are dedicated to stressing photovoltaic modules under accelerated conditions outdoors. The high-voltage stress testbed places 600-2000 V across the module leads and frame and then measures leakage currents. The Outdoor Accelerated-weathering Tracking System reflects sunlight at 2.5 concentration to increase light exposure on the modules.

Several grid-tied, 1- to 2-kW PV systems are installed at the OTF. These systems employ various module technologies, such as copper indium diselenide, cadmium telluride, amorphous silicon, and crystalline silicon. These systems are monitored for long-term performance and reliability. Several types of stand-alone PV systems are monitored at the OTF, including remote solar home systems and area streetlights. Test procedures are developed to determine how well the system components perform as a complete system.

Researchers at the OTF also work with industry to set uniform and consensus standards and codes for testing photovoltaic devices. These standards and codes include those of the Institute of Electrical and Electronics Engineers (IEEE), the American Society for Testing and Materials (or ASTM), the International Electrotechnical Commission (IEC), and the National Electric Code (NEC).

2.4 Sacramento Municipal Utility District PV Program (1984–Present)

The initial foray of the Sacramento Municipal Utility District (SMUD) into photovoltaics was a joint program with DOE to install 1 MW of PV adjacent to the Rancho Seco nuclear power plant in 1984. This was intended to be the first segment of a 100-MW plant to be built through the late 1990s. A second 1-MW segment was added in 1986; both segments, as well as an additional 1.5 MW of PV added between 1997 and 2001, continue to operate. Much was learned at this facility regarding PV operation and maintenance, though there was no emphasis on grid impacts.

In 1991, SMUD began its PV Pioneer program to install PV on residential and commercial customers' roofs. By the end of 2001, nearly 10 MW of PV was installed at more than 1000 facilities around Sacramento. These have led SMUD to support the development of PV communities, such as the Premier Gardens subdivision discussed later. Although earlier programs led to some pockets of aggregation, high penetration had not been a concern until plans began to emerge for large subdivisions. These subdivisions, sought by the utility, will offer both high efficiency and PV generation. The intent is to reduce the primarily air-conditioning-driven peak demand that SMUD experiences. Premier Gardens continues to be a source of distribution system impact and load reduction data and analyses.

2.5 Arizona Public Service STAR Facility (1985–Present)

Arizona Public Service (APS) has adopted a strategy of performing small to medium-sized R&D projects (from a few watts to several hundred kilowatts) to gain an understanding of the issues related to the large-scale use of renewable energy to generate electricity. The STAR (Solar Test And Research) Center is one of the projects carried out to test solar technologies from a utility perspective. In 1985, APS decided to construct the STAR Center because numerous issues could not be addressed at existing APS R&D projects. STAR began operating in January 1988.

One of the key requirements in the design of the center was flexibility. Since STAR was expected to be constantly changing due to new products and advanced technologies, careful attention was paid to ensure that expansion could be accommodated quickly, economically, and efficiently. The overall purpose is to keep APS up to date on state-of-the-art solar technologies and applications. This knowledge will prepare APS to use solar power generation as the economics of various applications improve. STAR's specific goals are as follows:

- To compare promising solar hardware in a southwestern desert environment
- To determine the potential of photovoltaics
- To provide engineering data needed to design future PV systems
- To stimulate manufacturers to improve their products
- To advise APS customers with accurate, up-to-date information on solar energy.

STAR remains a focal point of the APS solar testing and evaluation program. In addition to the center's ongoing tests, a number of other APS research installations are coordinated through STAR. These include a solar monitoring network to assess the solar resource in the APS service territory and additional PV systems installed at customers' sites to address some of the practical issues associated with installing, operating, and maintaining PV systems.

2.6 Rokko Island, Japan (1986–2000)

Rokko Island is a man-made island in the industrial section of Kobe, Japan (Figure 2-5). Beginning in 1986, the Japanese government funded two PV R&D projects there, the first to develop basic technology for small grid-connected PV systems and the second to establish technical guidelines for utility interconnection of dispersed power generators such as PV, wind, and fuel cells.

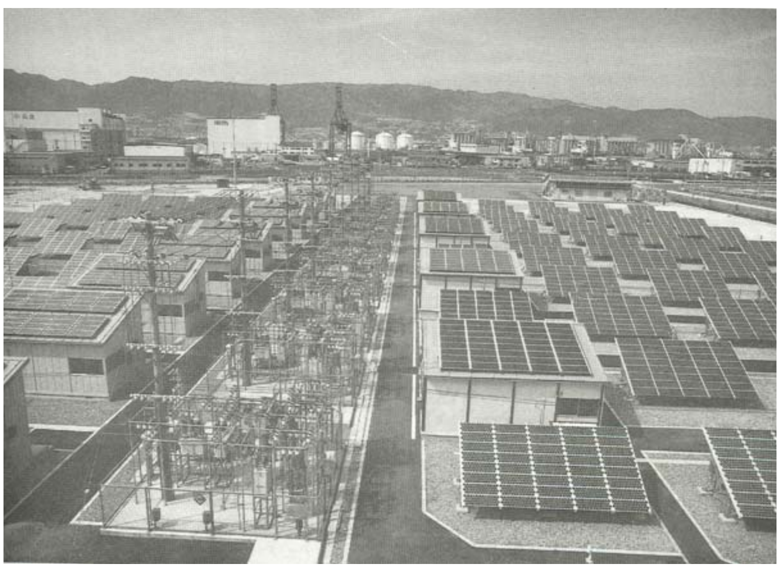

Figure 2-5. Rokko Island Test Facility, Japan

Under the two projects and with a budget approaching $100 million, Kansai Electric Power Company (KEPCO, the local utility) and the Central Research Institute for the Electric Power Industry (CRIEPI, the Japanese equivalent to the Electric Power Research Institute [EPRI] in the United States), established the Rokko Island test facility, which began operating in 1990. The overall facility included 102 PV systems ranging in size from 2 to 50 kW (400 kW total), two 16.5-kW wind turbines, and 17 fuel cells (1000 kW total), all connected through a reconfigurable 6-kV distribution system built to Japanese utility standards. The 100 small PV systems were situated on mock-up residential structures that included common residential loads ,such as washing machines and refrigerators, all of which had controlled operation. Additional programmable loads on the distribution system allowed for precise load/generation balancing and ensured that power was not fed back to the utility.

The issues investigated at the facility included the following:

- Islanding
- Reverse power flow
- Harmonic distortion
- Voltage fluctuation
- Protection coordination

Although most of the reports from the project are in Japanese, several conference papers have been presented in English [1, 2]. One, for example, was prepared for the International Energy Agency by Dr Akio Kitamura, the project's most prominent spokesman.

2.7 American Electric Power Dolan Technology Center (1987–Present)

Though PV is not one of its focus technologies, a very interesting candidate for excellent grid and load interaction testing is the Dolan Technology Center, sponsored and run by American Electric Power (AEP) in Groveport, Ohio. Although the name "Dolan Technology Center" goes back only to 2000 when a merger and reorganization occurred, the electrical laboratory was established at this location in 1987 when AEP relocated its headquarters from New York City to Columbus, Ohio.

The DTC is an AEP entity that performs a variety of testing services to the company, such as new device qualification, protection packages, telecommunications systems, and controls. They are also involved in projects at AEP demonstrating flywheel, sodium sulfur (NaS) battery storage, utility-grade inverters, and the like.

The center also does work for outside entities, e.g., the Consortium for Electric Reliability Technology Solutions (CERTS) microgrid and the national laboratories. DTC has been used as a development laboratory by outside product developers and has considerable experience in testing DER. The center reports having access to a fleet of people to augment in-house expertise, if needed. Currently, a joint development project for a 1-MW fuel cell package is under way.

So far, the DTC has built a test bed with comprehensive instrumentation originally designed for testing systems up to 250 kW. Tests focus on voltage sags and swells, capacitor switching, transient overvoltage, voltage, and current imbalance. Also included is utility equipment such as reclosers, breakers, and switches, as well as variable resistor and inductor banks (2000 kW and 100 kVAR, respectively). Fixed capacitor banks can be switched in steps to test the DER response and power factor range. Equipment can also pick up part of the building load. The DTC can test up to 3 MW, and it has a 200 psi natural gas line for fuel supply. It also has an environmental chamber for temperature testing for smaller DER.

The primary focus has been on electromechanical compatibility. This means the center can connect DER to the grid and see how the grid affects DER and how DER affects the grid (or nearby DER and other devices such as regulators and tap changers). Another major focus is on inverter-to-grid interconnections and performance, in both grid-connected and stand-alone (islanded) situations. This is a primary role of the CERTS Microgrid Test Bed project.

The DTC is planning to increase its capability for testing up to 6 MW to accommodate the fuel cell development project. In addition, the center is involved in the specification, procurement and commissioning of the next megawatt-scale NaS battery energy storage project on the AEP system, unique in its ability to adaptively island a portion of a distribution feeder based on load.

2.8 PVUSA (1987–2000)

The Photovoltaics for Utility-Scale Applications (PVUSA) project was a public-private partnership that provided a utility "behind the fence" facility for evaluating the performance and operation of grid-connected PV (Figure 2-6). Though the much of the project's focus was on performance comparisons of the various systems installed at the site's Davis, California, facility, utility interconnection issues were prevalent from the facility's initial design stages. The local utility, Pacific Gas & Electric (PG&E), which was also the technical and organizational lead for the project, imposed strict requirements that included redundant facility-level relays and transfer trip.

Figure 2-6. PVUSA Site, Davis, California (circa 1999)

A major activity of the project was the 500-kW PVUSA Kerman PV system [3]. Completed in 1993, it was the first system installed specifically to evaluate the potential benefits of PV generation within a utility distribution system. PG&E engineers reviewed numerous distribution feeders to find locations that met a variety of criteria—such as overloaded (or nearly overloaded) equipment, relatively slow load growth, and available land area—to come up with an appropriate test site. The Kerman PV plant was the subject of ongoing monitoring and numerous special tests to define and evaluate a comprehensive group of distribution benefits, including voltage support, equipment upgrade deferral, and grid reliability enhancement.

2.9 NREL DER Test Facility (1997–Present)

The Distributed Energy Resources Test Facility is an integral part of NREL's electric systems R&D (Figure 2-7). It was designed to assist the U.S. distributed power industry in developing and testing distributed power systems. Researchers use advanced state-of-the-art laboratories and outdoor test beds to characterize the performance and reliability of distributed power systems, support standards development, and investigate other emerging complex system integration issues for renewable and distributed technologies.

The 2,000-square-foot test facility is operational and works closely with the DER community - especially those in industry- to study and evaluate advanced or emerging distributed power technologies. This work includes characterizing, testing, and evaluating the performance of interconnection systems, power electronics, and controls to ensure that they operate properly and meet interconnection, communication, and other standards. It also involves the development of protocols and procedures for testing and evaluating systems to ensure that they meet performance, safety, and compatibility standards; testing advanced designs for grid-connected or stand-alone use, microgrids, and hybrid systems; and coordination of laboratory and industry testing activities, in particular by defining and providing standard testing and evaluation procedures.

The facility can also test up to three power systems simultaneously and can integrate up to 15 power systems components (generation, storage, loads) at any single time. The systems can be tested in stand-alone, grid-connected, microgrid, or hybrid configurations. This unique capability enables R&D in the way distributed power systems interact with each other and the utility.

Figure 2-7. NREL DER Test Facility

2.10 Distributed Utility Integration Test (2001–Present)

The Distributed Utility Integration Test (DUIT) is a full-scale test of DER and electric utility interaction (Figure 2-8). The overall objective of the DUIT project is to perform comprehensive testing to evaluate the potential impacts of high penetration of distributed resources in the electric distribution system. Another key objective is to better understand the benefits and challenges associated with substantial DER penetration to ensure the safe, reliable, and cost-effective inclusion in the electric systems of the future. Commercial-grade off-the-shelf DER systems are tested.

The DUIT facility is located at PG&E's laboratories in San Ramon, California, and interconnected to the PG&E grid at 21 kV. At present the facility includes three classes of equipment:

- Residential (single-phase, ≤ 5 kW) in Test Bay 1
- Commercial (three-phase, 30 kW to 250 kW) in Test Bay 2
- Industrial (three-phase, ≥ 250 kW) in Test Bay 3.

Both inverter-based and rotating machine-based generation and storage devices are included. Project funding is primarily provided by the California Energy Commission's Public Interest Energy Research Program and DOE through NREL. Other program sponsors include PG&E, other utilities who provide equipment and or technical assistance, and DER and supporting equipment suppliers.

Figure 2-8. DUIT Test Facility, PG&E, San Ramon, California

A total of 17 classes of tests (see Table 2-1) can be performed at the DUIT Facility, in accordance with a Distributed Utility Integration Test Project Plan published by NREL in 2000. Each class involves test sequences across multiple DER devices. The data acquisition system was expressly designed to meet the needs of a comprehensive suite of tests envisioned by the DUIT Test Plan.

Table 2-1. DUIT 17 Test Classes (in alphabetical order)

- Abnormal Conditions
- Adjacent Feeder Faults
- Capacitor Switching
- Cold Load Pick-up
- Control Strategies
- Fuse Coordination
- Network Systems
- Intentional Islanding
- Power Quality
- Reclosing Coordination
- Synchronization
- Short Circuit Current
- Stability
- Substation Backfeed
- Sectionalizer Testing
- Unintentional Islanding
- Voltage Regulation

Unintentional islanding and voltage regulation tests were identified by an industry advisory group as having highest priority for initial DUIT testing. A general description of the project can be found in DUIT: Distributed Utility Integration Test [4]. Some project results are available online at www.dua1.com/DUIT and www.energy.ca.gov/pier/final_project_reports/CEC-500-2005-122.html.

2.11 DISPOWER, Europe (2001–2005)

A project funded by the European Union and ISET in Germany was undertaken to review high penetration of renewable energy systems, as described in the report Distributed Generation with

High Penetration of Renewable Energy Sources [5]. The report describes three major European testing facilities:

- Test and Certification Center for DER (ISET, Germany)
- Distributed Power Generation Test Facility (CESI, Italy)
- Hybrid Power Plant Test Facility (CRES, Greece).

2.12 Japan CRIEPI and NEDO Testing (2004–Present)

Ota City is a unique 535-home PV subdivision. Probably the most unusual and relevant characteristic of the subdivision, besides its size, is the inclusion of lead-acid storage batteries at each home. These are used to sink excess PV generation at times when the distribution system voltage is high and backfeed would cause it to rise unacceptably.

The Mt. Akagi Test Center of CRIEPI is a follow-on activity to the Rokko Island facility discussed earlier. It has been expanded during the same time period as the development of the Ota City project to help with the theoretical evaluation of that project. Experiments related to the Ota City project have been going on for some time. One building houses a PV inverter test facility designed to accommodate 60 PV invertors parallel-connected to simulated grid lines and fed from a commercial PV simulator. This microgrid experimental facility also contains various other distributed power sources.

3.0 Project Approach

Like the other studies in this series of reports, the first issue was a matter of understanding the breadth of issues related to high-penetration photovoltaics. This was done in conjunction with the report on advanced PV system designs and technology requirements, documenting the experience of the authors, literature research, and input from the utility and PV communities.

We also received information and feedback from DOE, Sandia, and NREL, and in particular, from the project leaders on the other reports, such as EPRI, GE, and Navigant. Next, we reviewed PV interconnection-related test results and descriptions from current and previous projects. Finally, we obtained information from utility colleagues on new and planned PV projects that might represent field evaluation potential.

4.0 Project Results

After presenting general monitoring and field test requirements, the subsections that follow touch on some specific issues. Note that this report is not meant to be comprehensive in the discussion of issues and solutions. It is also not meant to be judgmental as to whether a suggested solution is practical; such discussions are in the RSI companion reports. Rather, this report describes as comprehensively as possible the test facility requirements—both controlled laboratory settings and field demonstrations—needed to evaluate the breadth of possible issues and solutions. These issues provide a context for broadly discussing testing and demonstration needs.

4.1 General Monitoring Requirements

Although numerous tests are described in the following sections, some common measurements are made in many of the test scenarios. Table 4-1 lists some general parameters and typical measurement requirements for steady-state measurements. Transient measurements are described in Table 4-2. Specific tests may require additional measurements, such as distribution conductor or transformer temperatures and the device status of items such as voltage regulators and transformer load tap changers. Using the higher sampling rates for steady-state voltage and current allow real and reactive power values to be calculated rather than using independent transducers. However, this also requires simultaneous sampling techniques.

Table 4-1. Suggested Steady-State Monitoring Requirements

Measurement Parameter	Quantity	Typical/ Nominal Range	Accuracy	Data Rates Sampling (Hz)	Recording (Sec)
Utility Primary Voltage	3 Φ	27 kV 15 kV	1.0%	1 - 600	1 - 1800
Utility Primary Current	3 Φ		0.5%	1 - 600	1 - 1800
Utility Primary Real Power/Energy	1		1.0%	1	1 - 1800
Utility Primary Reactive Power	1		1.0%	1	1 - 1800
Utility Secondary/ Customer Service Voltage	3 Φ 1 Φ	600 V 300/150 V	1.0%	1 - 600	1 - 1800
Utility Secondary / Customer Net[1] Service Current	1 Φ/3 Φ		0.5%	1 - 600	1 - 1800
Utility Secondary/ Customer Net Real Power	1		1.0%	1	1 - 1800
Utility Secondary/ Customer Net Reactive Power	1		1.0%	1	1 - 1800
Customer Total Real Load (Real Power to loads)	1		1.0%	1	1 - 1800
Customer Total Reactive Load (Reactive Power to loads)	1		1.0%	1	1 - 1800
Customer Total Real Generation (Real Power from PV)	1		1.0%	1	1 - 1800
Customer Total Reactive Generation (Reactive power from PV)	1		1.0%	1	1 - 1800
PV Array DC Output Power	1		1.0%	1	1 - 1800
PV Array Temperature	1		1.0%	1	1 - 1800
Local Weather Conditions (e.g., irradiance, temperature, wind speed, etc.)			1.0 - 3.0%	1	1 - 1800

[1]Net = total load – generation. Note that Accuracy and bandwidth may require special metering class CTs and VTs, especially for medium voltage.

Table 4-2. Suggested Transient Monitoring Requirements

Measurement Parameter	Quantity	Typical/ Nominal Range	Accuracy	Data Rates	
				Sampling	Recording
Utility Primary Voltage	3 Φ	27 kV 15 kV	1.0%	10 kHz	Event-triggered, record ≥ 100 ms/event
Utility Primary Current	3 Φ		0.5%	10 kHz	Event-triggered, record ≥ 100 ms/event
Utility Secondary/ Customer Utilization Voltage	3 Φ 1 Φ	600 V 300/150 V	1.0%	10 kHz	Event-triggered, record ≥ 100 ms/event
Utility Secondary / Customer Utilization Current	1 Φ/3 Φ		0.5%	10 kHz	Event-triggered, record ≥ 100 ms/event
Inverter Status Information (communicated by the inverter)				Determined by inverter comm. rate	Record and time stamp all event responses
Utility Event Records				Set by utility SCADA	Record all events and system responses

Note: Accuracy and bandwidth may require special metering class CTs and VTs, especially for medium voltage. Specific tests may require faster sampling rates or longer recording intervals.

4.1.1 General Field Testing Needs

In general, there is a need to monitor, a variety of PV installations in the field. These installations should represent different geographic locations, utility design and operation practices, penetration levels, distribution system configurations, and load classifications. This is done to better understand what the actual power flows look like. For example, although our general understanding of utility distribution systems is very good, uncertainties remain with respect to the coincidence of PV output and customer power needs. We know, for example, that even with the same quantity and types of loads in a neighborhood of homes, individual usage is highly variable, depending on the makeup of the occupants (number, ages), their occupations, habits, and so on. Even in identically constructed homes, different levels of plug loads can further differentiate usage at one house from another, even when beside each other [6].

Cyclical loads (e.g., refrigerators) show even greater variability from one home to the next at any given time. On the other hand, aggregating enough homes on a line yields fairly consistent results. The diversity of customer loads—the concept exemplified by the idea that when one refrigerator is cycling down, another is cycling up—reduces the overall variability experienced by upstream equipment [7]. To illustrate this, and to present the kinds of information that will be needed from field testing, we can look at some data from the SMUD Premier Gardens subdivision in Sacramento, California.

4.1.2 Examples of Field Testing

Figure 4-1 shows measured 15-minute average demand over a sample day for 18 high-efficiency Premier Gardens homes. The day selected happened to include the peak ambient temperature (102ºF) for a cooler-than-normal June; thus, it represents a relatively high SMUD system-wide peak demand day (2,735 MW). (This was 66 MW below the record for the month, which occurred the next day, and more than 500 MW short of SMUD's all time peak of 3,299 MW).

The heavy red line in the upper part of the graph of Figure 4-1 shows the highly variable maximum house demand, essentially connecting the dots between the 15-minute peak values.[1] On that particular day, the maximum demand ranged between 1.6 kW and 8.2 kW. Similarly, the heavy blue line in the lower part shows a nearly constant minimum demand of about 0.2 kW.

The heavy black line in the middle shows the average demand for the 18 homes. So, despite the large disparity in demand between individual homes, the aggregate load (which is 18 times the average) that would be seen by a transformer supplying these 18 homes[2] is fairly smooth and similar to standard residential demand plots we might find in a textbook.

Each Premier Gardens home is equipped with a 2-$kW_{CEC\text{-}AC}$[3] PV system. Though the PV array on an individual home can be oriented to the west, south, or east, the average PV output for the 18 homes is fairly similar since they are all experiencing the same solar and weather conditions.

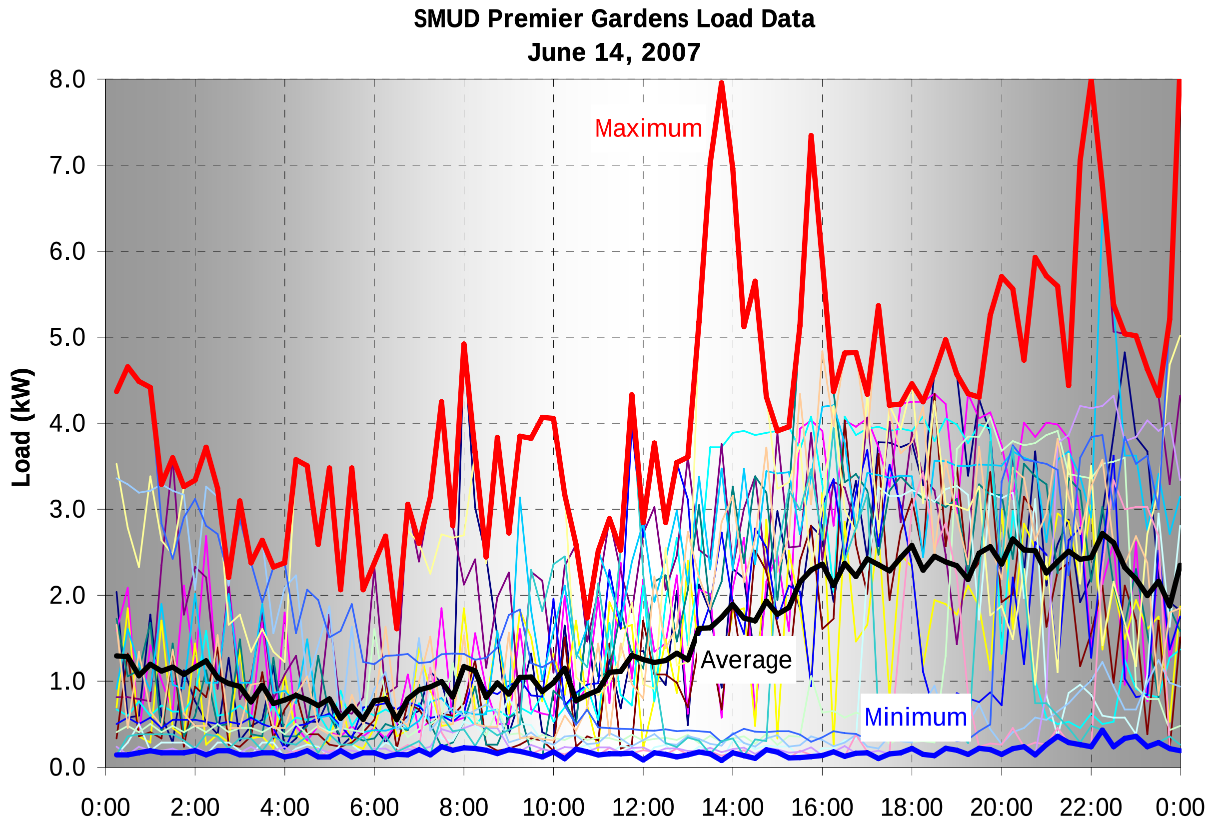

Figure 4-1. Sample residential load data showing maximum, average, and minimum demand (Courtesy of SMUD)

[1] Averaging, even over as short a period as a few minutes, will mask some of the variability of individual loads.
[2] The homes are actually distributed among nine distribution transformers in the subdivision.
[3] This is the method of AC system rating used by the California Energy Commission, which takes into account module temperature and inverter efficiency.

Figure 4-2 shows the average total load, the average PV output, and the average net load (the total minus PV) for the homes.

These plots show the kind of the information that can be obtained from the type of monitoring efforts that SMUD has undertaken. The goal of this phase of the SMUD project was to evaluate the impacts of PV and high-efficiency housing construction on SMUD's system peak demand. Not shown here are the forthcoming voltage regulation analyses results, also part of the RSI projects. New service voltage monitoring equipment was recently installed as part of RSI contract and we are just starting to receive that data. We intend to use voltage and current measurements from the substation and selected transformers along with the new customer service voltage data and the load data presented here to fully understand the impact of the Premier Gardens homes on distribution system voltage.

We anticipate that the analysis of these data will provide further insight into the impact of high-penetration PV on the distribution system. We believe that Premier Gardens will be a model for future residential subdivision monitoring efforts, as well.

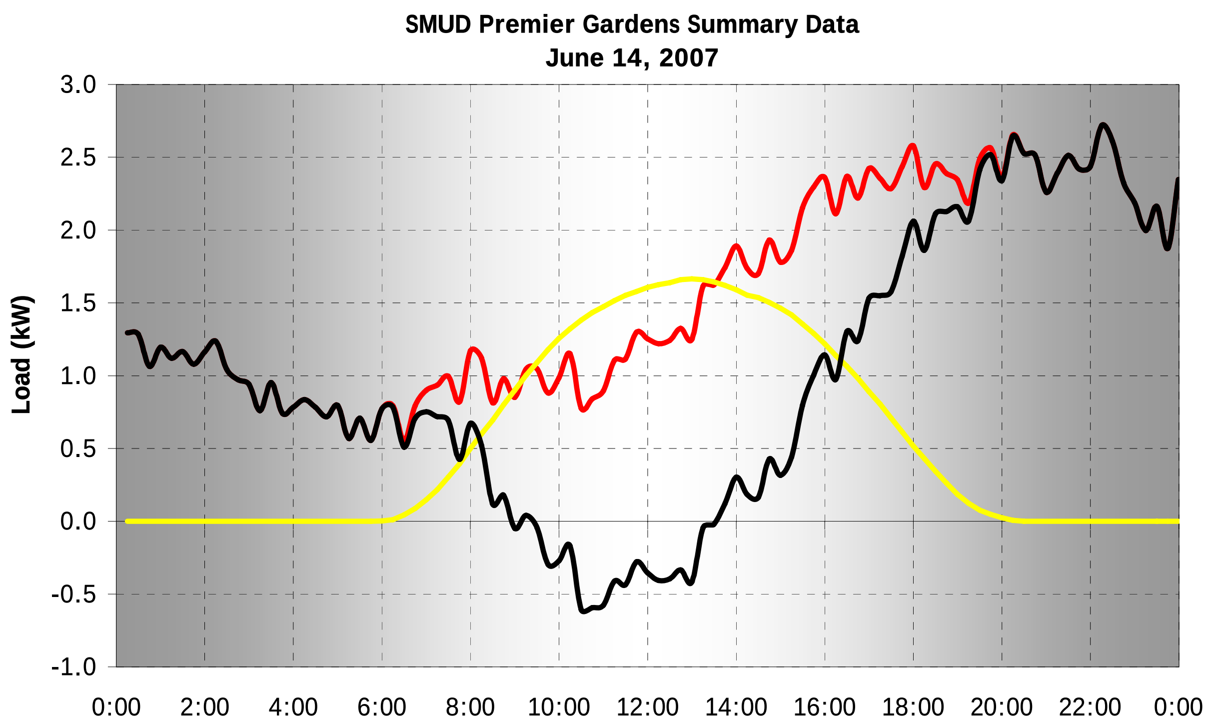

Figure 4-2. Total and net demand and PV output for one sample day (Courtesy of SMUD)

The Premier Gardens data incorporate the type of monitoring that will be needed to evaluate the grid impacts of high-penetration PV. Premier Gardens monitoring includes 1-minute to 15-minute averages of parameters shown in Table 4-3. The parameters in this table provide the basis for thoroughly evaluating real and reactive power (and current) flows in the system as well as the voltage at various points. Though energy is the primary accounting method used for utility billing purposes, what the customer uses is power. The demand for power determines the sizing of the utility generation, transmission, and distribution equipment. Power demand that exceeds the generating capabilities or equipment ratings can cause voltage and frequency excursions outside the allowable limits and lead to customers misoperating or damaging equipment. Understanding the relationship between production (e.g., output power from PV and storage) and demand is key to understanding the benefits and impacts of high-penetration PV. The parameters in Table 4-3 reflect that need.

Table 4-3. Suggested General Field Measurement Parameters

Parameter	Customer Facility				Feeder		Substation			
	PV System	Storage System	Loads	Facility (Net)	Secondary	Primary	Bus\Feeder	Primary		
Voltage				X	X	O	X	O		
Current				O	X	O	X	O		
Real Power from	X	O		X	X	O	X			
Real Power to	X	O	X	X	X	O	X			
Reactive Power from			O	O	X	O	X			
Reactive Power to			O	O	X	O	X			
Transient/Event Monitoring				O	O	O	O	O		
Utility Control Equipment					O – Vtg Reg, Cap Bank		O – LTC O – Recloser			
Other	Weather									

Notes: X = measured; O = optional. Parameters are assumed to be single- or three-phase measurements, as appropriate.

In a subdivision of hundreds of homes, it might not always be reasonable or feasible to monitor each home, transformer, and distribution line section. The selection of customers for Premier Gardens monitoring was based on a statistical sampling of homes based on the square footage. Selection of distribution transformers was based on both statistical sampling, such as a mix of Premier Gardens and non-Premier Gardens homes, and technical reasoning, such as accessibility of the transformer for monitoring purposes and whether or not monitored homes were connected to the transformer. The validity of the statistical sampling is demonstrated in Figure 4-1.

Field testing and demonstration are more effective for verifying performance and operational characteristics and less effective for developing solutions or evaluating protective functions. The latter requires setting up fault conditions and interrupting local service; both would be unacceptable in most situations. Computer modeling is especially helpful in cases like this. Highly accurate computer models of PV and distribution systems, loads, utility source impedances, and any other local DER could be used to dramatically reduce the number of experiments needed (in some cases, to none).

4.2 Excessive Service Voltage/Voltage Regulation Support

4.2.1 Discussion

The first problem related to high-penetration PV systems—one that is already being seen in a few situations—is excessive service voltage,[4] which is caused by the reverse power flow from exporting PV systems. The utility designs the distribution for several volts of drop. However, the reverse power voltage rise can be as much as several volts and can result in service voltages in excess of the maximum allowed regulation voltage—or even in excess of the inverter overvoltage trip setting. This problem occurs chiefly on the low-voltage distribution secondary, where the PV system interconnects (and where high penetration can most easily occur) especially when the utility feeder primary voltage is held high to accommodate voltage drops elsewhere on the feeder. It is more problematic on a shared secondary, where high voltage affects both PV-equipped customers (for whom there is a potential upside to living with the high voltage) and their non-PV-equipped neighbors. High levels of penetration on a feeder can also lead to excessive service voltage when that feeder shares a substation bus that is being regulated to address high loads or low voltages on adjacent feeders that include little or no DER.

Solutions to this problem include the following (see also the RSI report on advanced PV system designs and technology requirements):

A. Utility-side solutions

1. Reduce feeder voltage at the substation (change the load tap changer [LTC] control settings)
2. Reduce distribution system series impedance (larger conductors, more distribution transformers, fewer customers per transformer, shorter secondary conductor runs)
3. Use reduced output voltage distribution transformer (fixed or multitap)
4. Add line regulation equipment
    a. At the tap point feeding an aggregation of PV (e.g., solar subdivision)
    b. On secondary of the affected distribution transformer in spot cases

B. Customer/PV-side solutions

1. Reduce PV export during high voltage conditions using any of the following:
    a. Inverter foldback: operate array off the MPP
    b. On-site storage
    c. Load management
2. PV inverter VAR output

Beyond being a voltage-neutral good neighbor, distributed PV can also offer voltage regulation support services to the controlling utility. Voltage regulation support—supplying leading or lagging VARs or varying the amount of power exported—can be provided in response either to local voltage conditions or to a signal provided by the utility. For example, the inverter might be programmed to supply lagging (i.e., capacitive)VARs whenever the service voltage drops below a nominal threshold, or leading (i.e., inductive) VARs when the voltage rises above a threshold, possibly with a deadband between the two thresholds. Note that storage and load management (B.1.b and B.1.c, above) can be used in conjunction with the PV system output to reduce or increase facility import or export for voltage support purposes.

[4] "Service voltage" is the voltage provided by the electric utility to the customer at the point of common coupling.

4.2.2 Test and Demonstration Needs

Utility-side options A.1 through A.4 are traditional options available to the utility distribution engineer and have well-known, well-understood costs, characteristics, and reliability impacts. There are a few opportunities for characterization testing, such as the response of a particular line regulator to reverse power flow or to rapid power fluctuations caused by intermittent passing clouds. However, even these issues should already be addressed within the equipment specifications. Field demonstrations at locations with high penetration comparing systems with and without these options would be instructive and beneficial for promoting them as reasonable solutions.

The PV-side solutions, on the other hand, represent substantial testing opportunities. Options B.1a through B.1.c will need standardized requirements; primarily, how much the facility export must be reduced (through foldback, transfer to storage, or dump load increase), under the current export and utility line voltage conditions, to provide acceptable voltage.

An inverter incorporating a dynamic response would have to be validated and certified. Utilities in Japan have apparently required option B.1.a in some situations, while CRIEPI and NEDO are completing an analysis of the 535-home Ota City PV demonstration project incorporating option B.1.b (as mentioned earlier). Option B.1.c would also make an interesting demonstration of the integration of a PV inverter and EMS system to provide the functionality needed. It is also likely that option B.1.c would require B.1.a or B.1.b as a fallback in case no dump loads were available.

Voltage regulation using inverter VAR control also has a substantial need for test and field demonstration. Each PV array is likely to be too small to provide substantial voltage regulation through VAR control. Therefore, methods for determining an appropriate level of VAR output for a particular situation—whether determined by the inverter based on local measurements or commanded by the utility based on wider area measurements—need to be developed and verified. Limits on VAR output to ensure stability need to be determined and confirmed by testing to establish those limits and verify their suitability. Communications methods, if used, will need to be defined and verified.

Such a system might be best demonstrated by finding an existing PV system or group of systems that are experiencing overvoltage conditions and retrofitting the new control system. Optimum conditions would be a long primary or secondary distribution line in an overload or near-overload state. Microgrid testbeds would also provide testing opportunities, since they can simulate the same problem of not having any single generator strong enough to control the system voltage. A test facility could be set up with a relatively high-impedance, low-voltage secondary system to mimic a worst-case shared secondary.

4.3 System Stability with Intermittent Clouds

4.3.1 Discussion

Intermittent clouds passing rapidly over a large, central-station PV plant may cause its output to change faster than thermal plants, which must make up the difference, can respond. Small amounts of storage or various operational strategies can be applied to stabilize the PV plant output and reduce the ramp rate.

4.3.2 Test and Demonstration Needs

The first need is to verify that an intermittent cloud problem exists and the conditions under which it could become critical. Under certain wind conditions, fair-weather cumulus clouds, such as those in Figure 4-3, can move quickly across the sky, causing rapid variations in PV output. Coordinated high-speed irradiance measurements (e.g., 1-second samples) taken at distributed locations representing the edges of a large, single PV system—or the boundaries of an area with many individual PV systems—will provide an indication of the rate of change of irradiance and length of shadowed and sunlit intervals. A single effort to characterize these parameters would be valuable for worst-case conditions in specific geographic locations or to determine general worst-case conditions for the United States.

Fair-weather cumulus clouds will have more of an impact on a single-site, central-station system where the shadow is likely to cover a significant portion of the array. When a PV system is distributed over a larger area, it is more likely that some part of the system will be in the shade and some will be in the sun, thus reducing the potential impact. In that case, a strong weather front—a clear sky followed by a line of clouds demarking the beginning of a storm system—can similarly cause a high rate of reduction in PV output, but without the subsequent ramp-up associated with cumulus. Such weather fronts may also be associated with dramatic changes in wind speed, which can have a similar impact on wind generation on the same system. Increases in output from the wind plants would probably not be properly timed to offset the reduction in PV output. However, it would be desirable from a utility perspective to understand the aggregate impact of such a storm system. First-order evaluations should consider PV strictly with its own ramping.

Figure 4-3. Fair-Weather Cumulus Clouds (Photo by Ronald L. Holle, from University of Illinois Cloud Catalog)

This information can be used to define the rate of change of PV output. When that is combined with knowledge of the ramp rate of the serving utility's generating facilities, we can determine the amount of storage or the characteristics of the operational strategy needed to sufficiently reduce the ramp rate of the PV plant.

The effectiveness of the approach chosen can be evaluated using a suitable PV simulator programmed with a standardized high-rate-of-change irradiance profile. The resulting inverter/system could be characterized by a maximum rate of change for the standard profile.

4.4 Unintentional Islanding

4.4.1 Discussion

A utility-originated "okay to operate" signal transmitted via power line carrier communications (PLCC) would provide a reliable means for determining that the circuit to which the DER generating system is connected is under the utility's control. Loss of the PLCC signal would be interpreted as a loss of utility and further reduce the possibility of unintentional islanding. Such a system could be susceptible to nuisance tripping. Options to provide reliability and robustness would be valuable and will need adequate testing to ensure proper operation.

4.4.2 Test and Demonstration Needs

Work on utility data transmission via power line carrier has been going on for some time. However, several issues still need to be resolved (see, for example, the discussion in the RSI report on advanced PV system designs and technology requirements. Once the utility-side issues are resolved, standards need to be developed regarding the signal to be transmitted, requirements for the DER-side receiver, and certification testing requirements.

System operation can be readily exhibited in laboratory testing and field demonstrations with adequate number of PLCC-equipped PV systems. On the other hand, validating PLCC reliability to the satisfaction of both the utility and the DER communities may be limited to modeling and lab testing because of the need to repeatedly set up islanding conditions.

4.5 False Trips Due to Utility Line Transients (Adjacent Feeder Faults)

4.5.1 Discussion

The undervoltage/overvoltage and underfrequency/overfrequency abnormal-condition trip requirements in IEEE 1547 have been described as "trip-happy" by some system integrators. The relatively narrow settings were selected because, lacking direct communications with the controlling utility and other methods (e.g., ground fault relay or distance relay), they represent the primary fault detection means for DER. The survey in the report on advanced PV system designs and technology requirements included one response suggesting that some inverters connected to a distribution feeder in Arizona tripped in response to a transient event that occurred at a power plant in California, thousands of miles away. This response did not serve the customer, who lost a small amount of energy and risked an increased demand charge primarily because of a restart delay of up to 5 minutes imposed by IEEE 1547. Neither did it benefit the serving utility, which had to cope with the increased load, reduced voltage, and other effects of the loss of generation.

IEEE 1547 mandates that DER used in systems of 30 kW or greater must have field-adjustable trip settings, and utilities can, at their discretion, widen those trip settings when appropriate. From a distribution system perspective, narrower trip settings provide better feeder fault response characteristics. However, from a system stability perspective, the increased use of DER will lead to greater need for widened settings, particularly underfrequency and undervoltage settings. These are most likely to operate under utility system stress conditions, for which the loss of generation is the worst response.

4.5.2 Test and Demonstration Needs
Many active anti-islanding techniques used in PV inverters rely on abnormal trip settings to cause the unit to trip. Currently, IEEE 1547 does not consider the impact of adjustable trip settings in its evaluation of active anti-islanding techniques. So, it is unclear how changing these settings will affect trip times. Initial testing should investigate the impact of widened trip settings on islanding trip time to determine the maximum settings that enable the unit to meet the anti-islanding requirements.

Use of other means for detecting fault and loss of mains, such as the power line carrier described in the previous discussion, may offer sufficiently effective alternatives to comfortably allow even wider trip settings. Testing should determine and compare the efficacy, robustness, and economy of alternate detection means in conjunction with widened abnormal condition trip settings.

4.6 Reverse Power Flow in Secondary Network Distribution Systems

4.6.1 Discussion
IEEE 1547.6 is defining suitable approaches for applying DER in spot and grid secondary network systems. These networks provide a number of challenges to DER, not the least of which is the need to ensure that power is never exported from the network back to the utility feeder through the network transformer and network protector. One approach would be to use storage to capture the excess power produced when the PV output exceeds some predefined percentage of the facility's instantaneous load. Different strategies could be implemented for different secondary configurations. Zero export or some minimum import would be required for a single facility on a spot network; some controlled level of export may be allowed under certain conditions on grid networks.

4.6.2 Test and Demonstration Needs
First-order testing will be used to develop operational strategies such as determining how much storage capacity must be available over the day to ensure that the facility's export limits (which, for example, would be zero for a single facility on a spot network) are not exceeded. Testing also helps to determine how the system should respond when the battery is full or the battery system fails. It will also help to determine how much margin is required in the facility export limit to ensure that network protectors are not opened. In addition, the storage system response speed should be compared with that of various network protectors to demonstrate system effectiveness.

It is important to understand as a result of this testing how all of these characteristics change with different network configurations and characteristics (e.g., feeder phase voltage and loading imbalance). Finally, test results should be used to help define any needed changes to standards, such as IEEE 1547.1 for certifying components and systems.

4.7 DER Modeling Needs

4.7.1 Discussion
One respondent to the utility survey described in the report on advanced PV system designs and technology requirements noted that few if any modeling tools allow distribution system planners and engineers to simulate the relevant system-level behaviors of small, distributed PV systems. Many of the tools can model inverters internally, simulating switch bridges and control circuits

physically or quasi-physically, and there are also highly detailed control system models of inverters. Distribution system engineers do not usually have ready access to the inputs required for these models, however. They also model the PV system in so much detail that the computational burden, in terms of simulation time and memory requirements, can be extremely large. The models are thus not suitable for the types of studies that the survey respondent wants.

4.7.2 Test and Demonstration Needs

A suite of PV system modeling tools is needed that is targeted to the distribution system engineering and planning community. Each model in the suite must capture a set of PV system behaviors that are relevant at the system level, including such functions as active anti-islanding, over/undervoltage and frequency trips, maximum power point tracking, harmonics, fault response, and interactions with other DERs.

As communications become more prevalent in PV inverters, they will also need to be included in the simulations. At the same time, the models must be mathematically and computationally simple, minimizing microprocessor time and memory requirements. These models should utilize simulation tools and environments commonly used by the distribution systems engineering community. The models will need to be thoroughly experimentally validated, which will require close cooperation between model developers and laboratories with the experimental capabilities discussed earlier.

4.8 Suitable Communications

4.8.1 Discussion

Many of the solutions discussed in this and the other reports rely on various forms of communications exhibiting a broad range of requirements, as described in Table 4-4.

Table 4-4. Communication System Characteristics

Speed	The amount of time it takes for a message to be transmitted from the source to the receiver
Bandwidth	The amount of information that can be included in the message
Reliability	Methods and characteristics used to ensure that any transmitted message is received
Accuracy	Methods and characteristics used to ensure that any message transmitted is accurate; methods for handling transmission errors
Directivity	Concerns whether different information needs to go to different receivers or whether broadcasting a common message to multiple receivers is suitable
Distance Limits	The maximum allowable distance between communications nodes
Security	The likelihood of a third party intercepting a message and the consequence of that interception or of that third party forwarding an altered message to the receiver
Cost	Capital and operating costs

Most of these communication needs can probably be met with today's communications options (e.g., cable, DSL, and others in development such as AMI [automated metering infrastructure] and BPL [broadband over power line]), so there might be little need for fundamental testing. However, the current means for transmitting protective function signals from the utility to a customer—usually via a lease-line, which is a hard-wired connection from the customer to the utility—are prohibitively expensive for systems smaller than a few megawatts. In addition, the speed, reliability, accuracy, and security that utilities require for this purpose have not been demonstrated with other options. The DER industry would welcome an improved, cost-effective communications option for protective functions, and so would utilities that need to provide these types of services internally.

Moreover, even if physical communications channels and existing protocols are adequate to the task, suitable control schemes using various means of communication must be developed. There will be considerable interplay between the capability of the control schemes and the capability of the selected communications scheme; therefore, communications capabilities and distributed controls are likely to develop side by side.

4.8.2 Test and Demonstration Needs

A combination of laboratory and field testing will be needed to establish communications requirements for different types of solutions and to verify that a particular piece of equipment has met those requirements.

Laboratory testing will be needed to define and verify the technical characteristics of any communications option described in Table 4-4, the robustness of the option under adverse weather and electrical conditions, and other forms of interference. Much of this testing will involve traditional communications and will progress to meet broad needs beyond PV or DER—such as AMI, BPL, and substation automation. At the fundamental level, the ongoing RSI role will be more to review industry results than direct specific research. Evaluations of specific implementations will be needed, though these might be adequately addressed by labs that traditionally evaluate device communications.

There will also probably be some uncertainty surrounding any proposed communications option for which the utility has had no (or a bad) experience, regardless of laboratory results. Field demonstrations showing the characteristics, reliability, and limitations of a proposed communication method will be needed to provide all parties with experience and confidence in the method. Field sites with a sufficient number of units implementing the communications method and a variety of noise/disturbance sources (e.g., industrial processes) will be key.

4.9 Microgrids and Other Ancillary Services

4.9.1 Discussion

The ability to operate autonomously, or intentionally island, is a defining characteristic of a microgrid—a collection of loads and generation that can operate in grid-parallel or stand-alone mode. Microgrids could have significant economic advantages over other power supply options. For example, they can increase power supply reliability to loads for which even short-term outages result in large financial losses. They can also provide combined heat and power, or

CHP. In most CHP systems, the primary product of the system is heat; electricity is the by-product.

Microgrids have generated a great deal of interest recently because of the additional benefits they can provide in the areas of power supply reliability, security, and diversity; recovery from events on the host utility system; and their ability to utilize more of the capabilities of renewable energy sources, such as reductions in fuel usage and emissions. Hospitals, financial institutions, and military installations are among the early adopters of microgrid technology.

In a microgrid, as a rule, no single DER has sufficient capacity to carry the entire load. The challenges that arise in a microgrid are thus related to load sharing, cooperative control, and integration with EMS schemes. Most microgrid concepts being discussed today, such as the Power Quality and Management System (PoMS) concept in Europe [8] and the CERTS concept in the United States [9], are based on the idea of adapting techniques used in modern utility power systems to microgrids. Large-scale power systems have fast controls in generators that handle such things as voltage and frequency regulation, and these represent one form of distributed control. These fast controls are usually fully automatic. Slow controls that involve system reconfiguration or require economic and policy decisions are usually centralized.

Massive data acquisition and communications systems feed information back to a central controller (with human oversight), and this central controller feeds command and control signals to the power system elements. In a microgrid, individual DERs would have fast electrical controls to handle load sharing and voltage regulation, and slow controls that would include EMS functions and any other ancillary service-related commands. In the CERTS concept, the fast controls are the so-called droop controls, in which power decreases linearly as frequency increases, providing regulating feedback on each generator’s output power. In the PoMS concept, node voltages are communicated to a central controller that issues voltage regulation and load sharing commands. Both CERTS and PoMS use centralized controllers to handle the slow control.

Initial results of the CERTS and PoMS projects, along with many others, appear highly promising. However, the amount of engineering effort required to make either of these concepts work on a real-world microgrid is still very large. Also, a number of simplifications have been made in most experimental microgrids to prove particular concepts—for example, all the generators may be the same type, or power import/export restrictions may be imposed. A great deal of work remains to be done to make these systems more “plug-and-play,” to lift restrictions, and enable the full capability of microgrids to be used.

A different control technique might also be applied: fully distributed control, sometimes also called “agent-based control” [10]. The fundamental concept behind agent-based control is the reduction or elimination of centralized control; all decisions are made communally by the DERs. This is appealing in theory, because a fully distributed control system could be more secure since it has no single point of failure; in practice, agent-based controls are extremely complex and difficult to implement. A number of early prototypes of agent-based systems have demonstrated the promise of the concept [11, 12, 13].

4.9.2 Test and Demonstration Needs

Research and development of both types of microgrid concepts (adaptations of large-grid concepts to microgrids and fully-distributed agent-based control) need to be pursued. Because microgrids are expensive to build, modify, and maintain, two parallel efforts should be pursued:

- Development of microgrid testbeds at national laboratories such as Sandia and NREL that could be used by investigators from both inside and outside the laboratories. These valuable microgrid user facilities should include a power electronics fabrication capability. (See Section 5.2 for a short list of current U.S. microgrid testbed facilities.)
- Development of a suite of computer modeling tools that will enable the power systems community to quickly (and with high confidence) run virtual experiments on microgrid hardware, software, and communications configurations. These models must be thoroughly verified; the aforementioned national laboratory testbeds would be ideal venues for this verification.

5.0 Gap Analysis and Recommendations for Future Research

This section discusses the need for laboratory and field demonstration facilities dedicated to evaluating the impacts, issues, and solutions. It also lists facilities and new PV projects that may address these needs.

5.1 Laboratory Test Facility Needs and Options

5.1.1 Laboratory Testing Needs

The companion RSI reports and others referred to in this report cite numerous interconnection issues, most of which become more profound with increasing levels of penetration. The list of interconnection issues here were culled from these various sources and are organized into two broad categories: general issues and specific issues.

General Issues

- DER modeling needs
- Characterization/verification/certification
  - Abnormal conditions
  - Power quality
  - Synchronization
  - Unintentional islanding
- Control schemes/strategies: autonomous, semi-autonomous, master
- Suitable communications
- Microgrids
- Ancillary services
  - Voltage/frequency regulation
  - Spinning reserve

Specific Issues

- Excessive service voltage/voltage regulation support
- stability (e.g., system stability with intermittent clouds)
- Cold load pick-up
- Substation backfeed
- Sectionalizer testing
- Recloser coordination
- Inverter response to faults
  - False trips caused by utility line transients/adjacent feeder faults
  - Capacitor switching
- Inverter short-circuit contribution (e.g., fuse coordination)
- Network systems (e.g., reverse power flow in secondary network distribution systems)

Basic considerations include a facility's electrical capacity, availability of programmable loads, monitoring equipment, and options for providing or simulating PV output. In addition, assessing the suitability of a given laboratory for providing the services needed for this R&D will involve evaluating the lab's ability to tackle several issues on a range of PV system capacities.

5.1.2 Current Test Facilities

A number of laboratory-style U.S. test facilities would be useful for the component- and system-level testing described here. In preparation for establishing a test facility for the Distributed Utility Integration Test, Distributed Utility Associates prepared a comprehensive evaluation of current test facilities for a report (*DUIT: Distributed Utility Integration Test*) published by NREL in 2003 (available at www.nrel.gov/docs/fy03osti/34389.pdf). The report describes 14 facilities:

- Pacific Gas and Electric Co. Modular Generation Test Facility/DUIT, San Ramon, California
- University of California at Irvine, California
- American Electric Power Co. Dolan Test Center, Groveport, Ohio
- Southwest Research Institute, San Antonio, Texas
- Electric Power Research Institute, Knoxville, Tennessee
- Sandia National Laboratories, Albuquerque, New Mexico, and Livermore, California
- National Renewable Energy Laboratory, Golden, Colorado
- University of Wisconsin–Madison, Wisconsin
- Pacific Northwest National Laboratory, Hanford, Washington
- Arizona Public Service Solar Test and Research Center, Phoenix, Arizona
- Oak Ridge National Laboratory, Oak Ridge, Tennessee
- Colorado State University, Fort Collins, Colorado
- DTE Energy Technologies, Novi, Michigan
- Salt River Project, Phoenix, Arizona

The DUIT report describes the capabilities of these facilities. In the four years since it was published, many of these organizations have enhanced their facilities and they continue to do so. BEW Engineering has received some updated information from several organizations (see Section 2.0).

No one known facility can perform all of the testing that could be needed. However, it is likely that most of that testing can be performed at the facilities listed here, possibly with some expansions or modifications to meet specific needs.

5.2 Field Demonstration Needs and Options

5.2.1 Field Demonstration Needs

Demonstration projects are useful for representing an issue (if there is one), a solution, or a group of solutions to a broad audience. The issues listed above can also apply to field demonstration needs. Some solutions may find a purpose-built demonstration useful or even necessary to display its particular attributes. In many cases, it will be easier and cheaper to work with large, planned DER systems or solar subdivisions.

Some general characteristics of potentially useful field demonstration sites include the following:

- Willingness of customers to participate in trials of new equipment; inconveniences would have to be limited to short-duration outages for installing and removing equipment
- High-penetration commercial park
- Availability of AMI, BPL, or other communication options within the demonstration area
- A variety of distribution system quality levels (e.g., low or no marginal capacity for additional load vs. high marginal capacity; long skinny-conductor feeder vs. short fat-conductor feeder, high load growth vs. low load growth)
- Other multimegawatt systems connected to the distribution system on the same or adjacent feeders.

Specific characteristics such as the number of PV systems or the capacity of the individual PV system will depend strongly on the needs of the individual test. For analyzing grid impact issues, more houses with larger PV systems are likely to show issues more readily. For equipment demonstration and evaluation purposes, a smaller number of homes with smaller PV systems may be necessary so a test can be performed cost effectively. DOE could also develop a central clearinghouse of information on old, new, and future PV projects so researchers can find demonstration sites that meet their needs. Some specific examples of the kinds of demonstration characteristics that should be sought include the following:

- New development with high-penetration PV (e.g., Premier Gardens)
- High-penetration PV on a legacy (weak) feeder
- High-penetration PV on undersized/overloaded primary
- Large PV on single feeder back to sub (high penetration at sub) (e.g., Nellis Air Force Base)
- Commercial building with enough PV to cover the load and EMS and/or storage
- High penetration commercial PV systems
- Microgrid with PV.

5.2.2 Potential Field Demonstration Sites

A few examples of systems installed, under construction, or in the planning stages are described below; they could provide excellent opportunities for evaluating a variety of conditions and solutions. They are all early examples of the kinds of high penetration that the PV community is hoping to see on a large scale. At least one party involved in each of these sites has expressed an interest in participating in a high-penetration PV study. DOE participation in some form of monitoring and analysis of grid performance appears reasonable at each of the facilities. The willingness of a particular facility to incorporate new equipment for testing purposes would have to be determined on a case-by-case basis.

5.2.2.1 MMA Renewable Ventures/SunPower PV System at Nellis Air Force Base

The 14-MW MMA Renewable Ventures/SunPower system at Nellis Air Force Base presents an excellent opportunity to evaluate high-penetration PV at the substation level (Figure 5-1). The system will be interconnected through two 12-kV feeders; several times a year, the PV system output could exceed the base load and backfeed the 69-kV transmission line feeding the substation. The PV system represents a penetration of almost 140% on one feeder, 240% on the other, and more than 40% of the substation as a whole. The actual level of expected backfeed will be insignificantly small. Nellis AFB and Nevada Power engineers are satisfied that even full PV output backfeed (i.e., zero AFB load) would not cause a safety, reliability, or operational concern. The 14 MW feeding a single substation and the potential for transmission level backfeed represent milestones for PV if not DER in general.

Figure 5-1. Nellis SunPower PV System

BEW has been working to obtain MMA's approval to acquire and install additional voltage and current monitoring at two points on the 12-kV feeder where the PV systems connect. Construction is on schedule; the last of three phases were scheduled to come on line in December 2007. This initial monitoring would help establish basecase winter performance and thus help to prepare for spring, when the highest backfeeds are expected, and summer, when the highest loads are expected.

5.2.2.2 SMUD Premier Gardens

SMUD has long been a leader in PV installation efforts. The Premier Gardens subdivision includes not only significant amounts of PV but a high level of energy efficiency, as well (Figure 5-2). The 95 Premier Gardens homes are in an infill residential development east of downtown Sacramento. Both developers include energy conservation measures in their construction (exceeding the standard California Title 24 energy requirements), but Premier Gardens houses use more aggressive conservation methods and tend to be slightly smaller than the other houses.

Each Premier Gardens house also includes a net-metered photovoltaic power generation system rated at 2.0 kW_{CEC-AC} to help offset annual energy consumption.

Identified key parameters for data analysis were compiled into a database table for use during analysis. BEW Engineering has been working with SMUD to collect distribution system primary data to understand the impact of the PV systems under a variety of conditions. Currently, there are power-quality monitoring points at the serving substation and at two distribution transformers. There is also power flow monitoring (load and PV, in and out) at 18 of the PV residences. In addition, BEW procured additional equipment to monitor the utility service voltage at five of the residences equipped with PV monitoring. Peak conditions for 2007 appear to have occurred during the last week of August.

Figure 5-2. SMUD Premier Gardens Project (Courtesy of SMUD)

5.2.2.3 SMUD Solar Smart Project

As part of the next stage in its zero-energy-home development activities, SMUD is working with a number of local builders on plans for about 2,200 homes to be built over the next 4 or 5 years. Each home will incorporate efficiency measures that exceed the already stringent California Title 24 energy efficiency requirements and will include a 1.5- to 2-kW PV system.

Table 5-1. SMUD Solar Smart Project Summary

Builder	Subdivision	No. of Units	Location
Centex		107	
DER Horton		187	
Homes by Towne		360	
Lennar Anatolia II	VILLAGE 12B	8	Anatolia, Rancho Cordova
Lennar Anatolia III	VILLAGE 17	94	Anatolia, Rancho Cordova
Lennar Anatolia III	VILLAGE 18	90	Anatolia, Rancho Cordova
Lennar Anatolia III	VILLAGE 20	103	Anatolia, Rancho Cordova
Lennar Anatolia III	VILLAGE 22	96	Anatolia, Rancho Cordova
Lennar Anatolia III	VILLAGE 23	20	Anatolia, Rancho Cordova
Lennar Anatolia III	VILLAGE 24	29	Anatolia, Rancho Cordova
Lennar Anatolia III	VILLAGE 24	13	Anatolia, Rancho Cordova
Lennar Westlake Village Greens	PH 1B	44	South Sacramento
Regis Homes		32	
Reynen & Bardis		260	
Standard Pacific		520	
Terrasante		45	Natomas
Tim Lewis Construction	Amberleigh	60	Elk Grove
Tim Lewis Construction	Brentwood Estates	34	Orangevale
Tim Lewis Construction	Brentwood Villas	88	Orangevale

Table 5-2. SMUD Solar Smart Project: Upgrades to Title-24 Standards

Measure	Base	ZEH
Attic Insulation	R-38	R-38
Radiant Barrier	No	**Yes**
Quality Installation*	No	**Yes***
Low Air Infiltration*	No	**Yes***
Windows	E-Star	E-Star
FURN AFUE	0.80	**0.90+**
A/C SEER	13 (3.7 ton)	**14/12 w/TXV (3.1 ton)***
ACCA Design*	No	**Yes***
Duct Testing*	No	**Yes***
Lighting	T-24	CFL (all down-lights)
Solar Electric	NA	**1.5 - 2kW Solar PV**

*HERS verification required.

SMUD will be setting up monitoring similar to that for Premier Gardens, though most likely in greater numbers to match the increased scale of this project. The number of builders and multiple phases involved will provide many opportunities to step in.

5.2.2.4 PG&E Juliana's Garden

A new solar subdivision totaling about 300 homes will be going up northeast of Bakersfield, California. The first of three phases is currently under construction. PG&E, the serving utility, will be instituting revised design practices specifically to address the backfeed-related voltage rise. It is planning to install some monitoring and is likely to welcome DOE participation. Juliana's Garden would provide a different perspective on distribution system impacts from the two SMUD subdivisions because of the differences in such factors as location, home design, PV system size, and utility design practices. See www.bakersfield.com/137/story/72511.html and www.renewableenergyaccess.com/rea/partner/story?id=45853 for more information.

5.2.2.5 Other Possible Sites

Other sites are in planning stages. One will involve providing significant amounts of PV to an isolated system serving 4,000 customers with a 6.5-MW peak load over a 3-circuit, 12-kV distribution system. This site has the potential to provide information on very high penetration system impacts as well as to address some possible ancillary services.

None of the planned U.S. PV installations appear to include storage or an integrated EMS, presumably because there are no local incentives to encourage their use. Assuming that a follow-up DOE program includes the development of equipment to provide these functions, DOE could partner with the more active utilities, PV integrators, and builders to identify suitable opportunities and help fund the installation of sample equipment. Given its tendency to combine energy efficiency and PV in new construction, SMUD would be a good candidate for this activity.

Numerous commercial rooftop PV systems are being installed around the country, but none clearly represents a high-penetration situation. Although these installations may not provide the best opportunities for monitoring grid impacts, they are more likely to have an EMS that could be modified or replaced with one incorporating the features described in this and other reports in the series.

6.0 Conclusions and Recommendations

Tests and demonstrations are needed to better understand and support high-penetration PV. However, specific testing requirements are difficult to define. Nevertheless, a number of laboratories, utilities, state energy organizations, and system integrators would be eager to participate in all aspects of the testing needs described in this report. The laboratories described in Section 5.0 feature a broad array of testing capabilities. Any capabilities beyond those will probably have to be very specific and require special planning and funding.

The number of proposed new PV systems is growing rapidly. Many of these systems represent residential PV subdivisions that would offer high-penetration measurement opportunities and possible demonstration sites for new PV or distribution system equipment and solutions.

Sites yet to be identified include the following:

- Skinny feeder application—long, low-capacity feeder (e.g., in rural applications) with large new homes and large exporting PV systems as well as known or suspected voltage rise problems
- High-penetration commercial application
- PV on grid secondary network—having the potential to apply storage to eliminate export.

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