Final Technical Report

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Executive Summary

The core objectives of the Plug & Play PV Systems Project were to develop a PV system that can be installed on a residential rooftop for less than $1.50/W in 2020, and in less than 10 hours (from point of purchase to commissioning). The Fraunhofer CSE team's approach to this challenge involved a holistic approach to system design – hardware and software – that make Plug & Play PV systems:

- Quick, easy, and safe to install
- Easy to demonstrate as code compliant
- Permitted, inspected, and interconnected via an electronic process

Throughout the three years of work during this Department of Energy SunShot funded project, the team engaged in a substantive way with inspectional services departments and utilities, manufacturers, installers, and distributors. We received iterative feedback on the system design and on ideas for how such systems can be commercialized. This ultimately led us to conceiving of Plug & Play PV Systems as a framework, with a variety of components compatible with the Plug & Play PV approach, including string or microinverters, conventional modules or emerging lightweight modules. The framework enables a broad group of manufacturers to participate in taking Plug & Play PV Systems to market, and increases the market size for such systems.

Key aspects of the development effort centered on the system hardware and associated engineering work, the development of a Plug & Play PV Server to enable the electronic permitting, inspection and interconnection process, understanding the details of code compliance and, on occasion, supporting applications for modifications to the code to allow lightweight modules, for example. We have published a number of papers on our testing and assessment of novel technologies (e.g., adhered lightweight modules) and on the electronic architecture.

Figure ES-1: The June 2016 demonstration of PnP system installation.

The project team demonstrated the installation of Plug & Play PV Systems to the public on three occasions, with a system being installed on the rooftop of a purpose-built structure and going through the electronic permitting, inspection and interconnection process and being commissioned. With a team of three working on the installation, a 3kW system installation was completed in 75 minutes –

substantially shorter than the 10-hour target. We conducted a cost assessment that indicates that Plug & Play PV systems can be installed at a cost of $1.56/W in 2020.

The team determined a core of the Plug & Play PV Framework that needs to be adhered to by all market participants, regardless of the type of hardware used. This is the electronic permitting, inspection, and interconnection process, and accordingly we have filed provisional patents on these aspects of the systems. The team developed a standard that defines Plug & Play PV Systems, that can be used to identify which systems developed can be trademarked as Plug & Play PV. This standard has been drafted and circulated to key stakeholders who have provided their feedback, and will now be passed on to an industry group for further development.

At the conclusion of this SunShot project, we are close to forming a Plug & Play PV Systems Alliance, bringing together utilities, municipalities, manufacturers, installers, and distributors who will work together with Fraunhofer CSE to bring Plug & Play PV Systems to market by advancing the development of fully listed systems, establishing pilots in which commercial ready Plug & Play PV Systems are installed on the rooftops of inhabited homes, giving AHJs and utilities the opportunity to gain practical experience with the processes, and refining the Plug & Play PV Systems standard.

1 Introduction

The Plug & Play PV project sought to drive down the cost of residential PV by focusing on three specific technical targets: (1) installation and commissioning time of less than 10 hours; (2) reduction or elimination of the need for specialized labor qualifications during PV installation; and (3) development and demonstration of a fully electronic PI&I (ePI&I) process that uses standardized data exchange formats and processes to transact approvals. The Project Team developed and implemented a broad array of technical solutions that define a feasible pathway for meeting these goals. Sections 2-5 of this report summarize the results of these efforts, and are organized as follows:

- Section 2 summarizes the development of integrated, turnkey PV systems that implement an electronic “proof of compliance” methodology by which the field-installed PV System verifies that it is compliant with local electrical and building codes;
- Section 3 summarizes development of enabling component-level technologies that help reduce installation time and reduce or eliminate labor qualifications, specifically focused on PV System electronics
- Section 4 summarizes development of a centralized Plug & Play routing server that implements a standardized Data Exchange Protocol to transact data between stakeholders throughout the permitting, inspection, and interconnection process
- Section 5 summarizes the development of enabling structural and mechanical technologies, specifically focused on innovations related to lightweight, adhesive PV Modules and cable management

In addition to these technical targets, the Plug & Play PV project also aimed to develop an eco-system to foster the adoption of Plug & Play PV, including broad-based industry support (multiple vendors, installers, utilities, jurisdictions, and distributors), standardized communication and certification test procedures, and supported by multiple technical approaches. Sections 6-8 of this report summarize the results of these efforts, and are organized as follows:

- Section 6 outlines the Project Team’s technology demonstration and stakeholder outreach initiatives
- Section 7 outlines the development of a Plug & Play PV Standards framework
- Section 8 summarizes ongoing efforts to commercialize Plug & Play PV Systems and develop a Plug & Play PV industry alliance.

2 Development of Plug & Play PV Systems

2.1 Overview

The Project Team designed and implemented two different "pre-commercial" Plug & Play PV systems. Both systems integrate commercial or near-commercial technology into an integrated system that was designed to comply with the requirements of the Plug & Play PV Standard, and were subjected to a Plug & Play Compliance Test as outlined in the draft Plug & Play PV System Standard (Appendix A1):

- A "Version B" System, using SunPower ACPV modules
- A "Version AP" System, using Lumeta adhesive PV modules and VoltServer Digital Electricity technology.

Documentation packages consistent with the Plug & Play Standard requirements were generated, followed by field-testing of the system to audit compliance. These design packages are incorporated as supporting examples within the appendix of the Plug & Play PV Standard (Appendix A3). The field-testing of the PV systems focused on ascertaining that the system under test meets the following requirements, as outlined in the Plug & Play PV Standard:

- It accurately detects pass/fail modes of the field-assembled system that were identified in the system's Proof of Compliance Plan as "validated by electrical self-test";
- It communicates with external stakeholders in compliance with the Plug & Play API; and
- It follows the appropriate protocols for determining when to energize the system.

Sections 2.2 and 2.3 provide high-level descriptions of the technical approach adopted for each of the two systems.

2.2 "Version B" AC Module-Based Plug & Play PV System

The "Version B" AC-Module based Plug & Play implementation was designed using SunPower ACPV modules, pre-fabricated, connectorized cables, and a Plug & Play-compliant commissioning application that checks key code requirements that are prone to installer error. The system connects to premises wiring through a standardized solar connection device (SCD). For the demonstration system, the SCD was integrated into a meter socket, suitable for a new construction application. Core elements of the Version B system were based on commercial technologies: notably the system uses a conventionally racked PV system and AC modules from SunPower's ACPV product line. The Version B System was designed as a collaboration between SunPower and Fraunhofer, and implemented by SunPower with a goal of implementing key elements into the SunPower product roadmap. Key innovations relative to the existing state of the art include:

- Development of an "AC combiner" box that integrates commissioning and monitoring functions, branch circuit overcurrent protection, and input/output connectors in a single enclosure
- An electronic system self-test that incorporates newly developed branch circuit mapping and end-cap detection technology, and compares the "as-built" system against code and permit requirements.
- A fully connectorized cabling system ensures that cables are properly specified and terminated, that connections are complete and secure, and that ensures continuity of grounding conductors.
- Integration with the newly developed Plug & Play Solar Connection Device
- A commissioning application that implements the Plug & Play PV API for transacting information with other stakeholders in the Plug & Play ecosystem, and that guides the installer through

executing a self-test, gathering visual documentation, and energizing the system after approvals have been secured.

- Design and test, per the Plug & Play PV System Standard, as an integrated system

Table 2-1 summarizes key aspects of the approach used to comply with the Plug & Play PV System Certification requirements. A detailed compliance test report is included in Appendix C.1.

Table 2-1: Version B Plug & Play System Compliance Approach

Compliance Criteria	Verification Approach	Description
System Properly Grounded	Design	Factory-integrated grounding conductors
System is configured correctly	Self-Test	Interrogation of field-installed ACMs
AC bus wiring properly specified	Design	Pre-fabricated, keyed, connectorized cable
Overcurrent Protection	Self-Test	Comparison of calculated max current to known breaker sizing
AC Interconnection	Self-Test	Pre-Installed premises-side receptacle w/ integrated OCPD
Cable Management	Visual	Digital photo of conduit
Array Layout	Visual	Digital photo of PV array

Figure 2-1: SunPower ACPV Plug & Play System Installation

2.3 Version AP String Inverter Plug & Play PV System

The Version AP Plug & Play PV system is a string-inverter PV System that incorporates a combination of emerging technologies that fully realize Plug & Play project technical goals related to (1) <10 hours installation; (2) reduction or elimination of labor qualifications; and (3) integration with an electronic PI&I process. The Version AP System was integrated by Fraunhofer CSE, and is composed of technologies sourced from multiple vendors and project partners. Key innovations relative to the existing state of the art include:

- Lightweight, frameless, adhesively-backed Lumeta PV modules (see Section 5 for additional detail). These PV modules eliminate the need for grounding conductors, racking system, and roof penetrations. PV modules incorporated electronics that implement module-level shutdown and enable remote interrogation of each module
- DC power is distributed from the roof to the inverter using a Class 2 power distribution protocol ("Digital Electricity", or DE, see section 3.3). Notably, class 2 circuits typically do not require

qualified electricians to install and offer a high degree of flexibility with respect to wiring method

- A commercially available string-inverter that was retrofitted with: (1) connectorized inputs from the DC bus; (2) embedded technology to convert from Class 2 digital electricity to conventional DC; (3) an embedded commissioning layer to conduct system self-test and communicate with the Plug & Play Server.
- An electronic system self-test that verifies system configuration, and compares the “as-built” system against code and permit requirements.
- A fully connectorized cabling system ensures that cables are properly specified and terminated, that connections are complete and secure, and that ensures continuity of grounding conductors.
- Integration with a Plug & Play Solar Connection Device
- A commissioning application that implements the Plug & Play PV API for transacting information with other stakeholders in the Plug & Play ecosystem, and that guides the installer through executing a self-test, gathering visual documentation, and energizing the system after approvals have been secured.
- Designed and tested, per the Plug & Play PV System Standard, as an integrated system

Table 2-2 summarizes key aspects of the approach used to comply with the Plug & Play PV System Certification requirements. A detailed compliance test report is included in in Appendix C.1.

Figure 2-2: Demonstration of Version AP Plug & Play PV System

Table 2-2: Version AP Plug & Play System Compliance Approach

Compliance Criteria	Verification Approach	Description
System Properly Grounded	Design	Rackless (adhesive) “peel and stick” PV modules
System is configured correctly	Self-Test	Interrogation of field-installed smart junction boxes
DC Bus wiring properly specified and installed	Design	Class 2 wiring, pre-fabricated cable
DC Overcurrent Protection	Self-Test	None required (based on array configuration)
AC Overcurrent & Interconnection	Self-Test	Pre-Installed premises-side receptacle w/ integrated breaker
Array Layout	Visual	Digital photo of PV array

2.4 Cost Analysis of Plug & Play PV Systems

To evaluate the impact of the Plug & Play framework on the cost of residential PV systems, the Project Team conducted a bottom up cost analysis of commercialized versions of the two systems demonstration systems developed under this program – (1) Version AP system, using Lumeta PV Modules and Digital Electricity; and (2) Version B system, using AC Modules. The analysis uses the following approach:

- BOM costs for each of the two PV systems were generated based on a 7.5kW Plug & Play PV system (Table 2-3). Specific component cost assumptions are noted in footnotes. BOM costs reflect *cost* to the manufacturer, prior to any supply chain markups, as distinguished from *price*.
- Installed costs (Table 2-4) were estimated using the cost-modeling framework outlined by NREL's 2015 Price and Cost Benchmarks.[1]
- Installed costs for the Version AP system are based on a "direct to consumer" (point of sale) distribution model, such as at a home improvement store, enabled by the elimination of labor qualification and facile installation. This scenario incurs higher markups on hardware, but eliminates traditional PV installer costs associated with customer acquisition, overhead, and profit.
- Installed costs for the Version B system assume a traditional installation supply chain, but significantly expands the pool installers to incorporate local tradesmen such as roofers, HVAC, and electricians – which typically have a far more streamlined cost structure.

As indicated, installed cost for a mature PLUG & PLAY PV market is estimated at $2.05-$2.20/W based on current costs, declining to $1.56-$1.66/W in 2020. More generally, the premise underlying this analysis is that Plug & Play PV Systems have the potential to greatly expand the pool of *who* can install PV systems, and hence will induce competition and greatly increase labor utilization.

Table 2-3: Plug & Play PV System BOM Costs

Component	2017 Version AP	2020 Version AP	2017 Version B	2020 Version B
PV Module[2]	$0.91	$0.72	$0.70	$0.55
Module Electronics[3]	$0.05	$0.03	$0.44	$0.30
Racking[4]	-	-	$0.12	$0.10
Cables & Conduit[5]	$0.02	$0.02	$0.02	$0.02

[1] Chung, D, Davidson, C, Fu, R, Ardani, K, and Margolis, R. "US Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems." National Renewable Energy Laboratory. NREL/TP-6A20-64746. Sept 2015.

[2] 2017 Module costs based on NREL 2015; 2020 costs based on SunShot 2020 goal. Version AP assumes 30% price premium for lightweight modules.

[3] Version AP System: 2017 cost based on cost of Tigo TS4-S junction box. 2020 cost assumes additional cost reduction for module-level shutdown technology Version B System: 50% price premium is assumed for a microinverter relative to string inverter.

[4] Version AP – no racking. Version B: 2017 Racking costs based on NREL 2015. 2020 costs assume incremental cost reduction

[5] Cables and conduit based on ~40 ft cabling per branch/string circuit, at $2/ft

Inverter[6]	$0.31	$0.21	-	-
AC Combiner[7]	-	-	$0.07	$0.07
Premises Connection[8]	$0.09	$0.06	$0.09	$0.06
Plug & Play Licensing Fee[9]	$0.01	$0.01	$0.01	$0.01
Plug & Play Integration Costs[10]	$0.02	$0.01	$0.02	$0.01
Total	**$1.45**	**$1.09**	**$1.47**	**$1.13**

Table 2-4: Installed Cost of Plug & Play PV Systems

Component	2017 Ver. B	2020 Ver. B	2017 Ver. AP	2020 Ver. AP
BOM Cost	$1.47	$1.13	$1.45	$1.09
Dist. Markups[11]	$0.15	$0.11	$0.44	$0.33
Install Labor[12]	$0.08	$0.08	$0.05	$0.05
PI&I[13]	$0.01	$0.01	$0.01	$0.01
Sales Tax[14]	$0.08	$0.06	$0.09	$0.05
Installer Overhead[15]	$0.11	$0.11	-	-
Installer Cust. Acq.[16]	$0.18	$0.05	-	-
Installer Profit[17]	$0.13	$0.10	-	-
Total	**$2.20**	**$1.66**	**$2.05**	**$1.56**

[6] 2017 based on NREL 2015 inverter cost, 2020 based on SunShot goal. Both include incremental additional cost associated with PLUG & PLAY integration

[7] AC Combiner costs based on price of Enphase AC Combiner from online distributor. Online cost quote reduced by 25% to account for supply chain markups, which are accounted for separately.

[8] Premises connection assumes meter collar integrated with Phoenix Connector. Incorporates overcurrent protection and AC disconnect, quote reduced by 25% to account for supply chain markup. 2020 cost assumes additional cost value due to volume and value engineering.

[9] $0.01/W licensing fee for participation in Plug & Play

[10] Miscellaneous mfr costs for PLUG & PLAY system integration (e.g., certification, system design, software integration, etc)

[11] Version B system assumes 10% markup, based on NREL 2015. Version AP System assumes higher markup (30%) to account for direct-to-consumer distribution model.

[12] Version B system installation labor assumes 16 hrs installation labor @ $32/hr fully burdened, blended avg. Version AP System: assumes 8 hrs of handyman labor, fully loaded @ $25/hr, plus $200 truck roll for meter collar installation.

[13] PI&I costs assume $75 in permitting & interconnection fees.

[14] 5% sales tax, applies to hardware + distribution cost.

[15] Version B System overhead assumes 1.5x labor cost; n/a for Version AP System

[16] Version B System assumes declining customer acquisition cost due to increasing volume and changing business model as market matures; n/a for Version AP System

[17] Version B System assumes decline to 7% profit, consistent with more competitive industries; n/a for Version AP System

3 Enabling Electronic Technologies

3.1 Overview

The Plug & Play PV framework is specifically designed to be technology-agnostic. However, through the course of the Program, the Project Team identified and developed a several enabling technologies that are aligned with the overall project goals. While numerous technologies were evaluated during the course of the program, the Project Team ultimately focused on development of three electronic component technologies that showed particular promise: a standardized solar connection device (SCD); a digital electricity power distribution system; and a smart AC combiner. (Enabling module technologies are summarized in Section 5.)

3.2 Standardized Solar Connection Device

One of the major cost drivers for residential installations relates to the complexity associated with connected to the premises wiring. The Plug & Play PV framework aims to address this issue through the commercialization of a standardized "solar connection device" (SCD) – a pre-installed, standardized premises-side receptacle with integrated overcurrent protection (sized appropriately for the system) that mates with a plug on the generation side of the PV system. When installed on the supply side of the customer service, these approaches eliminate the need for inspecting the main service panel. However, an SCD could also be housed in a service panel or subpanel on the load side of the customer service.

The Plug & Play Project Team developed a standardized solar receptacle, integrated this receptacle into several types of premises connection, and developed PV Systems that were designed to mate to the premises connection:

Standardized Solar Receptacle: We partnered with Phoenix Contact to develop tooling and parts for a standardized, dedicated solar connector and receptacle (Fig 3-1). The connector developed under the program is rated for 60A generation (roughly a 10kWAC PV system), and incorporates four auxiliary contacts that may be used to provide additional communications, commissioning power, or safety features (see Table 3-1). It is suitable for integration with a meter collar, meter socket, or standalone installation. The connector is expected to meet UL requirements, but is not yet listed.

Table 3-1: Solar Connector Pin Out

Contact #	Contact Name	Current	Voltage
1	Power (L1)	60A	240VAC
2	Power (L2)	60A	240VAC
3	Neutral (N)	60A	240VAC
4	Equipment Ground (G)	60A	240VAC
5	Vo	3A	30VDC
6	GND	3A	30VDC
7	D1	3A	30VDC
8	D2	3A	30VDC

Figure 3-1: Solar Connection Device Prototype

Premises Connection: *Prototype versions of the Phoenix receptacle were integrated with two different types of premises-side connection (Fig 3-2):*

- A Meter collar, suitable for retrofit applications, that fits between a standard bubble meter and meter socket. A non-connectorized version of the meter collar is currently UL listed and commercially available; ConnectDER and Phoenix are currently collaborating on development of a listed version of the connectorized version developed under this program.
- A meter socket with an integrated SCD receptacle

Both SCD implementations incorporate integrated overcurrent protection and AC disconnect, can provide low voltage DC commissioning power to the PV system, and provide Modbus communication to the SCD to assist with system discovery.

Figure 3-2: Solar Connection Device integrated with a meter collar (left) and meter socket (right)

3.3 Digital Electricity Power Distribution System

A Digital Electricity (DE) power distribution system enables high voltage DC output to be classified under the National Electric Code as a Class 2 power circuit. DE technology has been previously developed and commercialized by VoltServer, Inc., for telecom applications. Under the Plug & Play PV project, the Project Team adapted Digital Electricity (DE) technology for use in a solar application. The underlying premise behind doing so is that, by virtue of a Class 2 listing, this technology will enable reduced labor qualification and allow the installer significant flexibility with respect to wiring methods.

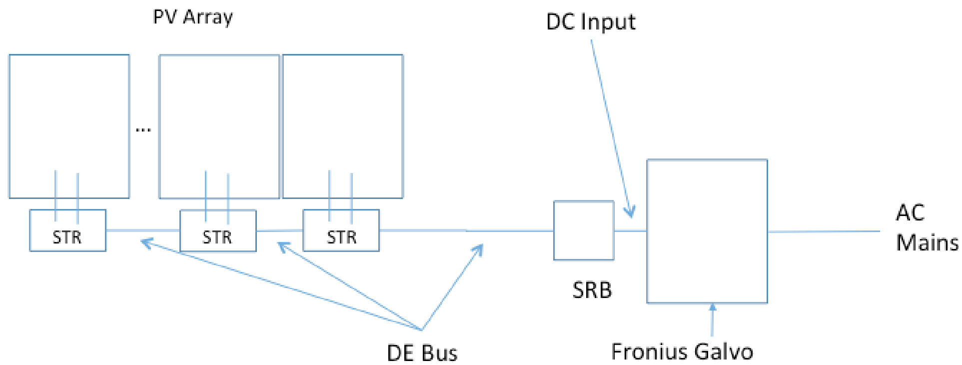


Figure 3-3: Module-level DE System Block Diagram

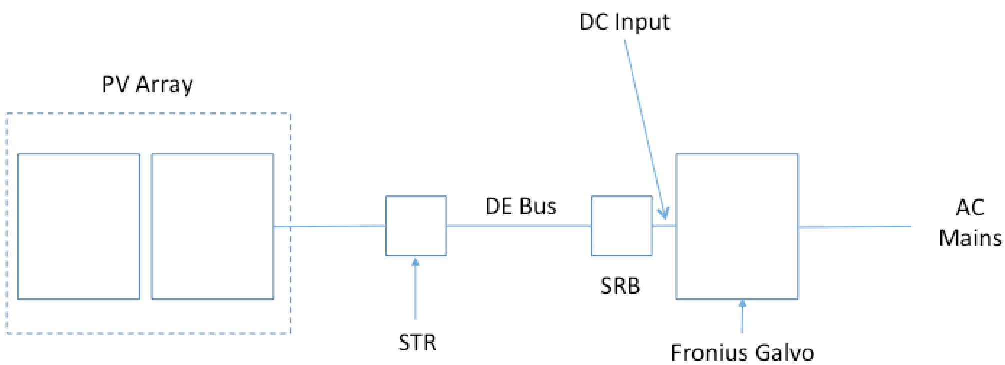


Figure 3-4: String-level DE System Block Diagram

The Project Team evaluated several approaches for implementing solar-integrated DE, and developed working prototypes of systems based on "module-level" (Fig 3-3) and "string-level" implementations (Fig 3-4):

- A "Module Level" configuration deploys Class 2 DE devices at each PV module – in this case, all of the wiring in the PV array, as well as array to inverter, would be considered a "Class 2" circuit. For this configuration, the DE device would also act as a module level shutdown (for NEC 2017 compliance), and could be adapted to incorporate MPPT as an option. There are numerous tradeoffs to this approach related to cost, efficiency, and overall complexity; the key benefit is that this approach entirely eliminates "Class 1" DC wiring from the PV system.
- A "String Level" configuration uses conventional wiring *within* the DC PV string, and a single Class 2 PET device at the end of the string, such that the wiring from array to inverter would be considered a Class 2 circuit. This could be deployed with module-level devices (e.g., optimizers or smart junction boxes) to comply with NEC 2017 module-level shutdown requirements.

Both approaches were found to be technically feasible and were demonstrated as part of integrated Plug & Play PV Systems during the course of the project. The Project Team concluded that the string-level implementation has a clearer path to market than the module-level option due to lower cost, higher efficiency, reduced complexity, and little differentiation with respect to the degree to which labor qualifications are reduced. Electronics have undergone initial NRTL testing for listing to IEC-62368; VoltServer plans to continue to develop DE technology initially as an adjacent offering to other DE-integrated product lines (e.g., solid-state lighting and telecom) in light commercial applications, with potential future licensing opportunities and broader deployment as this offering matures.

Additional findings are summarized below:

Reduction in labor qualification: Digital Electricity technology offers a viable means to reduce or eliminate labor qualification for DC bus PV systems. In practice, most AHJs allow non-experts – e.g., roofers – to perform in-array wiring of DC bus PV Systems. Installation of grounding conductors and homerun wiring, on the other hand, typically requires electrician or apprentice electrician labor. Class 2 circuits may typically be installed by non-experts, or practitioners with a “limited power source” license, a lower qualification threshold. As such, a DE-enable system, in tandem with a solution that addresses grounding requirements (e.g., non-metal panels & rack, or rubberized frames/racks, connectorized grounding solution) meet program goals related to reducing or eliminating labor qualifications.

Electronics development and integration: DE electronics were successfully integrated with a string inverter-based PV system, with several notable findings:

- No adverse interactions were identified with other electrical components. Demonstration systems were developed using a DE power distribution bus connected to the DC input of a Fronius Galvo 3.1 inverter, and connected to the output of a PV string equipped with Tigo TS4-S modules.
- Compliance with IEC-62368 restricts operation of DE-enabled PV systems in two respects: (1) it requires a galvanically isolated / floating inverter; and (2) there is a maximum operational string voltage of ~400V (which would correspond to a max OCV of ~500V) – requiring some reduction in string length. These limitations are a function of NEC requirements that limit Class 2 circuit voltages to +/-200V from ground.
- Operation of the string-level system was robust under stable over several days of outdoor testing. Extended on-sun operation (i.e., over weeks or months) has not yet occurred.
- The module-level implementation introduces some complexity related to multiple failure points, and providing stable power for on-module electronics. Prototype units were found to introduce false trips when PV modules enter a bypass mode; several potential solutions were identified, but not developed due to our focus on a string-level implementation. In addition, the module-level system introduces multiple failure points.

Efficiency: Both system implementations were tested at Sandia National Labs and at VoltServer to characterize the efficiency of a DE-integrated PV System (Fig 3-5). Preliminary results of this testing indicate that the string-level system incurs CEC-weighted efficiency of approximately 1.4 (@ 400V) to 3% (@ 284V) over the system’s operating regime. String level losses may be further reduced by implementing synchronous rectification; this approach was previously implemented on the module-level system. A detailed summary of results is included in Sandia’s final report.[18]

Cost: Based on current (low-volume) board level costs, BOM cost for a string-level DE system is approximately $130 ($71 for STR, $59 for SRB) for a 3kW string, approximately $0.04/W. It is anticipated that a cost-optimized, production version of the system could be realized for roughly half this cost. Based on current board-level costs, a module-level DE system is approximately $879 ($82 x 10 STRs, $59 per SRB), or $0.29/W, with potential cost down to ~$0.15/W.

[18] Burnham, L, Gonzalez, S, Ralph, M, and Lopez, R. “Technical Evaluation of the Fraunhofer-Developed Digital Electricity Photovoltaic System.” Sandia National Laboratory, Technical Report SAND2016-531099. October 2016.

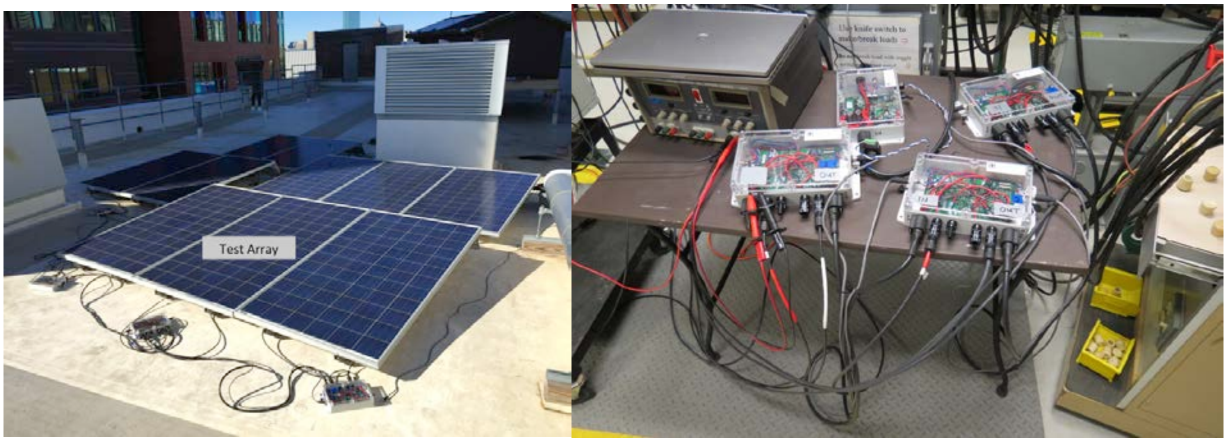


Figure 3-5: Rooftop testing of DE-integrated PV (Left); Benchtop efficiency characterization of DE at Sandia's Distributed Energy Test Laboratory (Right)

3.4 Smart AC Combiner

The purpose of the Smart AC Combiner is to integrate substantively all major balance-of-system electrical components in a single enclosure. In so doing, the AC Combiner enables significant reduction in labor, skill-level, and part count of a microinverter-based residential PV system. In addition, by factory integrating many components in a single package, it greatly facilitates the ability of the PV system to ensure code compliance. The AC Combiner (Fig. 3-6) incorporates the following elements:

- SunPower PVS5 Monitoring and communication platform
- Input and output connectors (ensures proper cable sizing and secure connections)
- Branch circuit overcurrent protection
- Branch circuit relays (enables branch circuit mapping)
- Rapid shutdown

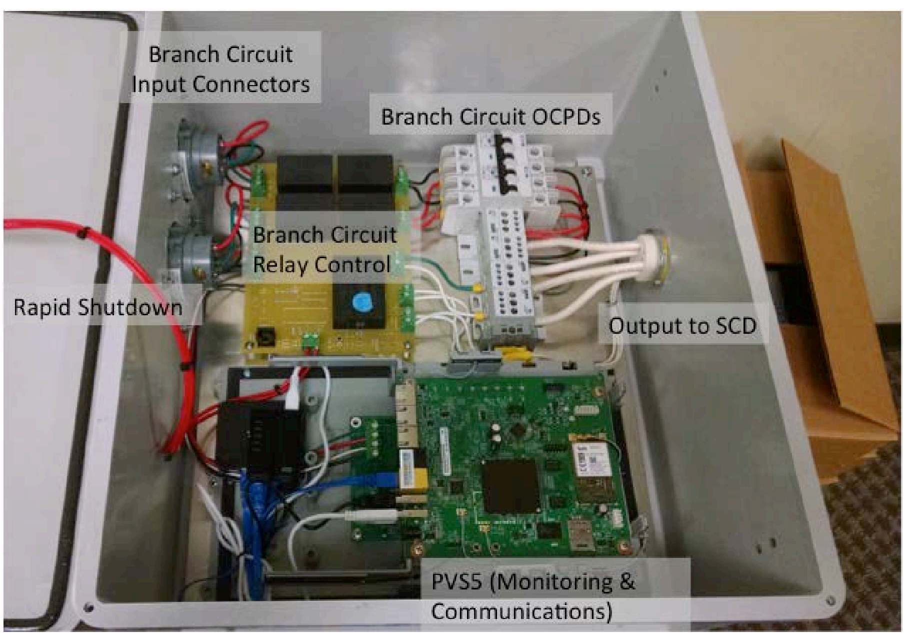


Figure 3-6: Smart Plug & Play AC Combiner

4 Implementation of an Electronic Permitting, Inspection, and Interconnection (ePI&I) Process

This section summarizes the development and implementation of an ePI&I process. One of the key cost drivers in residential PV systems relates to the time, cost, uncertainty, and complexity associated with the permitting, inspection and interconnection (PI&I) process. The Plug & Play Program aims to address this problem through the deployment of an *electronic* PI&I (ePI&I) process. The ePI&I process utilizes a standardized data exchange protocol for transacting information between stakeholders, such as utilities, AHJs, PV installers, and system manufacturers, with the purpose of processing approvals for a PV installation. This data exchange protocol is defined as part of the Plug & Play PV Standard (see Appendix D).

A reference implementation of the ePI&I process was developed using a centralized Plug & Play PV routing server that serves as a single point of contact for all stakeholders within the Plug & Play eco-system (fig 4-1). As implemented, information exchanges within the Plug & Play PV eco-system are transacted between stakeholders through a cloud-based server using the public internet or VPN channels. The Plug & Play PV Server routes information (e.g., submittal packages and approvals) between stakeholders while maintaining a database of information relevant to the ePI&I process. It also provides a framework for Approval Authorities, such as utilities and AHJS, to define and customize Approval Processes required to secure regulatory approvals, and it implements account management functions and security layers required to restrict access to data. By centralizing the routing function of the electronic information exchanges, the Plug & Play Server enables each Actor within the Plug & Play eco-system to only interface with a single entity. It provides users the ability to interface with the server through a web-based API, through email notifications, or a web-based interface. The API enables the server to tie in to 3rd party workflow packages.

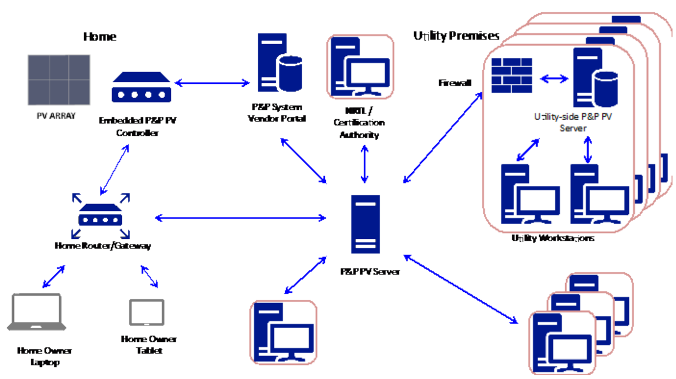


Figure 4-1: Plug & Play Network Topology

Under the Plug & Play PV project, the Project Team developed a reference implementation of a Plug & Play routing server that has been designed to host approval processes for multiple utilities and AHJs, and to integrate with 3rd party software packages, suitable for pilot deployments of Plug & Play PV Systems. A detailed description of the server design is included in Appendix B. The server is currently hosted at:

https://pnpserver.cse.fraunhofer.org:5000

Please contact Fraunhofer CSE directly to request demonstrations or account access.

5 Modules

5.1 Minimizing Roof Penetrations via Adhesive Mounting

For the "Version AP" system described in section 2.3, the Project Team developed a lightweight rooftop mounting system with zero roof penetrations, compatible with current roofing mechanical/structural, fire rating, and warranty standards.

Review of Mounting Approaches: The Project Team conducted an informal survey of known steep slope mounting technologies. Concepts for low penetration roof mounts were brainstormed. We quickly recognized that there is a great deal of market innovation for penetrating mounts for conventional modules. Thus, the decision was made to focus on studying the feasibility of adhesive mounting. An FMEA as well as a workshop identified a number of concerns associated with adhesive mounting. The top risks: adhesive durability, potential moisture damage, effects of temperature and code compliance became the primary technical focus of the Project Team's work.

Technical Feasibility of Adhesive Mounting: Together with project partners Lumeta Solar and Royal Adhesives and Sealants, a large number of tests were performed on the candidate adhesive: Heliobond PVA 900HM (Table 5-1). The adhesive bond was found to strengthen during high temperature exposure as the heat softens the adhesive enabling it to "wet-out" into the shingle granules. Creep was identified as a potential issue under conditions of extreme temperature, loading and roof pitch.

Table 5-1: Summary of Adhesive Testing conducted under the Plug and Play PV project.

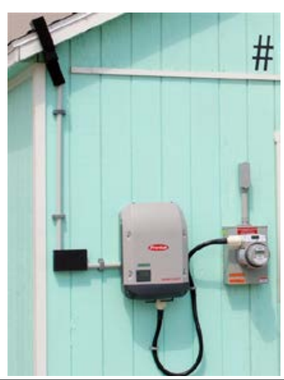
Category	Test	Result
Adhesive Durability	Dry Heat (7d at 85C)	136% Increase
	Wet Heat (7d in 85C water)	29% Increase
	1000h Damp Heat (DH)	90% Increase
	200 Thermal Cycles (TC)	120% Increase
	10 Humidity Freeze (HF) Cycles	59% Increase
	20 Freeze Thaw Cycles	5% Increase
Wind Uplift	Pull-Testing	150 mph equivalent
	Wind Tunnel	120 mph for 60 min
Creep Resistance	Angled Creep Testing	Potential concern at high load/temperature/pitch
Building (Heat)	Roof Temperature Study	Shingles cooled by 4-7C in ABQ
Module Performance	Yield Study	~3% yield reduction in ABQ
Building (Moisture)	Moisture Study	No effect observed to date

Market Acceptance and Adhesive Requirements: Market Acceptance of the adhesive mounting approach was promoted by establishing a route to building code compliance and by getting technical feedback from stakeholders (in this case shingle manufacturers). Code compliance was established by modifying the ICC (International Code Council) Acceptance Criteria 365, which addresses BIPV/BAPV on various roofs. The revised AC365 now includes specific tests that, when passed, enables ICC code compliance for the adhesive mounting of PV on steep-slope shingled roofs.

Discussions with Greg Marlarkey of Marlarkey Roofing and Jim Kirby of ARMA (Asphalt Roofing Manufacturer's Association) provided useful feedback including: suggestion to discuss the adhesive mounting approach with the insurance industry (e.g. Insurance Institute for Business and Home Safety – IBHS), as well as the point that standards are often consensus-based and thus represent the minimum performance target; market acceptance will likely require performance beyond the standards. After reviewing the adhesive test data, CertainTeed, a major shingle manufacturer, issued a letter stating that adhesive mounting of Lumeta modules does not invalidate its roof warranty. A document outlining the adhesive performance requirements for adhesive mounting including the tests, test metrics and test results for the PVA 900HM adhesive was generated.

Cable Management: Cable management underwent significant development during the course of the project. The final design (Table 5-2) was non-metallic to eliminate grounding, and featured openable enclosures to avoid having to pass the connector through (thus keeping the enclosures dimensions small).

Table 5-2: Cable management elements demonstrated on June 16, 2016.

Cable management elements demonstrated on June 16, 2016.	
On module cable tray  	On roof cable protector  
Eave Transition 	Off Roof split conduit 

5.2 Lightweight PV Modules

The Plug and Play PV project focused on reducing PV system weight, in order to reduce the need for structural review and to simplify installation.

Lightweight module classification: An informal survey of several AHJs determined that a structural review, and in most cases a building permit, is not necessary for installing a second layer of shingles (reroofing). As shingle weights can be as low as 2 psf (for 3-tab shingles), a weight threshold of 2 psf was set for the PV system. An analysis of module weights (Figure 5-1) determined that conventional glass-containing modules cannot meet the 2 psf weight target as standard 3.2mm PV glass already weighs 1.6 psf (8 kg/in^2). The weight of conventional modules plus standard rail-based mounting (system weight) exceeds 3 psf. In contrast, glass-less, frame-less modules with adhesive mounting weigh as little as 1 psf. The adhered Lumeta system has a weight of 1.17 psf.

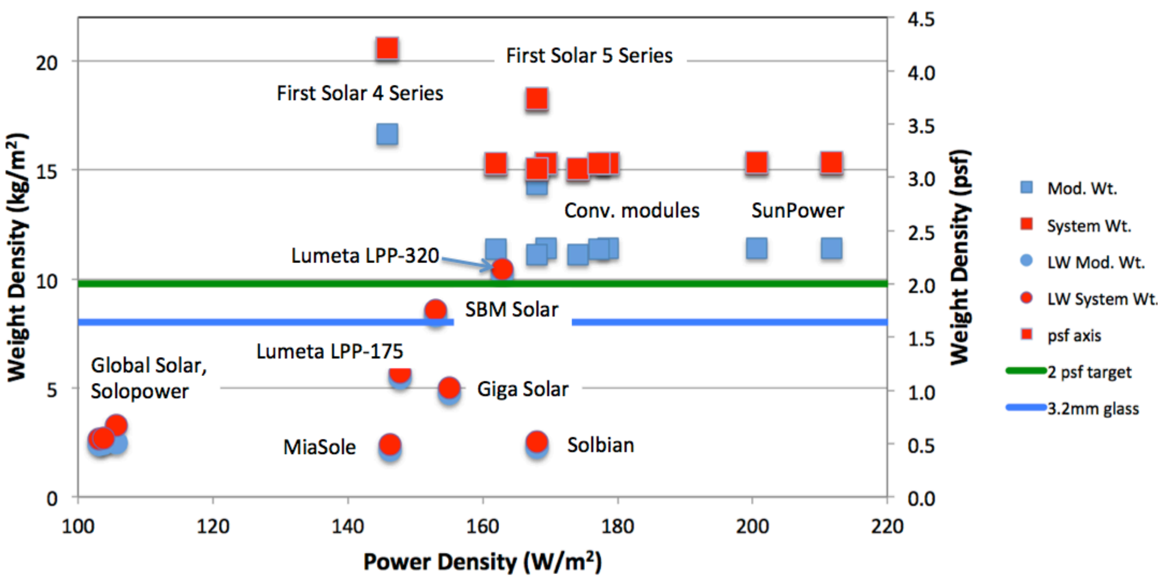


Figure 5-1: Plot of weight density vs. power density for conventional modules (squares) and lightweight (glass-less, frame-less) modules (dots).

The top green horizontal line corresponds to 2 psf and the bottom blue horizontal line corresponds to the weight of 3.2mm glass (8 kg/m^2 or 1.6 psf). The blue symbols represent the module weight whereas the red symbols estimate the corresponding system weight assuming that the lightweight modules are adhesively mounted and the conventional modules are rail-mounted.

Lightweight Module Design Evolution: As a pioneer in the adhesive mounting of lightweight modules Lumeta Solar played an integral role in delivering lightweight modules to Plug and Play PV project specifications. Module design evolved over the course of the project to accommodate power electronics and cable management (Figure 5-2).

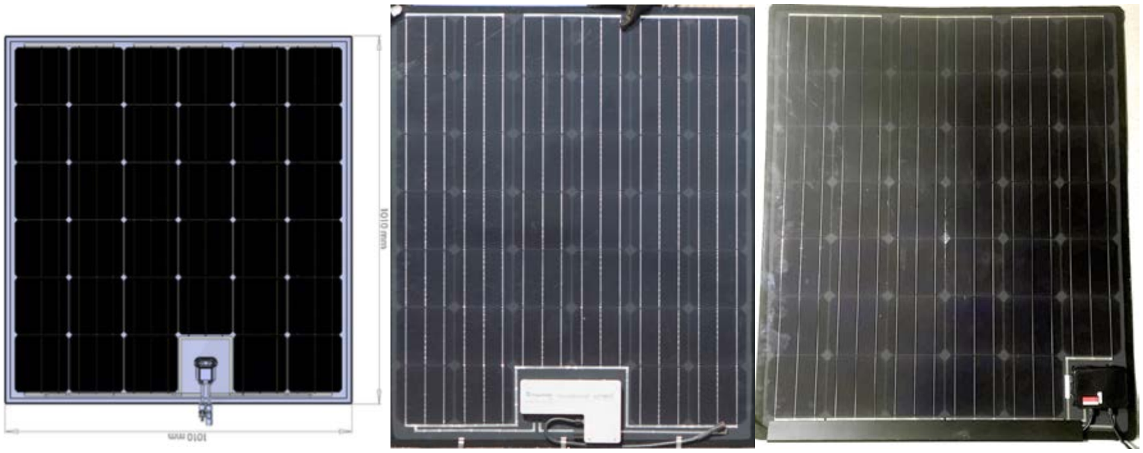


Figure 5-2: Evolution of lightweight module design from BP1 (left: 6x6 with standard j-box) to BP2 (center: 6x7 with SolarBridge micro-inverter and clips) to BP3 (right: 6x7 with smart j-box and integrated cable tray).

Lightweight Module Durability and Robustness: A series of durability and robustness tests were conducted on lightweight modules from three suppliers (Table 5-3). The durability tests were selected to assess potential vulnerabilities unique to lightweight modules. Custom-designed robustness tests evaluated sensitivity to damage during the installation process. Results indicate the glass-less, frame-less modules can be made durable and robust.

Table 5-3: Durability and Robustness Tests conducted in Task 4.

Durability and Robustness Tests conducted in Task 4	
Durability	DH1000
	TC500
	Hail
	Junction Box Adhesion
Robustness	Bending Test (Up/down; center/edge)
	Localized Pressure Test

Long-term outdoor performance, as well as installation testing in the field, is needed to increase market confidence that lightweight modules are sufficiently durable and robust.

Yield Study: To understand the effect of adhesive mounting on module output, an adhered module and a conventionally racked module were mounted on the Plug & Play PV roof-deck in Albuquerque to enable side-by-side comparison of power production. Thermocouples were attached behind each module and temperature data was collected for a one-year period (August 2014-August 2015). Analysis reduced the data to a ratio of specific yield (the ratio of the energy produced divided by the STC rated power of the module) (Figure 5-3).

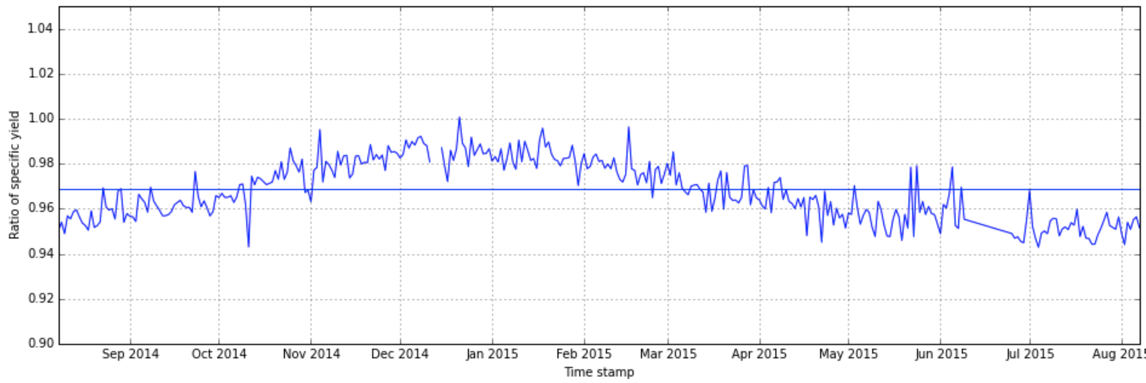


Figure 5-3: Ratio of specific yield of an adhered module compared with a conventionally racked module monitored from August 2014-August 2015 in Albuquerque.

Results: Although the Plug and Play PV framework is agnostic with respect to module type and installation method, adhesive mounting was chosen to represent an extreme case of simplified installation as shown the repeated demonstration of the rooftop installation of 3kW in less than 30 minutes with relatively unskilled labor. The broader testing of adhesives and lightweight modules conducted as part of the Plug and Play PV Project further supports the feasibility of this concept. The performance of the PVA 900HM adhesive meets the project-developed application requirements. Creep under conditions of high weight, high temperature and high slope may be an exception, but still deserves more investigation. Durability and robustness testing on several lightweight (glass-less, frame-less) modules showed both the potential as well as some of the current technical challenges. One vendor's modules suffered from a manufacturing defect. All modules exhibited cell cracking after hail testing. Despite these issues all modules exhibited <5% power loss after durability and robustness testing. Acceptable lightweight module lifetime will need to be demonstrated with extended indoor and outdoor testing.

Adhesive mounting of lightweight PV modules may be growing in popularity. Beamreach Solar (formerly Solexel) launched an adhesively mounted lightweight module for the low slope commercial roof market on June 21, 2016. The module with integrated adhesive mounting weighs 1.8 psf and is installed 5x faster than ballasted systems (according to Beamreach). The pressure for lower installed costs will maintain interest in adhesive mounting as a potential way to dramatically ease installation.

6 System Demonstrations & Stakeholder Engagement

Three system demonstrations were staged throughout the project, in November 2014, October 2015, and May 2016. These events showcased successively more mature systems being installed on rooftops; every demonstration featured two different types of Plug & Play PV system: e.g., string inverter versus microinverter; lightweight modules versus conventional modules. On each occasion, we started with a bare rooftop, installed all components of a 3kW system, ran the system self-test, demonstrated the electronic permitting, inspection, and interconnection process, and commissioned the system in a maximum of 90 minutes. This provided a compelling demonstration of the ease of installation, the ease of proof of code compliance, and the speed and simplicity of the electronic permitting, inspection, and interconnection process.

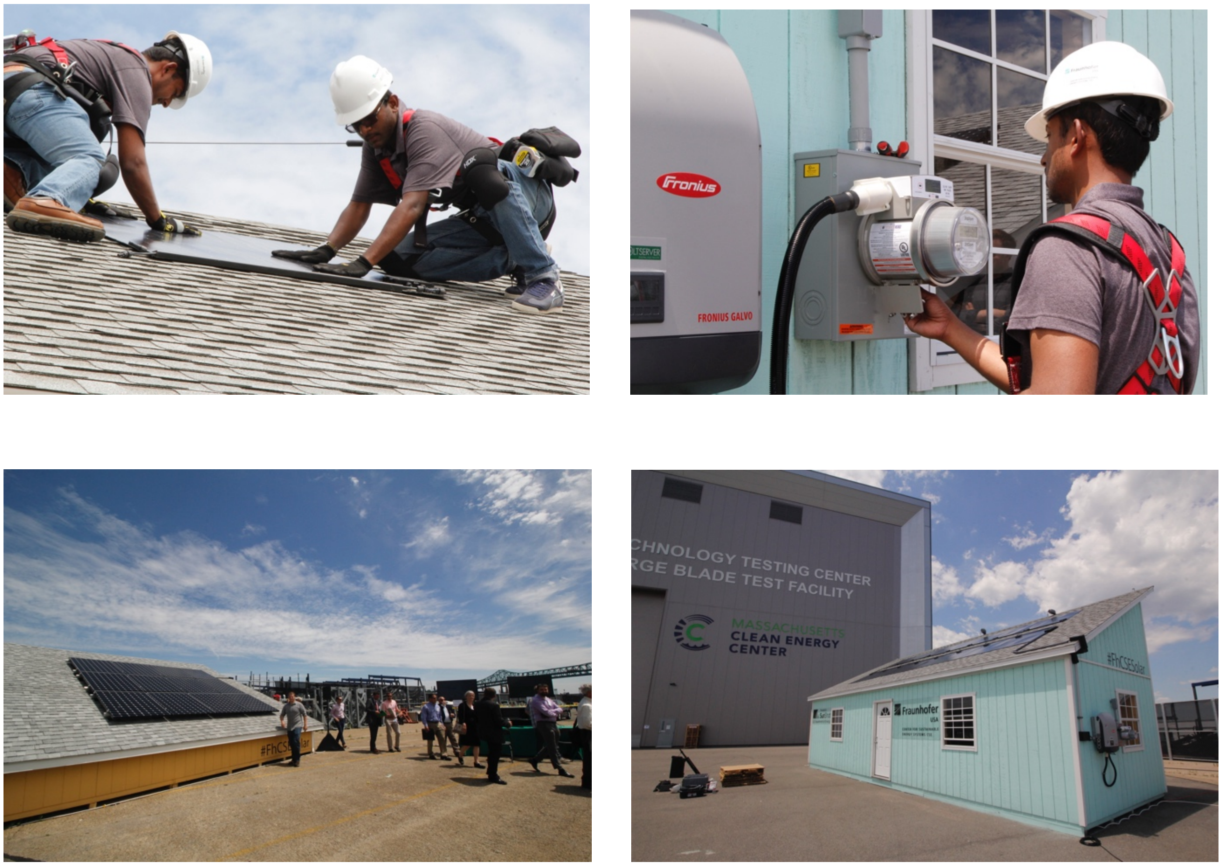


Figure 6-1: Photographs from the final project demonstration, May 2016.

Clockwise from top left: installing lightweight adhered modules; the inverter (left) and meter collar (right) on the side of the hut; the system using lightweight adhered modules after installation was complete; the system using conventional racked modules.

The audience for the demonstrations comprised representatives of all key stakeholder groups: manufacturers, utilities, inspectional services, installers, and state policymakers. Earlier demonstrations were useful in showing a tangible version of Plug & Play PV Systems to partners and stakeholders who had previously only seen the concept presented verbally, and enabled a deeper discussion in which stakeholders provided feedback on code compliance issues and other areas for improvement. (For example, the cable management on and off the roof underwent substantial development between the first and third demonstrations in order to ensure cables did not touch the rooftop, that debris and snow would not accumulate on top of enclosures, and that the cable management solution is effective and practical.) Later demonstrations showcased a Plug & Play PV system using conventional PV modules that are racked, as well as another system based on lightweight modules that are adhered; the conventional racked module system is one that can be put on rooftops that do not comprise of asphalt shingles.

Comments made by speakers at the November 2014 demonstration include the following:

> The program is "incredibly important because it not only addresses installation barriers, but also simplifies the interconnection process. These systems make solar adoption a less complicated and time-consuming process for our customers …"

- Penni Conner, Senior VP and Chief Customer Officer, Eversource Energy

"I'm really excited to see how the streamlining with this technology will really allow us to achieve our solar goals and help spread of residential solar penetration in the City of Boston …"

- Brad Swing, City of Boston Director of Energy Policy

"This is going to make a difference in the consumer market ... customers are going to love this system, inspectors are going to love this system, and the utilities will be very glad to be working with the customers and the inspectors and the community on integrating more renewable energy to the distribution system"

- Fouad Dagher, Manager of New Products and Services, National Grid

"The Commonwealth's partnership with Fraunhofer CSE continues to drive innovation and cut energy costs while making clean energy options like solar more accessible to residents…. we're proud to support these types of public-private partnerships that aim to transform clean energy marketplaces."

- Matthew A Beaton, Secretary of Massachusetts Executive Office of Energy and Environmental Affairs

Throughout the three-year project, there was ongoing consultation with manufacturers, utilities across the US, inspectional services departments, standard agencies, state representatives, and others to discuss the proposed approach and receive feedback that was used to identify appropriate modifications to the approach.

One other notable stakeholder event was a 4 hour Plug & Play PV Systems standard workshop in advance of Intersolar in San Francisco in early July 2015. Participants included representatives from UL, Ward Bower Innovations LLC, Brooks Engineering, National Grid, Enphase, Fronius, Bosch, KACO new energy, Tigo Energy, SunPower Corporation, ConnectDER, and VoltServer.

The workshop discussions focused primarily on NEC compliance and the ease of inspection and interconnection. Many aspects of the Plug & Play PV Systems approach were received favorably. Two areas in which the Fraunhofer CSE team has modified its approach in response to the group's feedback are (1) making the off-module cable management approach simple for non-expert installation, and (2) alternative approaches to the solar connection device based on some utilities' suggestions.

7 Plug & Play Standard

The Project Team developed a draft Plug & Play PV Standard. The purpose of the Plug & Play PV Standard is to:

(1) Define requirements and certification test procedure for certification as a Plug & Play PV System
(2) Define a standardized API for implementing a scalable ePI&I approval process
(3) Define a standardized premises-side receptacle for interconnecting a PV system

The Standard complements existing certification test procedures (such as UL component certification standards) and communication standards (such as SunSpec and IEC 61850) by addressing several existing gaps:

- It provides a framework for ascertaining that a PV System can verify that it has been installed in compliance with NEC or other code requirements. This represents a "meta-layer" of requirements on a PV system that overlays existing standards – i.e., the certification test procedure for the Plug & Play PV System Standard is intended to *verify that the system can verify that it meets NEC requirements*.
- The communication framework is specifically focused on transacting information related to completing PI&I approvals, such as user information, system configuration, and premises information - not operational data on PV performance.

Preliminary drafts were presented to stakeholders for comment, and incorporated into the final draft version. Finally, the draft Standard was used to define requirements for the demonstration Plug & Play PV Systems, including communications, documentation, and certification testing requirements. The Plug & Play Standard has been published in draft form, and is available on the Fraunhofer CSE website.[19] Ultimately, we anticipate hosting the standard under the umbrella of one or more established standard development organizations (SDOs), but initially, it is planned that the standard will be managed and developed by Fraunhofer in partnership with a Plug & Play Industry Alliance.

[19] http://www.cse.fraunhofer.org/pnp

8 Plug & Play PV Systems Alliance and Commercialization

We have consistently received very positive feedback about the potential of Plug & Play PV Systems from many players in the PV space, including installers and distributors, although identifying the team and the mechanism that will drive Plug & Play PV Systems to market is taking some time. Throughout the project, we have considered how different stakeholders benefit from involvement in advancing Plug & Play to commercialization; a summary of advantages for key stakeholders are provided in Figure 8-1.

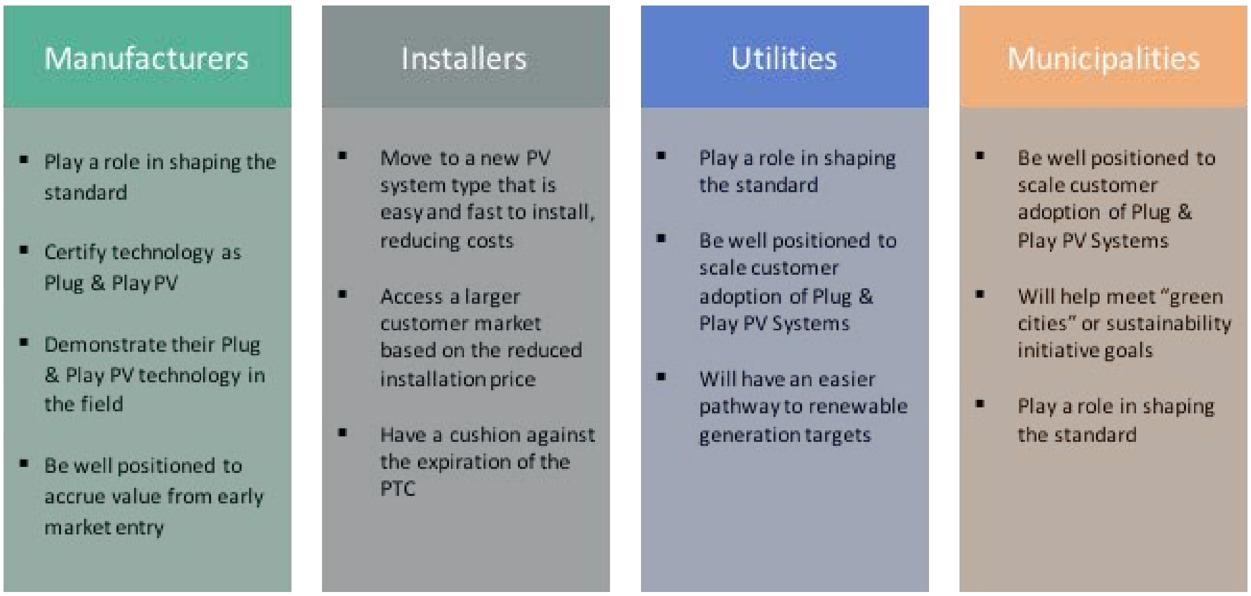


Figure 8-1: Advantages of Plug & Play PV Systems to key stakeholders

The key next steps are formation of the Plug & Play PV Industry Alliance, piloting Plug & Play PV Systems, and commercialization.

Plug & Play PV Industry Alliance: The purpose of the Alliance is to create awareness of the Plug & Play PV concept, educate the market, and gain traction with utilities and AHJs. The Alliance will also be responsible for moving the Plug & Play PV standard through various standard bodies, and for governing the certification of systems. Interest in participation has been indicated by 2-4 manufacturers, more than 4 utilities, and various other parties. The team is currently in discussions with multiple interested parties and will have further discussions following a second Plug & Play PV workshop at Intersolar in July 2016. Some of the interested parties are also pushing for first executing a true pilot on occupied homes before going public with an Alliance.

Pilots: Most interested parties agree that several highly visible true Plug & Play PV pilots on between 10 and 30 occupied homes are the most important stepping stone towards commercialization. Multiple electrical utilities in MA and CA have voiced interest in hosting such pilots. One of the challenges is that at least one but better two Plug & Play PV systems need to be available with all components having listings to applicable standards. The team estimates that this might be possible in the first quarter of 2017 but listing timelines are notoriously unreliable. Until those listing plans have been refined it will be difficult to commit to a specific pilot timeline.

Commercial Plug & Play PV systems: The team has reached out to manufacturers and industry supply chain partners outside of the DOE funded Plug & Play PV team to gauge their interest in designing systems towards Plug & Play PV requirements. There is clearly strong interest, but internal competition for product development resources is obviously strong in all such organizations. The team has, however, identified three very interested parties with whom it is currently discussing pathways to more Plug & Play PV compliant systems.

Understanding the stakeholder advantages is important in setting an appropriate target for level of engagement and level of financial commitment for Plug & Play PV commercialization. We aim for a large number of stakeholders to join the Alliance and show a foundational level of commitment to system standard advancement, with a small number of stakeholders committing substantially more time and money to advance the pilots and other key steps.

The Fraunhofer CSE team has evaluated the sources of revenue and the costs of an Alliance, and plans to transition to an Alliance model that is fiscally sustainable after the Plug & Play PV system pilots are completed. The current ideas behind this phased approach are outlined in Table 8-1 below.

Table 8-1: Phases of the Plug & Play PV Systems Alliance

Phase	**Initial: "start-up/pilot"**	**Later: "full adoption/commercialization"**
Goal	Goal is to establish at least 2 system pilots	Adoption and commercialization as broad and rapid as possible
Membership targets	Target ~10 members: major manufacturers, installers, and utilities	Target as many members as possible, extending to smaller players as well as the larger players already on board
Membership costs	Fixed annual fee for participation, plus contributions to pilot	Fiscally self-sustaining, scaled based on volume of PnP systems using a manufacturer member's technology
Leadership	Fraunhofer CSE leads	Industry-led steering committee; Fraunhofer role de-centralized

Fraunhofer will continue to push to advance Plug & Play PV system commercialization with these stakeholders in Q3 – Q4 2016.

9 Conclusions

The Plug & Play PV Framework has significant implications for driving down the cost of residential solar PV by: (1) Enabling a broadly scalable ePI&I process for adoption across multiple utilities and jurisdictions, while integrating data from all stakeholders within a common data exchange framework; and (2) Enabling the commercialization of Plug & Play PV Systems that are characterized by reduced labor qualification requirements, and easy-to-install, highly repeatable PV installations.

Accomplishments of the Plug & Play Project Team include the following:

- Development of a draft technical standard to support industry adoption of Plug & Play PV Systems
- Implementation of two example Plug & Play PV systems, based on commercial or near-commercial technology. Both systems were tested for compliance with the Plug & Play PV System Standard, and one of the systems was installed in approximately 75 minutes by three novice installers. Estimated 2020 installed cost for a Plug & Play PV system is $1.56-$1.66/W.
- Implementation of a Plug & Play PV routing server that supports a fully electronic PI&I process
- Development of a portfolio of component-level technologies that reduce installation time and/or qualification requirements for residential PV Systems. These technologies include adhesively mounted lightweight PV Modules, a standardized Solar Connection Device for connection to premises wiring, digital electricity-based power distribution protocol, and a smart AC combiner. These technologies show promise both as individual components in the marketplace, and as key enablers of turnkey Plug & Play PV Systems.
- Spearheaded a successful effort to modify ICC (International Code Council) Acceptance Criteria 365, to define ICC code compliance criteria for the adhesive mounting of PV on steep-slope shingled roofs.
- Outreach to stakeholders in industry to lay the groundwork for formation of a Plug & Play industry alliance.

Next steps for this work include the formation of a broad-based industry alliance to promote adoption of the Plug & Play PV framework, continued commercialization of Plug & Play component technologies, and pilot-scale deployments using listed hardware that adopts Plug & Play concepts on customer residences, and integration of ePI&I data models with installer, utility, AHJ workflow packages, and within the broader standards community.

Appendix A Patents, Publications, and Presentations

A.1 List of Publications

Abreu, J., McIlvennie, C., Terpstra, N. (2016). “Evaluation of the appeal of Plug & Play PV systems to the American homeowner – an application of the theory of planned behavior.” Working paper.

Abreu, J., Terpstra, N. (2015). “Gathering insights about the appeal of the Plug & Play PV Systems.” Behavior Energy and Climate Change Conference. Sacramento, CA. October 18-21.

Kromer, M., Hoepfner, C. Ashmore, J. (2015). “Making Plug & Play PV Systems a Reality: A framework for driving down the cost of residential solar installations in the United States.” Dec 2015. http://cdn2.hubspot.net/hubfs/55819/PnP/Making_Plug_and_Play_PV_Systems_a_Reality.pdf?t=1480954768678

Kromer, M., Hoepfner, C., Ashmore, J. (2016). "Plug & Play PV Standards Portfolio, Revision 1.” August 2016. http://cdn2.hubspot.net/hubfs/55819/PnP/Plug_and_Play_PV_Standards_Portfolio.pdf?t=1480954768678

Kromer, M., Hoepfner, C., Ashmore, J. (2016). "Reducing the Cost of Residential-Scale PV Through “Plug & Play PV” Systems and Standardized Electronic Workflows”. 43rd IEEE Photovoltaic Specialists Conference. June 9, 2016.

Shukla, N., Watts, A., Honeker, C., Kosny, J. (forthcoming 2016). “Hygrothermal Impact of Adhesive-applied Rooftop PV.” ASTM C16 Special Technical Program (STP) – Symposium on Advances in Hygrothermal Performance of Building Envelopes: Materials, Systems and Simulations.

A.2 List of Patents

Hoepfner, C., Kromer, M., Ashmore, J., Mahling, D., Perkinson, J. "Photovoltaic Systems and Related Techniques.” US Patent Publication #20160036373. July 14, 2015.

Kromer, M., Hoepfner, C., Mahling, D., Perkinson, J. "Photovoltaic Systems and Related Techniques.” US Patent Publication #20160036381. July 14, 2015.

Hoepfner, C., Mahling, D., Kromer, M., Perkinson, J. "Photovoltaic Systems and Related Techniques.” US Patent Publication #20160036372. July 14, 2015.

Del Olmo, O., Kromer, M., Hoepfner, C., Kinsey, G. "Photovoltaic Systems and Related Techniques.” US Patent Publication #20160036234. July 14, 2015.

Chapman, P., Singh, A. “Automated Commissioning and Inspection for PV Systems” US Patent Application #15/087,594. March 31, 2016.

Chapman, P., Rothblum, P. “Verifying Status of a Termination End Cap of a Microinverter Chain” US Patent Application #15/163,359. May 24, 2016.

Chapman, P., Singh, A., Rothblum, P., Rodriguez, F. “Techniques for Automated Mapping of AC Module Array Schematics” US Patent Application #15/294,098. October 14, 2016.

A.3 List of Presentations

Hoepfner, C., Kromer, M., Ashmore, J. (2016). 3rd Plug & Play PV Stakeholder Workshop. San Francisco. July 10, 2016.

Hoepfner, C. (2015). “Plug & Play Solar PV for American Homes”. U.S. Department of Energy Presentation. Oct 7, 2015.

Hoepfner, C. (2015). “Plug & Play Solar PV for American Homes”. Presentation at Solar Power International 2015. Anaheim, CA. Sept 14-17, 2015.

Hoepfner, C. (2014). “Plug & Play Photovoltaics for American Homes”. Poster Presentation. SunShot Grand Challenge Summit. Anaheim, CA. May 19-22, 2014.

Hoepfner, C., Ashmore, J., and Kromer, M. (2015). 2nd Plug & Play PV Stakeholder Workshop. San Francisco, CA. July 13, 2015.

Hoepfner, C., Ashmore, J., and Kromer, M. (2014). 1st Plug & Play PV Stakeholder Workshop. Las Vegas, NV. Oct 20, 2014.

Honeker, C., Fuller, E., Watts, A., Booth, D., Flaherty, B., Mao, E. (2016). “Reducing Installed Costs of Residential Solar by the Use of Adhesive Mounted Lightweight Solar Modules.” Presentation at the 43rd IEEE Photovoltaic Specialist Conference. Portland, OR.

Honeker, C., Singh, R., Watts, A., Shukla, N., Fallahi, A. (2016). “Residential Solar Systems as an Appliance – Plug & Play PV.” Technical Proceedings of the TechConnect World Innovation Conference & Expo, Volume 2, Materials for Energy, Efficiency and Sustainability, Chapter 9: Materials for Green Building.

Kromer, M. (2015). “A Framework for Plug & Play PV Systems.” Presentation at Intersolar North America Conference. San Francisco, CA. July 15, 2015.

Kromer, M., Hoepfner, C., Ashmore, J. (2015). “Making Plug & Play PV Systems a Reality: A Framework for Driving Down the Cost of Residential Solar Installations in the United States.” December 2015.

Schmid, C., Singh, R., Zimmermann, P., Ashmore, J. (2015). “Development of Qualification Tests for Glass-Less c-Si Modules.” Presentation at NREL Reliability Workshop. Feb. 24 2015

Shukla, N., Watts, A., Honeker, C., Kosny J. (forthcoming 2016) “Hygrothermal Impact of Adhesive-applied Rooftop PV.” ASTM C16 Symposium on Advances in Hygrothermal Performance of Building Envelopes: Materials, Systems and Simulations. Orlando, FL. October 26–27, 2016.

Shukla, N., Watts, A., Honeker, C., Kosny J. (2015). “Thermal Impact of Adhesive-applied PV Roof.” Presentation at 4th International Renewable Energy and Environment Conference (IREEC-2015). Prague, Czech Republic. June 4–6, 2015.

Appendix B Plug & Play Server Architecture

B.1 Overview & Requirements

The Plug & Play Routing Server ("Plug & Play Server") is a cloud-based platform that is designed to route information between stakeholders with the purpose of implementing an electronic permitting, inspection, and interconnection (ePI&I) process for residential PV systems. The server was architected with the following key requirements in mind:

- Communicate requirements needed to complete submittal packages within the ePI&I process
- Host information required to generate project submittals
- Route submittal information to relevant stakeholders
- Route approvals to relevant stakeholders
- Track project status
- Accommodate an arbitrary number of utility and AHJ approval processes, such that it can be widely and rapidly adopted
- Handle information transactions between the various classes of stakeholders who would participate in an ePI&I process. These include Installers, Manufacturers, Utilities, AHJs, Homeowners, PV Systems, and Certification Agencies.
- Allows users to interface with it through an API or web server interface, thereby enabling integration with 3rd party tools or standalone operation
- Accommodate transactions for conventional and Plug & Play PV Systems
- Implements security layers to protect access to sensitive information

B.2 Architecture

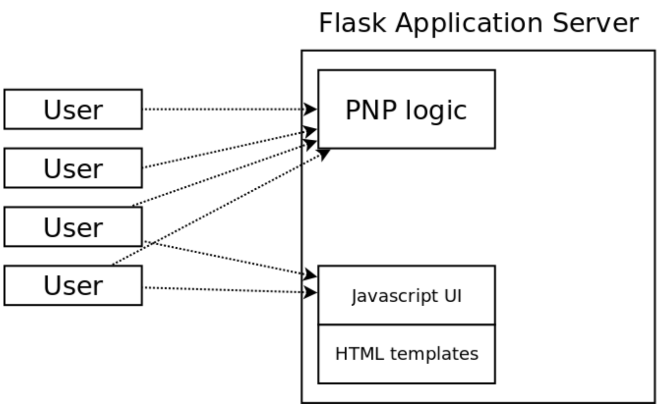
The Plug & Play service performs its functions at three different levels, and it's important to distinguish them in order to keep server logic and necessary complexity at the level where it is most important:

1. **Web Service:** This is the level presented to stakeholders to enable them to establish their policies, present them to other stakeholders, and then carry their policies out project by project. To that end, the server serves out HTML templates and Javascript code to present data in human readable and convenient form. The Web user is naturally anyone who chooses to interact with the PNP server by way of a common web browser.
2. **API:** At this level, server requests and responses use primarily JSON to collect and serve out data and transact steps in the commissioning process. The server presents the API in order to place and enforce a security policy between the stakeholders and the database that records their actions. It also assembles data from the database and turns it into different views of the same data, for the convenience of API users and the Web service above. The "API user" is a third party application that interacts with the PLUG & PLAY Server. This could be, for example, a utility or jurisdiction workflow application (e.g., PowerClerk, Municity); a vendor portal; a PLUG & PLAY PV System; an installer design package, or a mobile application.
3. **Database:** The database is designed to record, permanently and auditably, every transaction where one stakeholder hands responsibility over to another. The database schema is designed for easy performance tuning and concurrency, and to enable audits of the service with or without use of the two levels above. Any database administrator with knowledge of SQL can reconstruct the progress of a project through the commissioning process with just a few SQL commands.

B.3 Plug & Play Server Implementation

This section defines the components that comprise the Plug & Play Server, starting with the client facing Web front end, the RESTful API beneath, the server logic underneath, and the database and storage backend. The components chosen for building the database were chosen with one eye toward rapid development for demonstration purposes, and one towards a path for rapidly scaling up the design to accommodate a broad user base.

Web Server: The Web Server, the front-facing part of the architecture, apart from presenting a user interface usable for all stakeholders, also must implement the logic of the PNP protocols and logic. To that end, we used Flask, a Python-based application server platform. All stake holders interact directly with the Web Server's JSON-based RESTful interface. Those with browsers are also served some Javascript files and HTML templates to present the user interface.



Server Logic: In user interaction, all objects handled by the PNP process are represented as JSON objects. This includes user accounts, organization profiles, organizational policies, installation projects, submissions made for same, and actions on user submissions. The server implements the logic of the PnP process in Python. To that end, the server relies on the Flask family of code libraries, including Flask-Restful, Flask-Login, and Flask-SocketIO. The API and communications architecture is also compatible with other protocols besides JSON, such as XML, but these have not been implemented.

Object Relational Managers: For storage, all Python objects are stored in a SQL database, and the SQLAlchemy library is used as the database interface.

Database backend: The Plug & Play demonstration used SQLite for rapid deployment.

Scaling the PNP server: The Plug & Play process is not particularly resource intensive. The highest consumption of network bandwidth by the process comes from the uploading and downloading of photos and PDF or Word files, some of which may at times be bloated. But all other interactions with the service are succinct. For any project, the number of stakeholders looking at its progress is limited, making database contention unlikely. The bottleneck in terms of performance is the implementation of the PNP process in Python, which is a computational bottleneck. The Flask server framework facilitates scaling for this use case. Many Flask applications developers present their users with a conventional Web server (Apache or NginX) which uses a load balancer to forward queries and interactions to a dynamically managed set of Flask application servers, as per the figure below.

For PNP, a Flask & SQLAlchemy server node's resource footprint fits within a lower-end cloud-based server offering. A c1.medium node at Amazon Web Services (the lowest offering at this time) would fit 4 to 5 Flask instances. For a database backend, PostGresSQL would more than fit the process's requirements.

Incorporating new users into the server is straightforward. Following is a brief description of how the PLUG & PLAY Server functionality may be expanded to serve new user bases:

- New Users – new user accounts may be setup and configured online
- New Approval Authorities, such as AHJs and Utilities, are required to configure the specific Approval Process required to complete an ePI&I project within their organization. The PLUG & PLAY Server has been configured with a number of generalized datasets that correspond to data typically required for generating a submittal package. Approval Steps may be configured from this existing database, or by introducing new datasets. New datasets may be added to the repository using standard API calls or through a web interface.
- Incorporation of new Plug & Play PV Systems: Adding new certified PLUG & PLAY PV Systems to the PLUG & PLAY Server's repository is similar to adding other types of datasets.
- Integration with 3rd party workflow packages: Integration with 3rd party workflow packages entails mapping standardized PLUG & PLAY datasets to internal data points within the 3rd party software package.

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Appendix C Test Reports

C.1 Plug & Play PV System Compliance Field-Testing Report

C.1.1 Version AP System Compliance Field-Test Report

The field test for validating compliance of the Version AP system consisted of the following steps:

- Verify that the system under test can detect an improperly configured PV array – specifically, the system shall be required to detect improper PV string configurations that exceed voltage limits or the permitted power rating of the PV system, or that include improperly specified PV modules.
- Verify that the system under test can detect an incorrectly sized breaker on the premises-side connection
- Verifying that the system under test energizes only after required regulatory approvals are granted
- Verifying that the system under test properly communicates with the Plug & Play PV Server

The first two items in the above test procedure correspond to installer errors that were identified in the system's Code Compliance Plan as verified by electronic self-test.

Procedure for detecting an improperly configured PV array:

The configuration of the PV array was mapped and verified by comparing data queries from Tigo TS4-S smart junction boxes mounted on the PV panels against DC voltage measurements at the inverter input, using the following procedure:

1. Interrogate field-installed PV system:

(1) Count # of modules detected, based on cloud-based query
(2) Determine expected voltage, based on summing the measured voltages reported at each PV module terminal
(3) Query DE receiver output (i.e., inverter DC input) to report measured DC voltage

2. Based on these measurements, the Plug & Play commissioning software implements logic to verify that the as-built PV array has been installed correctly:

(1) The number of PV modules detected matches the permit
    a. # of PV modules detected = # of PV modules expected
(2) The PV module specifications match those specified by the permit
    a. Detected PV module part number = Permitted PV Module part #
(3) The as-built system does not exceed maximum DC string voltage limits:
    a. Voc x # of modules x tcorr < Vmax
(4) All of the PV modules detected are connected, and no additional (non-detected) PV modules are detected:
    a. $V_{Inverter} + V_{drop,\ max} < \Sigma V_{modules,\ detected} > V_{Inverter} + V_{drop,\ min}$

The system's ability to detect an improperly configured PV array was verified by configuring the system in n, n+1, and n-1 configurations, where "n" is the number of PV modules expected based on a permitting submittal (Fig C-1). This was supplemented by a review of relevant code.

Due to limitations in the Tigo API functionality exposed available to the Plug & Play System controller, the System Under Test did not have the ability to query modules to ascertain PV module specifications, such as the part #. This does not represent a fundamental limitation (i.e., this information is available through communication channels that we were not able to access).

Figure C-1: (Top) "n" module test (proper number of PV modules); (Bottom) "n+1" module test (improper number of PV Modules)

Procedure for detecting an incorrectly sized breaker on the premises-side connection: The System Under Test detects an incorrectly sized breaker through a modbus query to the Solar Connection Device. The SCD is factory programmed with a Modbus register that indicates the breaker sizing. The PLUG & PLAY Controller verifies that the breaker is within upper and lower bounds determined by the inverter's max breaker rating and by 1.25 x the inverters max current output, respectively.

This failure mode was verified by modifying the PLUG & PLAY Controller code to define the acceptable design envelope outside the bounds of the actual breaker rating (FAIL), and using the production code, which generated a PASS.

Procedure for verifying that the System Under Test Follow PLUG & PLAY Startup Procedures: The System Under Test was shown to energize if and only if all required regulatory approvals were granted and the user opts to energize the system. This was ascertained by configuring a sample project on the Plug & Play PV Server through various approval states.

Procedure for verifying compatibility with the Plug & Play PV API: Compatibility with the Plug & Play API was verified by conducting linking the System Under Test to a sample project on the Plug & Play Server, and by reviewing the subsequent handshakes between the Server and the System Under Test. The System Under Test was found to meet these requirements.

C.1.2 Version B (SunPower ACPV) Plug & Play PV System Compliance Field-Test Report

The field test for validating compliance of the Version B (SunPower ACPV) Plug & Play system consisted of:

- Verify that the system under test can detect an improperly configured PV array – specifically, the System Under Test shall verify that the branch circuit configurations match the permit, that the system's total AC power output matches the permit, and that none of the individual branches exceed current limits on modules per branch circuit.
- Verify that the system under test can detect that branch circuits have been properly terminated with an endcap at any terminal modules.
- Verifying that the system under test energizes only after required regulatory approvals are granted
- Verifying that the system under test properly communicates with the Plug & Play PV Server

The first two items in the above test procedure correspond to installer errors that were identified system's Code Compliance Plan as verified by electronic self-test.

In addition, the ACPV system specified a visual verification method for verifying that the premises-side OCPD was properly sized. Although the system does have the capability to verify OCPD sizing using the same Modbus protocol as discussed under the Version AP system, this capability was not implemented. Instead, the Installer is required to take a digital photograph of the OCPD, which can be remotely verified.

Procedure for detecting an improperly configured PV array:

The configuration of the PV array was mapped and verified as follows:

1. Controllable relays in the AC Combiner box allow the system to isolate individual branch circuit inputs in sequence. During the commissioning process, the system's commissioning application sequentially isolates each branch circuit and performs a "system discovery" process to detect modules that are present on that branch.
2. Module counts for each circuit are compared against expected values (relative to both approved permits and manufacturer specifications)
3. Module part numbers are compared against expected values

The array mapping function was tested by performing n, n-1, and n+1 tests on a branch circuit to ascertain that the system passes its self-test only if the proper branch circuit configuration is detected. Verification of system AC power was tested by modifying the permit application to mismatch the as-built AC power.

Procedure for end-cap detection:

A modified end-cap was developed that places a large impedance across L1 and L2 of the branch circuit. This creates a resistor network with a unique signature corresponding to the presence or absence of the end cap, which could be detected by a voltage sensor within the AC combiner. End cap detection functionality was verified by conducting self-tests with and without the end cap present.

Procedure for verifying that the System Under Test Follow PLUG & PLAY Startup Procedures: The System Under Test was shown to energize if and only if all required regulatory approvals were granted and the user opts to energize the system. This was ascertained by configuring a sample project on the Plug & Play PV Server through various approval states.

Procedure for verifying compatibility with the Plug & Play PV API: Compatibility with the Plug & Play API was verified by conducting linking the System Under Test to a sample project on the Plug & Play Server, and by reviewing the subsequent handshakes between the Server and the System Under Test. The System Under Test was found to meet these requirements.

C.2 Module Testing - SOPO BP3 Deliverables

C.2.1 Deliverable 4 (1 of 2) - Conclusions Durability and Robustness BP3

Task 4.2: Module Durability

A select set of module durability tests was chosen to survey the durability performance of commercially available lightweight (glassless, frameless) modules. Results indicate that lightweight modules have the potential to pass Hail, TC500 and DH1000 exposure (Table C-1). Hail-induced cracking was observed, however. Modules from SBM Solar showed widespread cell cracking, later confirmed to be due to a problem in manufacturing.

Table C-1: Summary of module durability test results.

	Post-(Hail+TC50)	TC500	DH1000
Lumeta	Passed ΔP = 0	1 Failure (burnt diode) 2 passed with ΔP = +2.0%	Passed ΔP = -1.3%
SBM	Passed ΔP = -1%	Failed (ΔP = -90%) Cracking	Failed (-80%) Cracking
Giga	Passed ΔP = -0.5%	Passed ΔP = +0.7%	Passed ΔP = -2.1%

In parallel with the TC500 and DH1000 tests, a set of junction-box dead load tests was conducted to evaluate the ability of the j-box adhesive to withstand the increased load due to potential Plug & Play PV module level power electronics (MLPE) (Fig. C-2). A set of j-boxes was mounted onto the module back-panel and loaded with increasing weight during TC500 and DH1000. No slippage of the j-boxes was observed after either TC500 or DH1000 exposure.

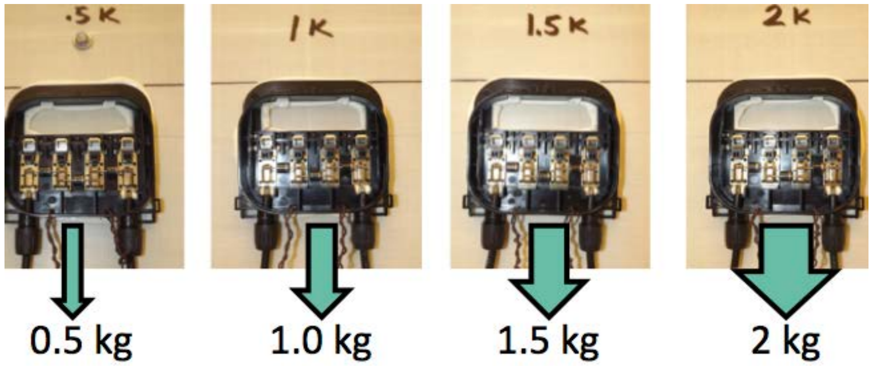

Figure C-2: Junction boxes attached to a lightweight module back-panel and loaded with increasing weights. Samples from all three lightweight module manufacturers did not show any slippage after TC500 and DH1000.

Task 4.3: Module Robustness

The custom set of robustness tests developed in BP2 were modified and applied to several commercially available modules (Table C-2). All modules passed the typical criterion of <5% power loss after the corresponding test sequence. The Lumeta design stands out as being the most flexible. In this case face-down bending causes audible cracking and an increase in power loss. The upside-down bending places the cells in tension greatly increasing the possibility of cracking.

Table C-2: Summary of module robustness test results.

	Bending: Face-Up	Bending: Face-Down	Localized pressure test
Lumeta	Passed ΔP <-0.5%	Passed ΔP < -1.2%	Passed ΔP < -1%
SBM	Passed ΔP < -4%	Passed ΔP < -1.6%	Passed ΔP < 2%
Giga	Passed ΔP = -0.5%	Passed ΔP <-0.5%	Passed ΔP <-0.5%

The results indicate that lightweight modules have the potential to pass extended durability testing as well as robustness testing.

C.2.2 Deliverable 4 (2 of 2) - Draft of changes to existing test standards (UL 1703, IEC 61215) BP3

Differences between Conventional and Light Weight Modules: There are two key differences between conventional and lightweight modules. First, conventional glass modules having a metal frame are robustly designed to resist wind and snow loads. Conventional mounting must manage the dynamic loads (wind) as well as the static loads (snow) of these (heavier) conventional modules. The lower weight of the frame-less, glass-less modules places fewer demands on the mounting approach (conventional or adhesive). Second, most lightweight modules are less rigid than conventional glass modules. Insufficient rigidity can lead to cell cracking during installation and operation, which in turn can leads to premature module degradation.

Test Protocol Recommendations

Draft IEC 61730 standard and front-sheet thickness.

The IEC 61730 standard "PV Module Safety Qualification" Edition I is designed to address safety issues such as electrical shock hazard, fire hazard, mechanical and structural safety. The second edition has been in committee for some time, but a recent draft contains a requirement that can significantly affect the costs of glass-less lightweight modules. A common high performance front-sheet for glass-less module is the fluoropolymer ETFE. The typical thickness of ETFE front-sheets for PV application is 50 microns (2 mil). The new draft 61730 requires a minimum front-sheet thickness of 0.15 mm (150 microns or 6 mil) (see Table C-3). This substantial increase in thickness would increase the cost of one of the most expensive components of lightweight glass-less modules with a questionable benefit for the module safety. For 61730-1 ed. 2 it may be possible to include the encapsulant in the .15 mm "front sheet" layer requirement. However, the encapsulant has to meet certain dielectric properties, which EVA for example might not meet. Previous editions requiring the modules to pass the partial discharge test represent a more relevant test metric.

Table C-3: Comparison of Edition 1 and Edition 2 (draft) of the IEC 61730 PV safety standard. The new edition requires a minimum front-sheet thickness of 0.15 mm (150 microns).

Table 2: Comparison of two modules classes designed for a system voltage of 1,000V and the impact of edition 2 on spacing. (PD=Pollution Degree, MG=Material Group)

	Edition 1	Edition 1	Edition 2	Edition 2	Where to find in Edition 2
Application Class / Class	Class A	Class B	II	0	Table 1
Requirements of polymeric materials serving as support for live parts	Based on UL746A Section 5.3 CTI>250 (Usys<600V)	Based on UL746A Section 5.3 CTI>250 (Usys<600V)	CTI>600 for MG=I V-1	CTI>600 for MG=I V-1	Annex B Section 2.1.4.1. Material groups
Thickness of Backsheet/Frontsheet	Not defined, results from partial discharge test	Not defined, results from partial discharge test	0.15mm	0.15mm	Table 3 and 4, 1b) Thickness in thin layers
Clearance	8.4mm (Table 4 in edition 1)	4.2mm (Table 4 in edition 1)	14.0mm	8.0mm	Table 3 and 4, 1a) Live parts and outer accessible surfaces
Creepage	Not defined and differently interpreted	Not defined and differently interpreted	6.4mm for PD=1 10.0mm for PD=2 and MG=I	3.2mm for PD=1 5.0mm for PD=2 and MG=I	Table 3 and 4, 1a) Live parts and outer accessible surfaces
Spacing live part to outer surface	8.4mm	4.2mm	6.4mm (PD=1) or 10.0mm (PD=2)	3.2mm (PD=1) or 5.0mm (PD=2)	

As a result of the Fraunhofer CSE team's work in Task 4.2 on durability and robustness testing, we propose the following recommendations for changes to the standards.

Damp Heat testing in IEC 61215

The debate [1] within the PV community over the value of the Damp Heat (DH) testing has particular impact on lightweight glass-less modules. Lightweight glass-less modules contain a higher proportion of plastic materials. The damp heat condition (85°C/85%RH) for long periods of time is too stringent for many plastic materials to survive. An overambitious durability test may unnecessarily restrict the materials palate from which a designer chooses to build a low cost lightweight module. Thus, a reduction in the damp heat condition may open the design space to lower cost plastic materials. Analysis and simulations have been done by NREL which suggests that Qualification testing (1000 h 85°C/85%RH) may be either over- or under-stressing a module relative to its expected lifetime, (over-stressing for cold environment and high activation energy, under-stressing for hot and low activation energy), i.e. for Insulated Back, Glass/Polymer: 20 year equivalent at 85°/85% RH for Denver is 454 hours, where it would be 2867 hours for Bangkok [3]. Tests which are designed for different climatic zones would be a possible option.

Mounting specific test setups

A common approach of lightweight module manufacturers is an integration of module design and mounting approach, like for example the adhesive mounting approach directly to asphalt shingles, also used in this project. A roof surface is not only uneven because of the shingle topography, but also at longer length scales – i.e., a roof can be nonplanar at a short distance due to shingles or a longer distance due to roof sag.

Durability test standards should include specifications of the mounting method. For example, for adhered modules, the support of the roof deck is integral for Hail and Mechanical Load Testing (MLT). Since the Hail and MLT performance of the module is affected by the mounting, clarification in the standard is needed for a consistent basis of comparison.

MLT tests need to match mounting methods. For example, negative loading (pressure from substrate side) is not experienced by peel and stick modules attached to roofs and so the test should be omitted.

Thermal cycling

Due to the higher proportion of plastic materials in lightweight modules compared to glass modules, the difference in the coefficient of thermal expansion (CTE) between silicon solar cells and the polymer materials can be larger compared to the material stack silicon-polymer-glass. This makes light weight modules susceptible to stress induced cracking of the solar cells during diurnal temperature changes. The TC test can uncover any potential issues and is recommended to be carried out after mechanical load testing and also after hail testing.

Hail testing

Many conventional glass modules show no degradation due to the hail test, and if a glass module fails the hail test it is commonly due to the front glass shattering. However, glassless modules cannot shatter. Studies conducted by Saint-Gobain Solar have shown that the module power reduction after the hail impact testing is well below 5%, which is the pass/fail criterion for the power decrease in the IEC61215 standard. Testing carried out in this project showed that the mechanical impact results in cracking of the c-Si solar cells. It is unclear whether subsequent field exposure over many years would cause the opening of tightly closed cracks or crack propagation and thus cause further unacceptable power degradation. In order to evaluate whether the hail damage will lead to further power reduction, a subsequent thermal cycling sequence on the hail-tested modules should be performed. Hail tests should be done in fashion that mimics the module installed condition, i.e., for peel and stick modules, hail test should be done with the module on the roof deck.

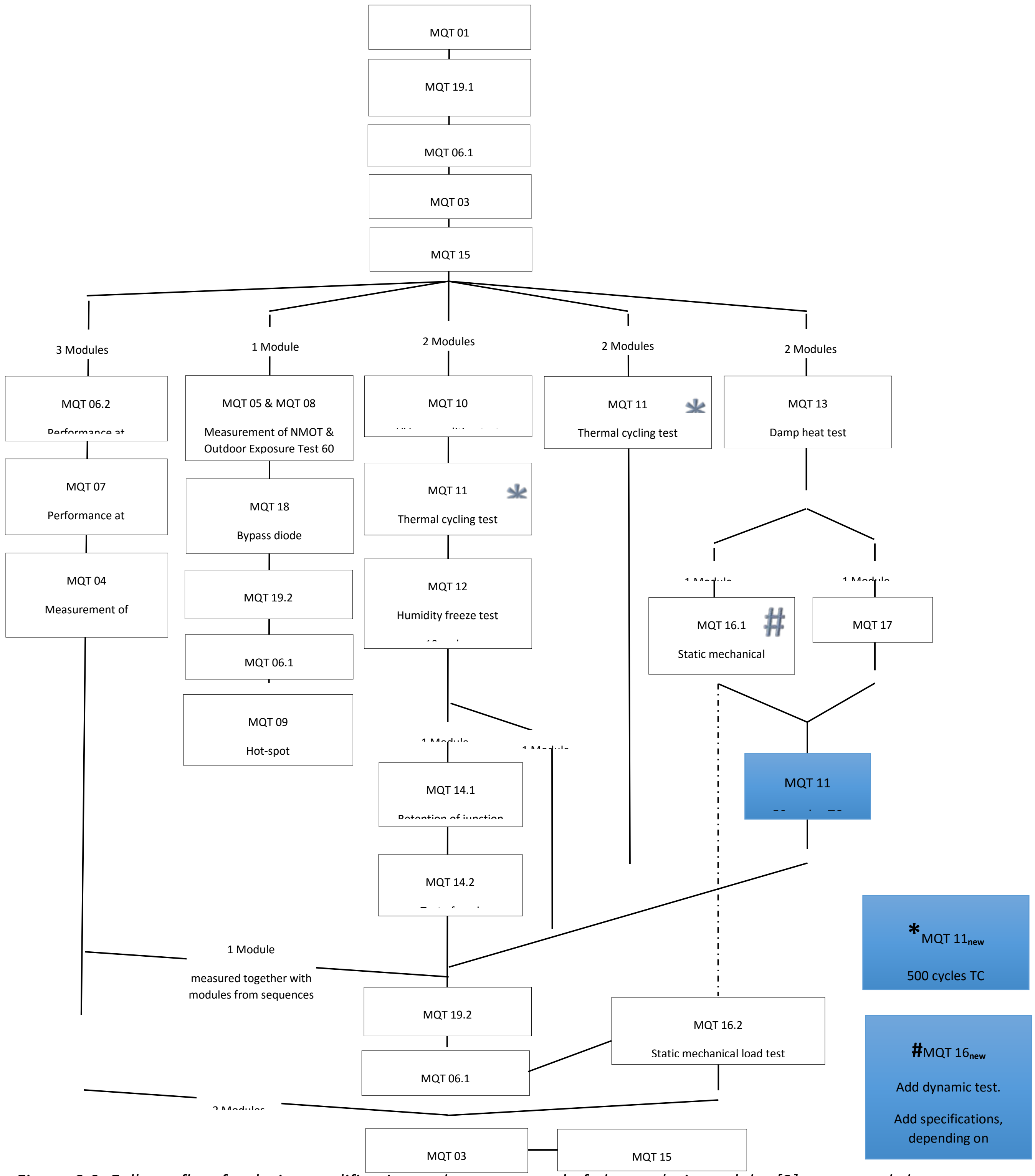

Figure C-3: Full test flow for design qualification and type approval of photovoltaic modules [2], suggested changes are marked in blue.

Robustness Testing

An additional robustness testing protocol which complements qualification testing was developed from the perspective of the vulnerability of the lightweight module to damage during handling. As far as possible, standard test methods were incorporated into the protocol. However, the prototype procedure modifies and extends these standard tests to accommodate the application. Details are described in the marketing acceptance requirements (task 4.1) document.

Bibliography:

1. Kempe, M. D., & Wohlgemuth, J. H. (2013). Evaluation of Temperature and Humidity on PV Module Component Degradation. IEEE 39th Photovoltaics Specialists Conference. Tampa, FL: IEEE p. 120.
2. IEC 61215-1 Ed. 1 – Draft March 2015.
3. Michael Kempe, Sarah Kurtz, John Wohlgemuth, David Miller, Matthew Reese, Arrelaine Dameron (2011), Modeling the Ranges of Stresses for Different Climates/Applications

C.2.3 Market Acceptance – Task 4.1

Definition of residential PV system lightweight module requirements for market acceptance

Conventional glass modules provide a design and installation process that satisfies many solar consumers' needs; however, for sites with weight constraints and high supply chain costs, lightweight modules are preferable.

The strategy of several new players in the market is to focus on the use of crystalline silicon-based absorbers, while replacing the glass front sheet with a thin transparent polymer sheet and using a back panel for structural stability. By removing the glass and aluminum frame the weight can be reduced by as much as 85% compared to a typical PV module. The lightweight modules developed using this approach have several benefits, including: enabling the PV application to weight-constrained buildings and transportation cost reduction across the supply chain. In addition, the fluoropolymer front sheet has typically over 95% optical transparency and lowers the glare, allowing use where glare is a critical safety issue, e.g., in high traffic areas, around airports or military bases. Innovative mounting approaches (such as adhesive mounts) minimize roof penetration, reduce the weight of installation even further, are less susceptible to wind loads and are generally more aesthetically favorable to the customer. The ability to produce larger modules is an advantage, which helps to reduce transport cost, BOS cost and lower installation costs.

Despite this set of benefits, before lightweight modules are broadly adopted it is important that module durability questions are addressed. The differences in the structural make-up and assembly of lightweight modules mean that the long-term effect of the design changes on module durability is unknown, which results in market uncertainty.

In today's market, conventional modules are certified to established standards including IEC 61215 for crystalline silicon modules, IEC 61646 for thin-film modules and IEC 62108 for CPV modules. These qualification tests have the purpose of identifying design, materials and process flaws, which can lead to premature field failures. These same qualification tests are currently being used to test lightweight modules, and the absence of testing standards that are specifically targeted to lightweight non-glass modules represents a major barrier to market growth. Therefore, changes to the current qualification test protocols are proposed in a separate document 'Deliverable 4 (2 of 2) - Draft of changes to existing test standards (UL 1703, IEC 61215) BP3' for lightweight module testing.

A module certification testing protocol must address both degradation and damage caused by potential stresses during installation as well as operation. Specifically, a module durability standard must include testing under typical mechanical loads that the module would experience on a rooftop, as well as the loads experienced during handling and transportation. The threshold parameters for these tests relate in part to module weight and, therefore, are different for lightweight modules compared to conventional modules.

Robustness Testing

Various standard tests exist to assess the performance of solar modules under various stresses including harsh weather conditions, susceptibility to fire and wind damage, electrical performance as well as damage during transportation. However, there are no standard tests to analyze potential damage to modules during their installation. A set of tests was developed to evaluate the robustness of solar modules against stresses experienced during installation. The tests were developed by analyzing all the activities that can potentially damage the modules during the period between delivering the modules and the completion of their installation on the roof. The different steps of the installation include unpacking and lifting the modules, carrying the modules, stepping or standing on the modules and pressing the modules to adhere them to the roof. Unpacking (and lifting the modules out of the box) as well as carrying the modules is expected to cause them to bend and flex. Lightweight glass-less and frame-less semi-flexible modules are assumed to be most susceptible to this deformation mode. Once the modules have been placed on the roof the installer may be required to press down on the modules to ensure that the adhesive sticks to the shingles firmly. The support of the shingled roof deck should reduce the possibility of module damage due to excessive pressing. However, the shingles overlap and there is a gap between adjacent shingles at the point of overlap. Applying pressure on these areas could damage the module considerably by cracking cells or breakage of interconnect ribbons. Moreover, stepping on the modules during the installation, especially at the junction of adjacent shingles can also cause cracks and breakage due to excessive localized pressure applied over a small area. Hence, tests were developed to assess the robustness of the modules during these installation phases.

The test procedures comprise of testing methods from established standards already being used in other industry that are applicable to light-weight modules adhered onto roofs. The main standard that was adopted in the robustness test was the FM 4470 Resistance to Foot Traffic Test.

A separate bending tests under an applied load for the front-side configuration and upside-down configuration. I-V measurements are taken at each step in addition to EL imaging. The modules are subjected to TC 50 to further propagate the cracks. A localized pressure tests was modified to comply with the AC 365 (Acceptance Criteria for BIPV). The modules are tested under 2 loads using a round steel plate as the loading disk, which is in accordance with the AC 365. I-V measurements and EL imaging are conducted after each step and the modules are subjected to TC 50 after the tests. The procedure for performing the different tests is described in the appendix of this document.

Robustness Test Procedure

Table C-4: Summary of installation phases and the associated failure modes.

Installation phases	Deformation mode	Likelihood	Proposed test
Carrying modules	Bending, flexing	Medium	X
Unpacking and lifting	Bending	low	Bending test
Stepping on module	Cracks and breakage due to concentrated pressure	Very low	X
Press on the roof	Cracks, breakage	High	Localized pressure test
Standing on module	Cracks and breakage due to concentrated pressure	Low	Localized pressure test
Dropping module	Shock	Very low	X

<u>Bending test</u>

1. Test is conducted on 6 modules
2. Weigh the modules and conduct EL, IV and VI of modules before and after the test and during each interim step
3. The test will be set-up as shown in Figure C-4, in 4 configurations
4. Clamps should be used to fix the modules in place (to avoid difficulty balancing the edge with the electronics on the rod)
5. Place the modules on two pipes that are placed as close to the edges of the module as possible without the module falling through. Measure and record the distance of the pipe from the edges of the modules.
6. The test will be conducted with a safety factor of 2. Hence, for a module of 6 kg, another 6 kg will be spread uniformly over the module using sandbags.
7. Place a thin layer of rubber/felt on the modules to prevent the bags from slipping to the center during the test.
8. The total weight placed on top of the module, including the sandbags and the rubber sheet, should be equal to the weight of the module.
9. Since the electronics have an additional weight, a total weight of 2x the weight of electronics will be applied to the module at the location of the electronics.
   - On samples without electronics, place sandbags with an equivalent weight of 2x weight of electronics over the location to replicate the actual conditions. For example, the electronics being used currently weigh 2.3 kg so a weight of 4.6 kg should be placed on the sample.
     On samples with electronics, sandbags with a weight of 2.3 kg will be mounted/ adhered to the electronics.

The additional weight at the location of the electronics should only be applied in the configurations where the electronics are at the center of the module, for both configurations- with the cells facing up and down.

10. The total duration of the test is 10 minutes in each configuration.
11. Measure and record the deflection from the top, using a straight edge and a tape

Solar cells facing right-side up

Test will be conducted on 3 modules

- Edge with electronics on the edge (supported) [Up(E)]
- Interim characterization (C2)
- Edge with electronics at the center (unsupported) [Up(C)]
- Interim characterization (C3)
- TC 50
- Interim characterization (C4)

Solar cells facing up-side down

Test will be conducted on 3 modules from each manufacturer

- Edge with electronics on the edge (supported) [Up(E)]
- Interim characterization (C2)
- Edge with electronics at the center (unsupported) [Up(C)]
- Interim characterization (C3)
- TC 50
- Interim characterization (C4)

TC 50

- Once the modules have undergone bending test in each configuration, each module is subjected to TC 50 (according to IEC 61215).
- Conduct EL, IV and VI after each interim step (bending with electronics on rods, bending with electronics at the center, after TC 50)

Figure C-4: Test setup for bending test

Various standards exist in different industries for performing bending and flexure tests on glass, plastics, flexible electronics, etc. The ASTM C158 provides a standard for strength test of glass by flexure and employs the four-point bending test, which is one of the most widely used tests. Besides this, ISO 178, ISO

1209 and ISO 14125 all provide standards for determination of flexure properties of rigid and semi-rigid plastics, cellular plastics and FRP composites respectively. The main tests employed in these industries are the four-point and three-point bending tests, though the two-point bending test is also used occasionally. The four-point bending test, as used by ASTM C 158 uses two support bearing points and two loading points over which the force is applied, as shown in figure below. However, in this case the maximum bending moment is applied between the loading points and gradually drops to zero at the edges. Since our test requires uniform distribution of weight over the module, it was decided that sandbags would be used to conduct the test under the desired weight instead of using the four-point bending test. This is in compliance with ASTM E1830-09: Standard Test Methods for Determining Mechanical Integrity of Photovoltaic Modules. Section 5.3.3.4 of ASTM E1830-09 allows the use of loose sand as a suitable method of applying pressure in a uniform manner.

Localized Pressure test

- The test is conducted on 3 modules
- Conduct VI, IV and EL imaging before and after the tests.
- The test will be set-up as shown in Figure C-5. In the first round of testing two methods were used to apply the localized pressure:
    - Sandbags
    - Calibrated pallet jack

The sandbags can be used to apply pressure up to 80 lbs., but not above it since the structure would be unstable. Hence, a calibrated pallet jack with a hydraulic ramp was used to apply weights of up to 200 lbs. However, in this case, the test set-up has to be flipped over and placed upside down to apply pressure from beneath. For the second round, only two weights (135 lbs. and 200 lbs.) are tested, therefore, the pallet jack method is used.

Figure C-5: Test setup for the localized pressure tests

Localized pressure test – 135 lbs.

- Install standard 3 tab asphalt shingles onto a piece of plywood of sufficient size.
- Cut the adhesive material and ensure that it has been applied in the designated pattern on the back of the module before placing the module on the shingles.

- The adhesive pattern should be uniform across all tested modules.
- The adhesive liner should not be removed to ensure that the module doesn't stick to the shingles.
- Place the module on the shingles, adhesive side down
- In order to perform the tests with a hydraulic load, using a pallet jack, flip over the roof assembly and place it on a rack. Weigh down the roof assembly from the backside to resist the load from underneath.
- Place the module upside down on a cart and wheel it underneath the test stand as shown in Figure C-5. Clamp the module properly to the test stand.
- Place a round steel plate of the required size on blocks on the calibrated pallet jack to nearly match the height of the module.

A1.1 The contact area specified for the localized pressure tests is a 3" diameter steel plate with rounded corners. A device capable of imposing a weight of 200lbs, according to AC 365, section 4.2: Penetration test for BIPV roof panels.

A1.2 According to the AC 365 the test panel assembly should be continuously supported by a rigid backing. A 200 lb. load will be applied on the most critical locations and the superimposed load will be reduced to zero and then reloaded for a minimum of 4 additional times.

1. Position the pallet jack/steel plate assembly under the module and hoist the jack up until the target load of 135 lbs. is displayed on the screen.
2. The block will be oriented as shown in Figure C-6 below to simulate the worst case scenario.

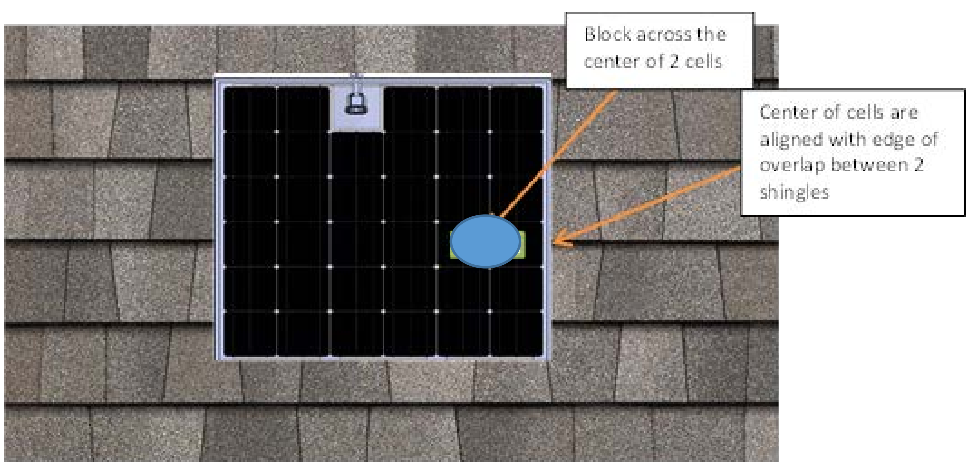

Figure C-6: Schematic for orientation of shingles, module and block in the test Level 2

A1.1 While arranging the set-up, the following specifications should be met

A1.1 Force is applied to a cell near the center of the module

A1.2 The load will be placed at the middle of a solar cell directly below the overlapping edge of 2 shingles as shown in Figure C-6.

A1.1 The total duration of the test is 1 minute. The superimposed load will be removed and reloaded 4 times on the same spot.

A2.1 Conduct EL, IV and VI after each interim step.

Localized Pressure test – 200 lbs.

If modules pass Localized Pressure test 1 then proceed with Localized Pressure test 2.

The tests will be conducted on the same 3 modules used in Localized Pressure test 1, but the weight will be placed at a different location.

Conduct VI, IV and EL imaging before and after the tests.

A contact area of 3" diameter will be used but an incremented pressure will be applied by placing a **weight of 200 lb. on the steel plate**. The reason for choosing this weight is because it is the industry standard for AC 365, section 4.2: penetration test and also for foot traffic resistance test for roof insulations and coverings (FM 4470).

- The test is conducted using the same procedure as in the previous localized pressure test.

TC 50

1. After both localized pressure tests and characterizations are complete, the modules are subjected to TC 50 to propagate possible cracks.
2. Final characterization (IV, VI, EL) is performed after TC 50.