California Solar Initiative

RD&D: Research, Development, Demonstration and Deployment Program

Final Project Report:

Improving Cost, Reliability and Grid Integration of High-Concentration Photovoltaic Systems

Grantee:

Amonix, Inc.

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Preface

The goal of the California Solar Initiative (CSI) Research, Development, Demonstration, and Deployment (RD&D) Program is to foster a sustainable and self-supporting customer-sited solar market. To achieve this, the California Legislature authorized the California Public Utilities Commission (CPUC) to allocate **$50 million** of the CSI budget to an RD&D program. Strategically, the RD&D program seeks to leverage cost-sharing funds from other state, federal and private research entities, and targets activities across these four stages:

- Grid integration, storage, and metering: 50-65%
- Production technologies: 10-25%
- Business development and deployment: 10-20%
- Integration of energy efficiency, demand response, and storage with photovoltaics (PV)

There are seven key principles that guide the CSI RD&D Program:

1. **Improve the economics of solar technologies** by reducing technology costs and increasing system performance;
2. **Focus on issues that directly benefit California**, and that may not be funded by others;
3. **Fill knowledge gaps** to enable successful, wide-scale deployment of solar distributed generation technologies;
4. **Overcome significant barriers** to technology adoption;
5. **Take advantage of California's wealth of data** from past, current, and future installations to fulfill the above;
6. **Provide bridge funding** to help promising solar technologies transition from a pre-commercial state to full commercial viability; and
7. **Support efforts to address the integration of distributed solar power into the grid** in order to maximize its value to California ratepayers.

For more information about the CSI RD&D Program, please visit the program web site at www.calsolarresearch.ca.gov.

Acknowledgements

Several organizations contributed to the success of this project through the efforts of their staff. The California Public Utilities Commission (CPUC), the U.S. Department of Energy (DOE), and Amonix, Inc., provided financial support. Stephan Barsun (Itron, Inc.) guided the project through changes necessitated by DOE contract requirements and University of California Irvine's careful site selection studies that listened to residents who would be living near the large Amonix concentrator photovoltaic (CPV) power plants. Stephan's guidance and that of Ann Peterson (Itron) were critical to this project's success.

Professor Scott Samuelsen, Director of the Advanced Power and Energy Program (APEP) at the University of California, Irvine (UCI), APEP Deputy Director Jack Brouwer, and their team of systems research engineers and graduate students conducted the electrical systems research needed to understand the impact of an innovative solar electric technology operating in a Southern California Edison (SCE) distribution grid. UCI's Richard Demerjian in the UCI Chancellor's office conducted the site selection studies, whose principal benefit was the total lack of neighborhood complaints when the large Amonix CPV systems were installed.

Dr. Sarah Kurtz, National Renewable Energy Laboratory (NREL) Research Fellow and Reliability & Systems Engineering Group Manager, and reliability scientists Drs. Nick Bosco and Timothy Silverman conducted fundamental research that identified a thermal cycling model that could be correlated with concentrator solar cell lifetime. DOE co-funded NREL's development of the thermal fatigue model, which is described in this report. This model was incorporated into an international CPV standards project approved by over 20 countries participating in the International Electrotechnical Commission (IEC) Technical Committee 82 (Solar photovoltaic energy systems), Working Group 7, which is responsible for developing IEC standards for concentrator modules. Amonix reliability engineers, Robert Gordon and Henry Gomez, conducted field failure analyses to separate Amonix field failures into design, manufacturing quality assurance, and lifetime categories for correlation with accelerated environmental chamber testing at both NREL and Amonix.

Mr. Vahan Garboushian, founder of Amonix provided technical guidance and support for two Amonix 7700 CPV power plants for UCI's grid integration studies and the reliability studies conducted by both Amonix and NREL. Garboushian's decades of CPV experience directly influenced the project's focus on longer solar cell lifetimes to lower levelized cost of energy (LCOE). DOE shared the cost of the two systems with Amonix. Mr. Brian Robertson, Amonix CEO, provided enthusiastic support and guidance for this project until his untimely death in December 2011.

Thanks to all of the organizations and individuals for their support and expert contributions.

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Abbreviations and Acronyms

A	Ampere
AC	Alternating current
AIP	American Institute of Physics
ANSI	American National Standards Institute
APEP	Advanced Power and Energy Program at University of California, Irvine
APS	Arizona Public Service
ARC	Anteater Recreation Center at University of California, Irvine
^{o}C	Degrees Centigrade
CEC	California Energy Commission
CEQA	California Environmental Quality Act
CPP	California Polytechnic, Pomona, California
CPUC	California Public Utilities Commission
CPV	Concentrator photovoltaic
CRADA	Cooperative Research and Development Agreement
CSI	California Solar Initiative
DNI	Direct normal irradiance
DOE	U.S. Department of Energy
EL	Electroluminescence
EPRI	Electric Power Research Institute
ETAP	Electrical Transient and Analysis Program
FEM	Finite element model for failure prediction
^{o}F	Degrees Fahrenheit
FTP	File Transfer Protocol
GW	Gigawatt (10^9 Watts, or 10^3 Megawatts)
HALT	Highly Accelerated Lifetime Test
ICEPAG	International Colloquia on Environmentally-Preferred Advanced Power Generation
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
kVAR	Kilovolt amp reactive
kV	Kilovolt (10^3 Volts)
kW	Kilowatt (10^3 Watts)
LCOE	Levelized cost of energy
MCC	Motor control center
MCM	One thousand circular mils (cross-sectional wire area)
M	Meter
min	Minute
MM	Amonix, Inc., CPV MegaModule®
MVA	Megavolt amp
MW	Megawatt (10^6 Watt)
NEPA	National Environmental Policy Act
NREL	National Renewable Energy Laboratory, Golden, Colorado

PPA	Power Purchase Agreement
PV	Photovoltaic
RD&D	Research, development and demonstration
RESCO	Renewable-based Energy Secure Communities
RMS	Root mean square
SCADA	System control and data acquisition
SCE	Southern California Edison
SolarTAC	Solar Technology Acceleration Center, Aurora, Colorado
TC82	IEC Technical Committee 82 for solar photovoltaic energy system standards
TUV PTL	Photovoltaic test laboratory for TUV service group, Tempe, Arizona
UASTP	University of Arizona Science & Technology Park
UCI	University of California, Irvine
UNLV	University of Nevada, Las Vegas
V_{oc}	Open circuit voltage of a PV component
WG7	IEC TC 82 Working Group 7 for CPV module standards
WIR	Wet insulation resistance
W	Watt
X/R	Ratio of reactance to resistance
Z	Impedance (expressed in voltage-to-voltage percent for a transformer)

Executive Summary

Introduction

Consistent with the California Solar Initiative (CSI) mandate for Research, Development and Demonstration (RD&D), this project's objective was to provide technology and knowledge advancements which will enable California to deploy ultra-clean, secure and reliable solar electric generation at the lowest possible cost. The California Public Utilities Commission (CPUC) funded a team led by Amonix for the project entitled "Improving Cost, Reliability and Grid Integration of High-Concentration Photovoltaic Systems". The Amonix high-concentration photovoltaic systems, often called concentrator PV or simply CPV, uses lenses to focus 500-times incident sunlight onto small, highly-efficient PV cells. An emerging technology in solar markets, CPV is well-suited for large multi-megawatt solar projects. Project members included utility systems research engineers from the University of California Irvine (UCI) Advanced Power and Energy Program (APEP) and reliability scientists and engineers from the National Renewable Energy Laboratory (NREL) and Amonix. The project agreement was signed on January 1, 2011, and task work was completed on December 31, 2013.

Project Objectives

Two principal R&D tasks aimed to answer the following questions:

1. What are the key integration barriers to installing and operating Amonix CPV systems in a distributed grid? This is an important question, because CPV has the potential for lower costs and fewer greenhouse gas emissions than conventional PV technologies. However, CPV's integration into a distributed grid could be hampered by its daily electricity production profile, which is different from that of conventional PV systems. Electrical systems researchers and engineers answered this question by analyzing CPV's electrical characteristics while operating in a distribution grid. No major barriers were discovered and after three years of operation, the two Amonix CPV systems continue to operate successfully in the UCI distribution grid.
2. How can the long-term durability of CPV, a relatively new technology in the solar marketplace, be assured so consumers may expect 25 years of reliable operation? Researchers and engineers correlated field failures and weather data with accelerated environmental testing in order to predict the lifetime of the solder attachment of the CPV cell. The quality of the solder attachment was determined to be critical to the lifetime of the CPV cell package. Based on this solar cell lifetime research, the researchers developed an international CPV durability standard for adoption by the International Electrotechnical Commission (IEC). This is the first lifetime reliability standard for CPV.

Accomplishments

The answers to the questions above have provided benefits to the state of California. The project exhibited no major barriers to CPV's distribution grid integration and no intrinsic issue with

CPV's long-term reliability. These two results are consistent with lowering CPV's levelized cost of energy (LCOE). Task accomplishments are prioritized and summarized below:

1) Amonix manufactured two CPV systems, operationally rated at a total of 113 kW AC, specifically for this project and installed them in UCI's distribution grid where they have operated successfully for over three years.
2) NREL developed a thermal fatigue model to predict CPV solar cell lifetime. The model became the basis for an international CPV durability standard IEC 62925. This is the first international lifetime reliability standard for CPV.
3) UCI's APEP developed a central power plant and CPV dynamic models for system operation. Their models were used to investigate the CPV penetration limits on the UC-9 circuit. Once the installed capacity of the CPV on the UC-9 circuit reached 420 kW, reverse power flow began to occur. However, before reverse power flow occurred, voltage limits at the Amonix bus were exceeded with only 240 kW installed CPV capacity. The voltage on the 12 kV side was only minimally affected by the CPV penetration. When the CPV capacity reached ten times the baseline-installed capacity (about 1,200 kW), effects on the 12 kV side became noticeable.
4) UCI's APEP documented the interconnection and operation of CPV systems within the UCI energy system.
5) Amonix and NREL conducted thermal cycling and humidity exposure of CPV solar cells in environmental testing chambers.
6) Amonix categorized CPV solar cell failures in its southwestern U.S. field installations according to design, manufacturing, and lifetime (so-called "wear out") problems; failures caused by design and manufacturing dominated the findings. No "wear out" failures were found consistent with the expectation of long-life for the CPV cell packages.
7) Amonix and UCI reaffirmed the importance of reaching out to the university residents for comments and approval before installing large CPV solar systems.
8) Project results were publicly documented in six papers at international CPV and PV conferences,[1,2,3,4,7,8,9] two international conference papers on Environmentally-Preferred Advanced Power Generation (ICEPAG),[5,6] and an approved IEC project for a new CPV durability standard.[10]

1.0 Improving Cost, Reliability and Grid Integration of CPV Systems

1.1 Introduction

The California Public Utilities Commission (CPUC) funded a team led by Amonix, Inc., for a project entitled "Improving Cost, Reliability and Grid Integration of High-Concentration Photovoltaic systems." The Amonix high-concentration photovoltaic system, often called concentrator PV or simply CPV, uses lenses to focus many hundred times of incident sunlight (500 times or more) onto small, highly-efficient PV solar cells. An emerging technology in solar markets, CPV is well-suited for large multi-MW solar projects in both utility distribution grids and transmission grids. Project members included utility systems research engineers from the University of California Irvine (UCI) Advanced Power and Energy Program (APEP), and reliability scientists and engineers from the National Renewable Energy Laboratory (NREL) and Amonix. The project agreement was signed on January 1, 2011, and work was completed on December 31, 2013.

1.1.1 Background

CPV had historically been a small portion of the PV market, until utilities started showing an interest in the technology due to its high efficiency, small footprint and a potential for lower cost, due to the use of steel and plastic rather than large areas of glass and semiconductors. Amonix was the first company to install large multi-megawatt CPV systems in 2006. Despite these advantages, CPV continued to lag behind conventional flat-plate PV in the utility market due to high initial cost, concerns about grid integration, and long-term reliability issues.

CPV's electrical production is governed by direct normal irradiance (DNI), because lenses can't concentrate diffuse solar irradiance. CPV has to track the sun in order to concentrate DNI, so the CPV electrical output starts rather abruptly when the sun rises and shuts off when the sun sets. Clouds also cause abrupt starts and stops of CPV electrical production. Thus questions arise as to how CPV will interact with loads and other generation units in the grid, since conventional flat plate PV systems have a more gradual rising and falling of electrical power output. UCI's APEP team was responsible for the grid integration study, while Amonix manufactured and installed two CPV systems in the UCI distribution grid.

As a relative newcomer, the long-term reliability of CPV was not well understood. Reliability of a key component, the small high-efficiency solar cells, is dependent on the transfer of excess solar thermal energy that can otherwise cause failure of the solar cell and its electrical contacts, leading to loss of its electrical output. This project aimed to quantify long-term reliability of solar cell packages and make projects more bankable through combining field testing at Amonix field sites with lab testing at NREL and Amonix. Showing long-term reliability also enabled a lower levelized cost of energy (LCOE) if the plant investment could be stretched over a longer lifetime.

2.1 Task 1: Grid Integration of Concentrator Photovoltaic (CPV) Systems

This task included the manufacture, installation, interconnection and assessment of the Amonix CPV systems operating in the UCI campus electrical grid.

2.1.1 Background

Amonix, a pioneer in the development of CPV, was founded in 1989 to develop high-concentration PV systems. In 2009 with the support of a U.S. DOE award, Amonix introduced its seventh-generation CPV technology using the world's highest-efficiency multijunction solar cells. In 2011, Amonix installed almost 40 MW of CPV systems, as rated by international standard operating conditions, resulting in more Amonix installations worldwide than any other CPV company. In 2013, Amonix achieved a world-record module efficiency of 35.9 percent conversion of sunlight to electricity under international standard test conditions, as verified by NREL in Golden, Colorado.

The Amonix 7700 product is a CPV system shown in Figure 1. Each system consists of seven MegaModules®, mounted on a torque tube and rotated by an elevation-over-azimuth hydraulic drive system.

The key components of the MegaModule® are a 10 ft x 49 ft rectangular steel structure; 36 lens parquets including 30 lenses each, and 36 receiver plates, to which are mounted 30 cell packages. Each cell package includes a multijunction solar cell bonded to a die attach, electrical contacts, and a secondary concentrator. To support testing and research, representative samples (mini-modules) were fabricated. The mini-modules included a single receiver plate and lens parquet with 30 cells, with a frame constructed of the same material as the MegaModule®.

UCI was originally interested in the installation of Amonix systems on UCI parking lots, as well as installation on a landfill. The parking lot installation would have required additional funds for designing and developing a 15-ft taller pedestal and was outside the scope of the CSI award. UCI's Campus Planning Office spent considerable time and effort studying the landfill installation of 14 Amonix systems. Extensive delays in getting environmental approvals (Coastal Commission, Wildlife Refuge, Fish and Game, City of Irvine, landfill agencies, CEQA, etc.) closed the window of opportunity for DOE and Amonix to share the costs of these systems under the Amonix award from DOE that ended in December 2011. This was a lost opportunity since Amonix had designed and implemented ballast foundations for other projects in Spain and the U.S. The ballasted foundations for those sites met requirements similar to those of the UCI landfill site.

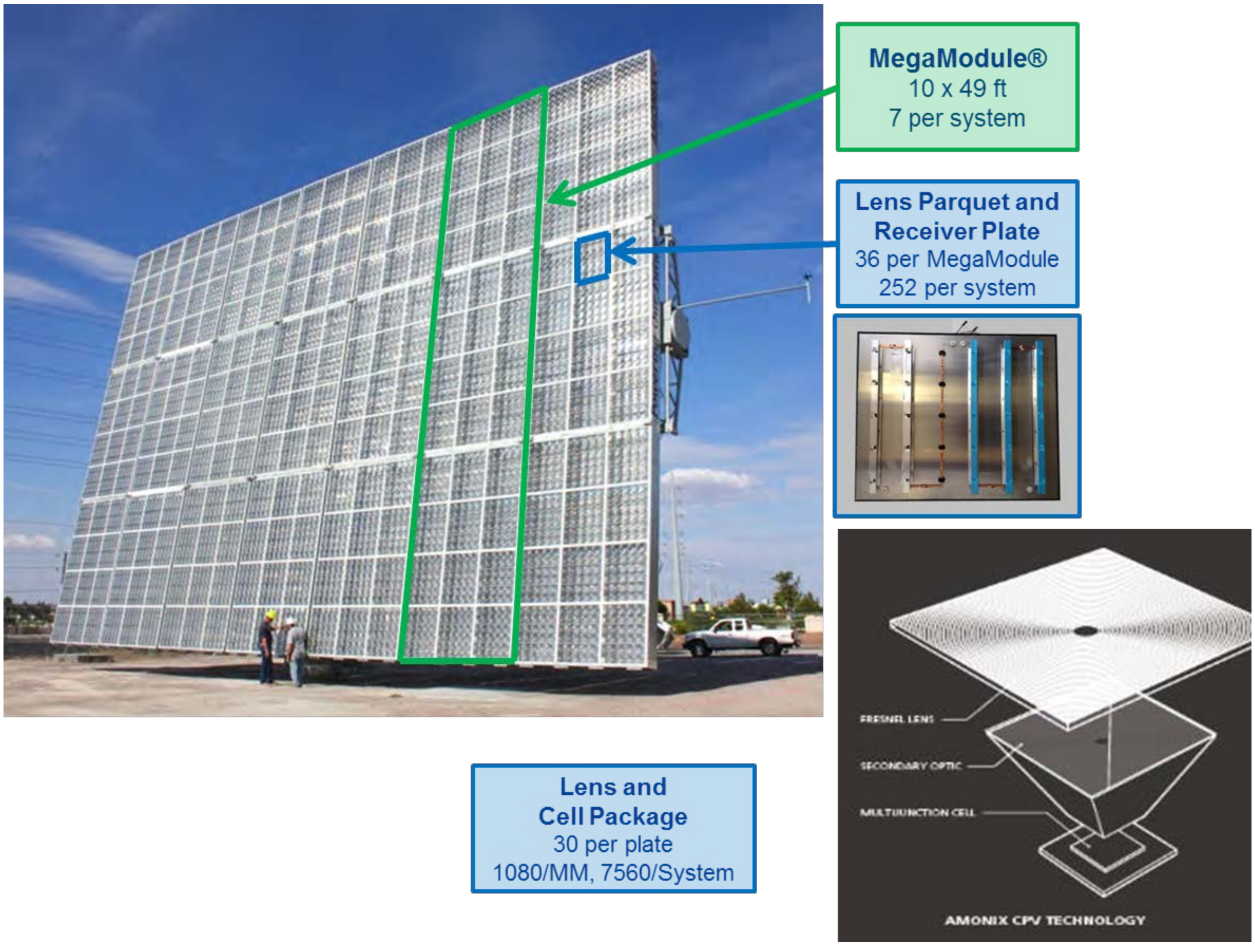

Figure 1: Amonix 7700 High-Concentration PV System.

2.1.2 Objective

The objective was to identify the key integration barriers to installing and operating Amonix CPV systems in a distributed grid. This is important since CPV has the potential for lower costs and fewer greenhouse gas emissions than conventional PV technologies. However, CPV's integration into a distributed grid could be hampered by its daily electricity production profile, which is different from conventional PV. Amonix installed two of its 7700 CPV systems on the UCI campus for studies of grid integration by UCI and joint studies of CPV reliability with NREL. As part of this deployment, the UCI Advanced Power and Energy Program (APEP) goal identified and documented the challenges and opportunities for installing large CPV systems in UCI's distribution circuits. APEP then assessed the preferred CPV integration by determining the value of peak solar generation and benefit of solar generation coordination with combined heat and power systems and demand management.

2.1.3 Approach

The RD&D tasks aimed to address key integration barriers to installing and operating Amonix CPV systems in a distributed grid.

- Amonix manufactured and installed two 7700 CPV systems on the UCI campus. A one-year delay in installation resulted in a no-cost one-year extension approved on December 5, 2012, followed by revisions to Amonix's agreements with NREL (approved March 1, 2013) and UCI (approved April 8, 2013).
- UCI's APEP studied the electrical interconnection of the 7700 systems to the UCI distribution electrical infrastructure, including a 15.8 MW gas turbine, 5 MW steam turbine, 1 MW rooftop PV system, and campus air conditioning and thermal energy storage. APEP then assessed and developed the preferred integration and operation strategies for the CPV systems in the UCI grid.

2.1.4 Results

2.1.4.1 CPV System Manufacture and Installation

The Amonix 7700 was assembled from seven large MegaModules® manufactured in Amonix facilities and shipped to the field for installation. Other 7700 balance-of-system components, such as the pedestal, tracker, inverter, etc., were separately shipped for a coordinated installation schedule.

Two 7700 systems were manufactured for the UCI installation at the Anteater Recreation Center. The first was fabricated with the 30 MW/year pilot manufacturing line located in Seal Beach, California, in 2009 (Figure 2). This early prototype 7700 system, rated at 53 kW AC and designated 7700-53, was installed at an Arizona Public Service (APS) location in 2009 and later returned to Seal Beach when APS closed its solar test program. From a reliability testing perspective, this early prototype 7700 already had "mileage on its odometer" when it was re-installed on the UCI campus in December, 2011.

Figure 2 Early 7700 MegaModule, rated at 53 kW, manufactured in Seal Beach, CA in 2009.

Figure 3 Later 7700 MegaModule, rated at 60 kW AC, manufactured in 2012.

The second 7700 system, rated at 60 kW AC due to design and manufacturing improvements, was assembled in January 2012 in the 90 MW/year North Las Vegas, Nevada, manufacturing facility (Figure 3) following the shipment of the last of the 504 systems installed in Alamosa, Colorado for the world's largest CPV installation (rated at 30 MW AC). This 7700-60 unit contained multijunction cell packages installed by the Amonix manufacturing contractor, Flextronics, in Milpitas, California, with a series of solder void areas suitable for long-term reliability studies. The UCI site is an excellent reliability test site, as its passing clouds alternately heat and cool the solar cells, thereby stressing the soldered contact (also called the die attach) to each solar cell. The research explored a potential correlation between this heating and cooling at UCI's field installation with aspects of NREL's thermal fatigue testing of cell packages in their laboratory.

The **first challenge** for the installation was selecting a site on the UCI campus. UCI's campus planning department had considerable experience in selecting sites acceptable to UCI residents and, if necessary, the City of Irvine. Figure 4 shows the substation site first selected for the CSI proposal, with superimposed photos of the Amonix systems. While electrical interconnection was considerably simplified, UCI's campus planning team rejected the site based upon meetings with residents in homes overlooking the site; Figure 4 is a view from those homes.

Three more sites were considered, and one (Figure 5) was selected near the UCI Anteater Recreation Center (ARC). This site was acceptable to the nearby community of UCI students but entailed considerable installation expense (about 2 ½ times more than planned), partially due to a 600-foot boring underneath the ARC playing fields for the electrical interconnection to a field house on the other side.

Figure 4: View with superimposed Amonix systems from homes overlooking the first site in the original proposal.

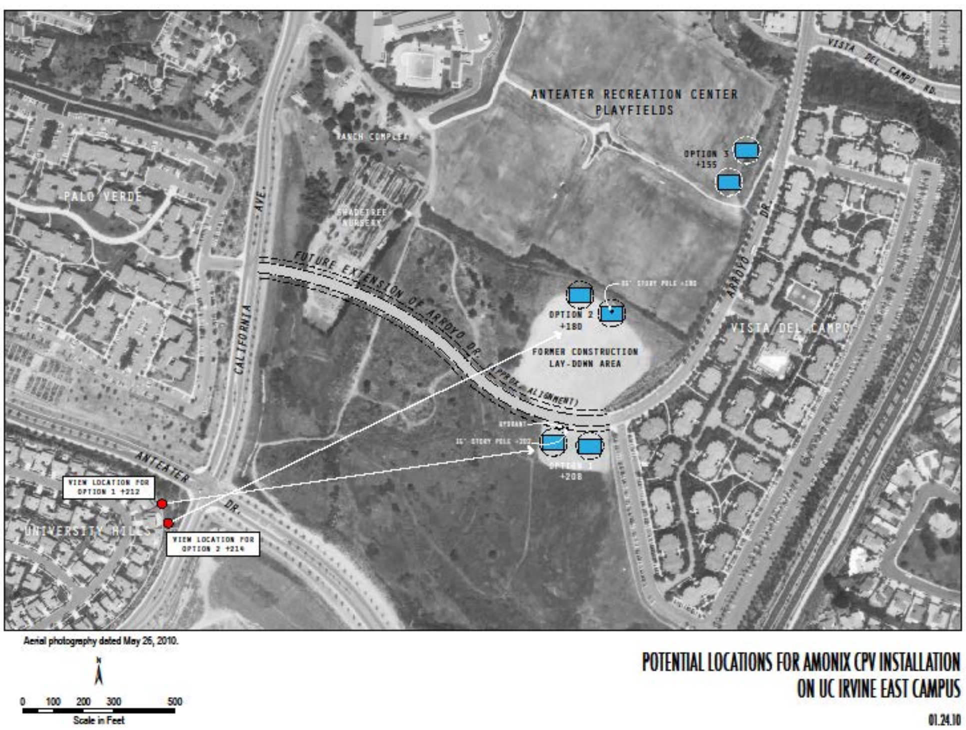

Figure 5: Photo of three potential ARC sites for Amonix CPV systems. The center site was selected.

The **second challenge** was to negotiate agreements with UCI and Southern California Edison (SCE). The SCE interconnection agreement was relatively straightforward. Amonix and UCI negotiated a land license agreement and a separate power purchase agreement (PPA) for electricity from the two systems. The final agreement stipulated that the annual electricity purchase by UCI offset the yearly land license fees owed by Amonix.

The **third challenge** was to obtain environmental approvals. UCI conducted its categorical exemption consistency analysis, confirming that the project on the ARC site is categorically exempt from the provisions of the California Environmental Quality Act (CEQA). The U.S. Department of Energy (DOE) required CEQA approval of the installation on the ARC site to meet National Environmental Policy Act (NEPA) requirements, because DOE shared the manufacture and installation costs under an earlier award to Amonix to develop, manufacture and field test the 7700. On the basis of the CEQA exemption, the DOE approved the installation on the ARC site as meeting NEPA requirements.

A **fourth challenge** was meeting unanticipated requirements by UCI for fire department approval and a UCI-mandated peer review by mechanical and civil engineering consultants of Amonix systems and their installation. While approval by the fire department was relatively straightforward, the UCI peer review required additional Amonix staff time and expense to respond to questions of wind loading and foundation design. The outcome was a redesign of the pedestal, requiring 3-ft pedestal extensions added to facilitate a non-standard 23-ft embedment for both pedestals.

Amonix began installation during the third quarter of the first year of the CSI award. The complete installation was relatively straightforward from thereon, including the two CPV systems, meteorology station, SCADA communications, fencing, etc. The first 7700-53 system was installed in December 2011, and the second 7700-60 system was installed in February, 2012. The two installed systems are shown below in Figure 6.

Figure 6: Two Amonix CPV systems overlooking the UCI Anteater Recreation Center (ARC) field.

2.1.4.1.1 Early Plans for Additional Systems

UCI was originally interested in the installation of Amonix systems on UCI parking lots as well as installation on a landfill. The parking lot installation would have required additional funds for designing and developing a 15-ft taller pedestal and was outside the scope of the CSI award. UCI's Campus Planning Office spent considerable time and effort studying the landfill installation of 14 Amonix systems. Extensive delays in getting environmental approvals (Coastal Commission, Department of Fish and Game, City of Irvine, landfill agencies, CEQA, etc.) closed the window of opportunity for DOE and Amonix to cost-share seven of these systems under the Amonix award from DOE that ended in December 2011. This was a lost opportunity, since Amonix had designed and implemented ballast foundations for other projects in Spain and the U.S. The ballasted foundations for those sites met requirements similar to those of the UCI landfill site.

2.1.4.1.2 Lessons Learned

Good selection of installation sites requires sufficient time to:

- Survey nearby communities and obtain their approval
- Negotiate and complete agreements between key participants and stakeholders
- Obtain all environmental approvals
- Respond to unanticipated challenges and
- Continually focus on project objectives.
- The additional systems for the landfill site were needed for reliability studies in Task 2 in order to increase the statistics of field failures among deployed systems for correlation with laboratory accelerated test failures. In order to compensate for the deferred landfill installation, Amonix reviewed field failure data from other large field deployments in order to obtain equivalent field failure statistics.

2.1.4.2 Distributed CPV Electrical Interconnection and Operation of the Campus' Energy Systems with regard to the Installed Campus CPV Resources

Following the CPV installations, the majority of the Task 1 effort focused on the interconnection and operation of the UCI energy system containing CPV. UCI's APEP conducted these studies. As a critical element of the Task 1 objective described in section 2.2.2, these studies determined the preferred CPV integration by assessing the value of peak solar generation and benefit of solar generation coordination with combined heat and power systems and demand management.

The UCI campus already had approximately 1 MW of installed flat-plate PV generation, to which 113 kW of CPV was added in this project. APEP continued the development of a full microgrid model using the Electrical Transient and Analysis Program (ETAP), a real-time power systems analysis software. This model was used for the management of microgrid operations as solar penetration increases with future installations. As additional solar resources are introduced into the microgrid, it is anticipated that some circuits will begin to experience issues associated with the increased penetration of solar generation. The microgrid model in conjunction with the deployment of the MelROK high-resolution metering system (described in section 2.1.4.3.2

below) served to enable the real-time management of these circuits, as well as to gain insight in microgrid behavior.

Data from the 113 kW Amonix CPV panels and ETAP load flow simulations were used to establish an understanding of the effects of high-penetration solar generation on the UCI campus. Data collection commenced on June 5, 2012. These collected data aided in simulating the UCI microgrid feeder voltage profiles using the ETAP model. To date, field data have been successfully imported into the ETAP, and a methodology has been developed to incorporate additional data sources as they become available.

2.1.4.2.1 UCI Microgrid System Description

The UCI microgrid circuit consists of 10 subcircuits (UC-1 through UC-10) that originate from a 66 – 12.47 kV, 56 MVA dual-fed substation (Figure 7). Downstream of the substation, local generation assets include a 13 MW gas turbine generator, a 5 MW steam plant, and 1 MW of solar generation distributed through the UCI campus for a total of 19 MW. During 2012, the average campus demand was approximately 21.5 MW; the remaining 2.5 MW of demand is provided from Southern California Edison (Figure 8).

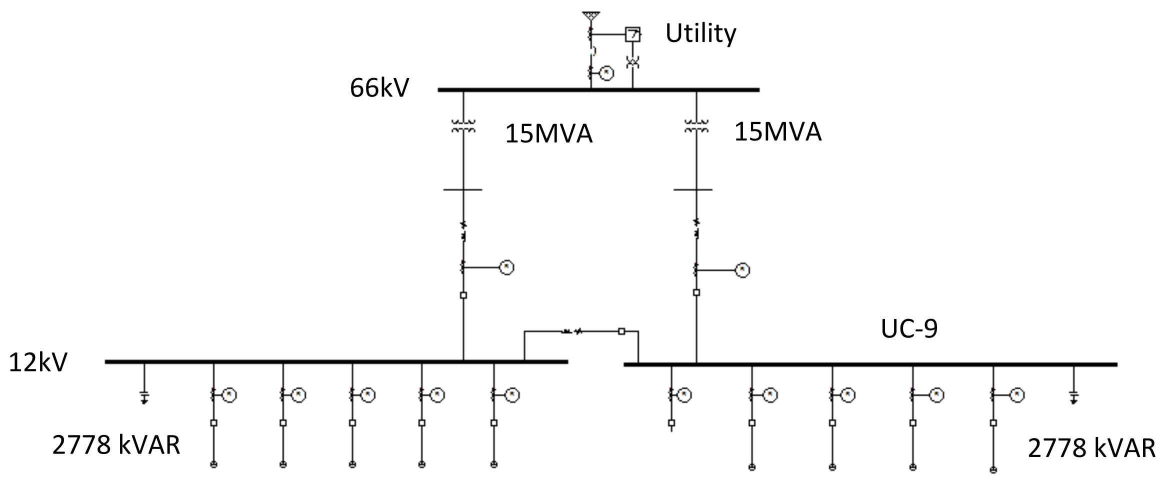

Figure 7: UCI Utility Connection and Main Switchgear.

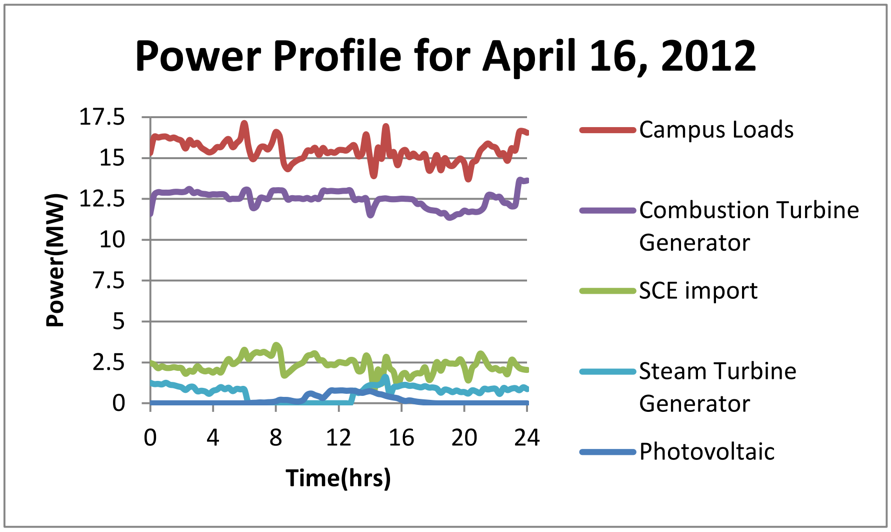

Figure 8: Campus Generation Profile for 4/16/2012.

2.1.4.2.2 Amonix CPV 7700

The Amonix installation and interconnection is located at the eastern side of the University of California, Irvine campus at 33° 38' 23.29" N, 117° 49' 30.33" W. The site contains two Amonix 7700 CPV systems with a combined peak output rating of approximately 113 kW. The record maximum AC power output was measured at 126.19 kW at 999.94 W/m^2 direct normal insolation (534 m^2 lens area), yielding an overall system efficiency of 23.63 percent. Each system contains a 21 x 12 mini-module array mounted on a two-axis tracker and a Solectria 7700 PVI inverter. The UC-9 branch circuit that connects the installation to the UCI microgrid also services the student recreation center, which represents an average load of approximately 300 kW. Data for this research was collected over the course of 443 days (June 5th, 2012 to Sept 5th, 2013) at a one-minute granularity from each CPV panel and at the points of common coupling of the inverters and the recreation center. An onsite weather station recorded insolation and meteorological data at the same sampling rate.

2.1.4.2.3 Additional UCI Solar Resources

In addition to the 113 kW Amonix installation, the campus hosted an additional 900 kW of flat-plate PV generation at 11 locations throughout the campus. The unique combination of a high PV penetration and on-campus generation allowed for detailed comparative studies on PV connected to microgrid circuits. Figure 9 and Table 1 summarize additional campus solar resources.

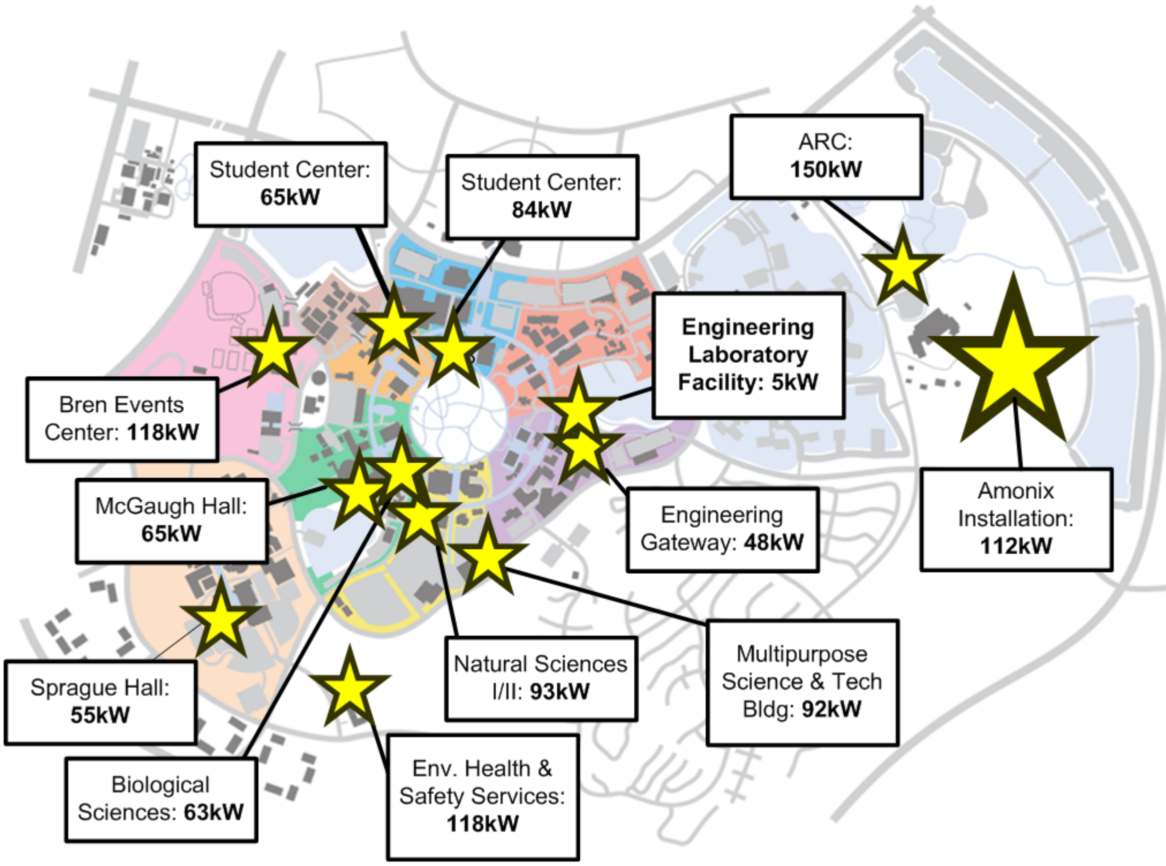

Figure 9: UCI PV Resources.

Location	PV Capacity (kW)	Circuit
Engineering Gateway	48	UC-9
Sprague Hall	55	UC-2 / UC-6
Biological Sciences	63	UC-1 / UC-6
McGaugh Hall	65	UC-8
Student Center 1	65	UC-6
Student Center 2	84	UC-6
Multipurpose Science & Technology	92	UC-1
Natural Sciences	93	UC-8
Environmental Health & Safety Sciences	118	UC-10
Bren Events Center	118	UC-3
ARC	150	UC-9

Table 1. Capacity of Additional UCI PV Resources.

2.1.4.3 Data Collection

2.1.4.3.1 Amonix Metering and Weather Station

The two Amonix systems were equipped with independent high-resolution power meters that collected voltage, current, real and reactive power, frequency, phase, and harmonic distortion measurements at a one-minute sampling rate. Current meters monitored the outputs of individual solar panel strings. An onsite meteorological weather station recorded wind speed, temperature, and insolation measurements. The data were collected by Amonix and then mirrored onto a FTP server for access by APEP researchers.

2.1.4.3.2 MelROK Metering System

To supplement data collection from the Amonix system, a campus-wide monitoring solution provided by MelROK was installed at UCI. The MelROK system consisted of 100 power meters placed at strategic locations throughout the UCI microgrid. Meter placement was selected to maximize visibility of the entire UCI microgrid. A comprehensive visibility study was conducted, taking into account relative building load, peak demand, and other factors. The data were archived into the EnergiView web-based application for storage, retrieval, and analysis. A secondary data feed (currently in development) will allow measurement data to be directly interfaced into the ETAP real-time engine.

2.1.4.3.3 Electrical Transient Analysis Program (ETAP)

Load flow simulations were conducted in ETAP to analyze existing and potential future CPV scenarios. In addition to traditional load flow simulations, the ETAP-Real Time software module was employed to provide real-time analysis capabilities. Available data sources from power meters, transformers, and generation equipment were combined into a unified data stream which was then linked to corresponding ETAP simulation inputs and used to evaluate microgrid operation. The UCI microgrid has over 140 building loads, 32 of which currently have online meters. Full coverage of the UCI microgrid was completed in 2013. Figure 10 is a screenshot of a load flow simulation of the Engineering Gateway building. Simulations allowed for determination of the maximum amount of PV that could be installed on each respective circuit while staying within voltage boundaries and taking into account intermittencies. In the future, it is expected that the ETAP UCI microgrid model will assist Facilities Management in operation of the UCI microgrid through interfaces such as those shown in Figure 11.

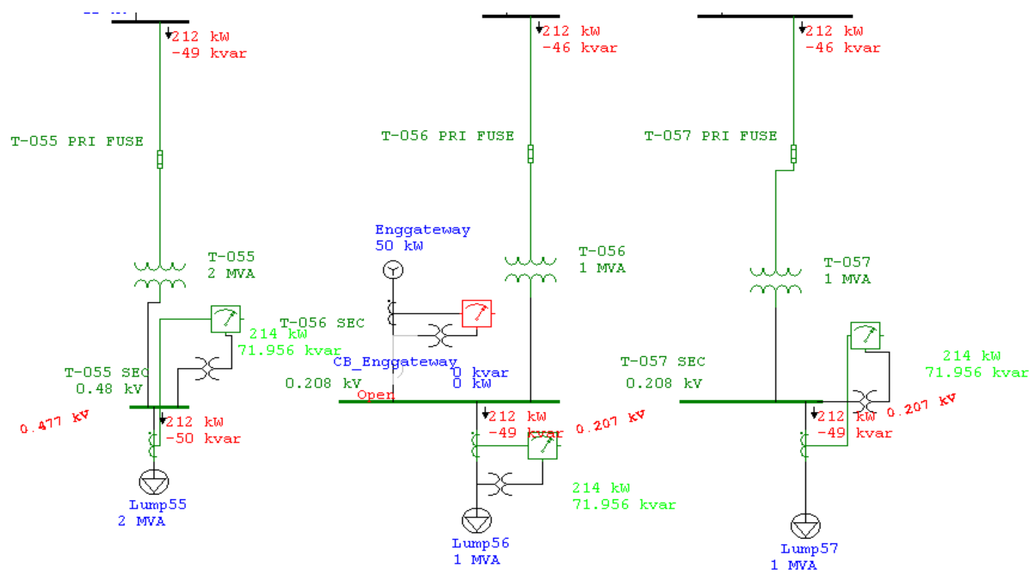

Figure 10. ETAP Online (Building: Engineering Gateway)

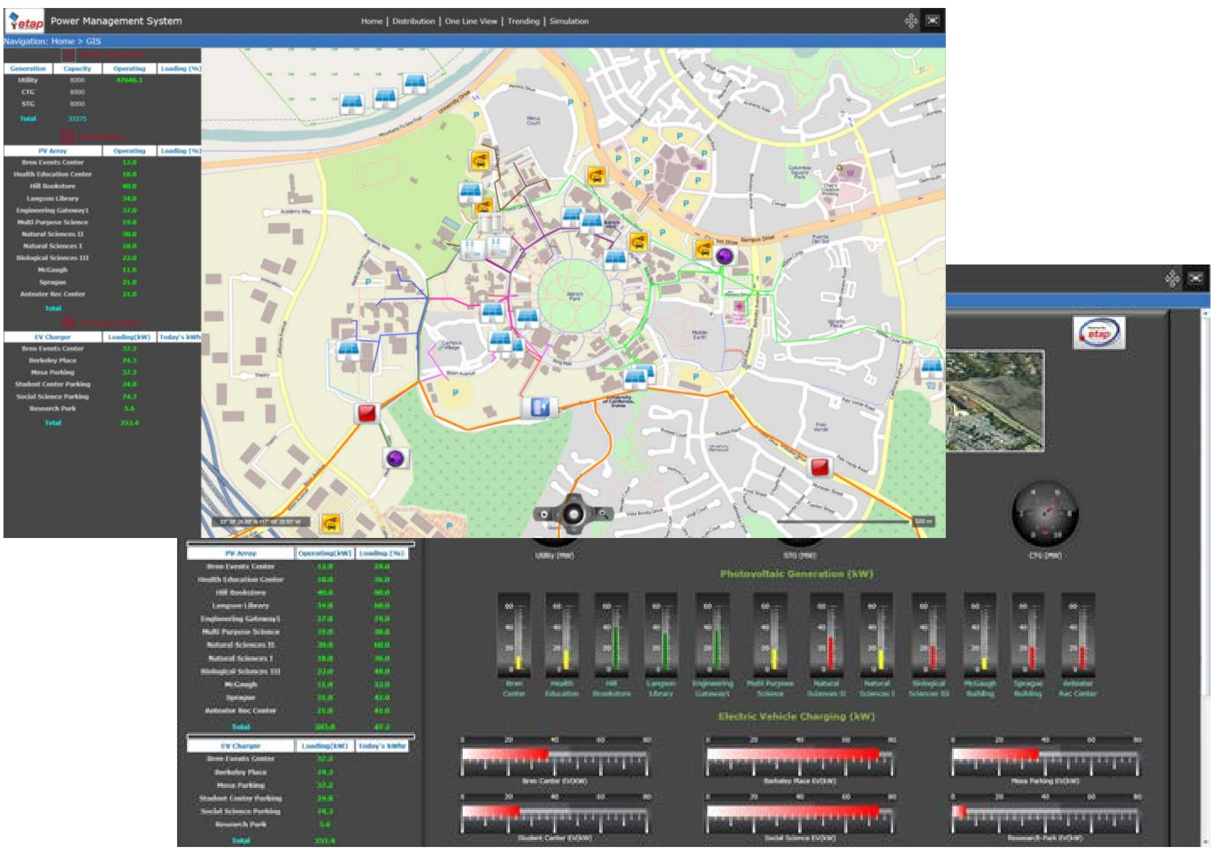

Figure 11. ETAP Software Interface for UCI Microgrid Operators.

2.1.4.4 CPV Performance

The intermittency of solar energy presented challenges to the integration of PV resources into the UCI microgrid. Characterizing the behavior of solar availability was crucial to maximizing the contribution of PV. Solar irradiance (direct normal, diffuse horizontal and global horizontal) and temperature data were collected over a period of 443 days, counted from an on-site meteorological station, and used to trend the solar availability at UCI. Figure 12 to Figure 18 illustrate the intermittent nature of solar CPV in a coastal region. Power production began when DNI levels exceeded approximately 300 W/m^2. Average system efficiency was measured at 23.3 percent. Ambient temperature effects were determined to be negligible.

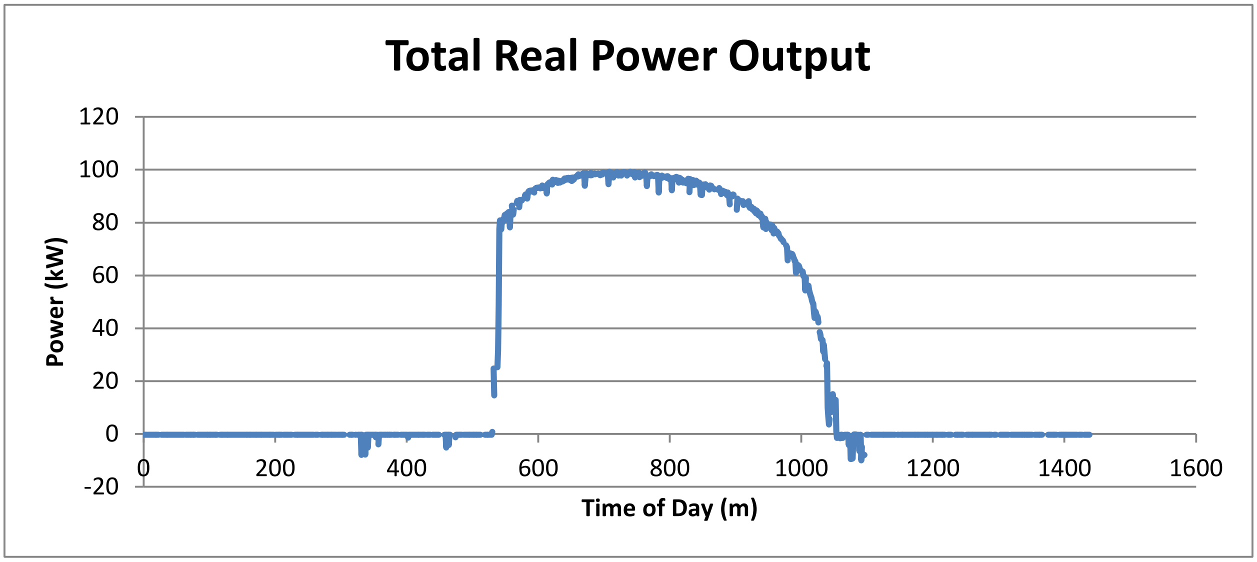

Figure 12. Typical Power Output Trend in the Absence of Intermittency.

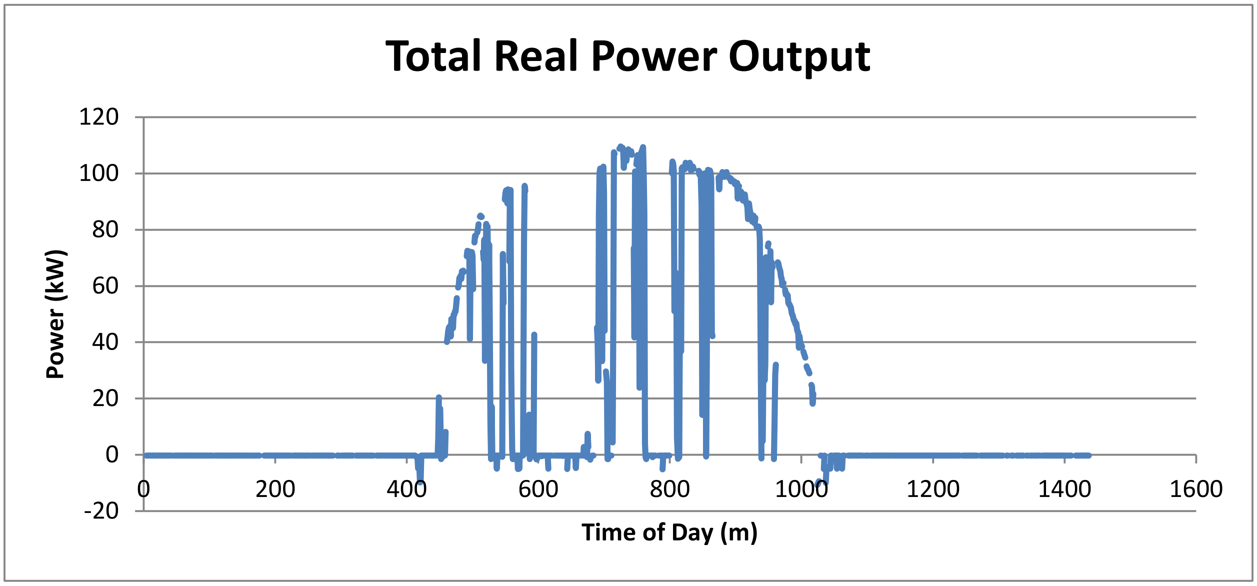

Figure 13. Typical Power Output Trend in the Presence of Intermittency Associated with Cloud Passage.

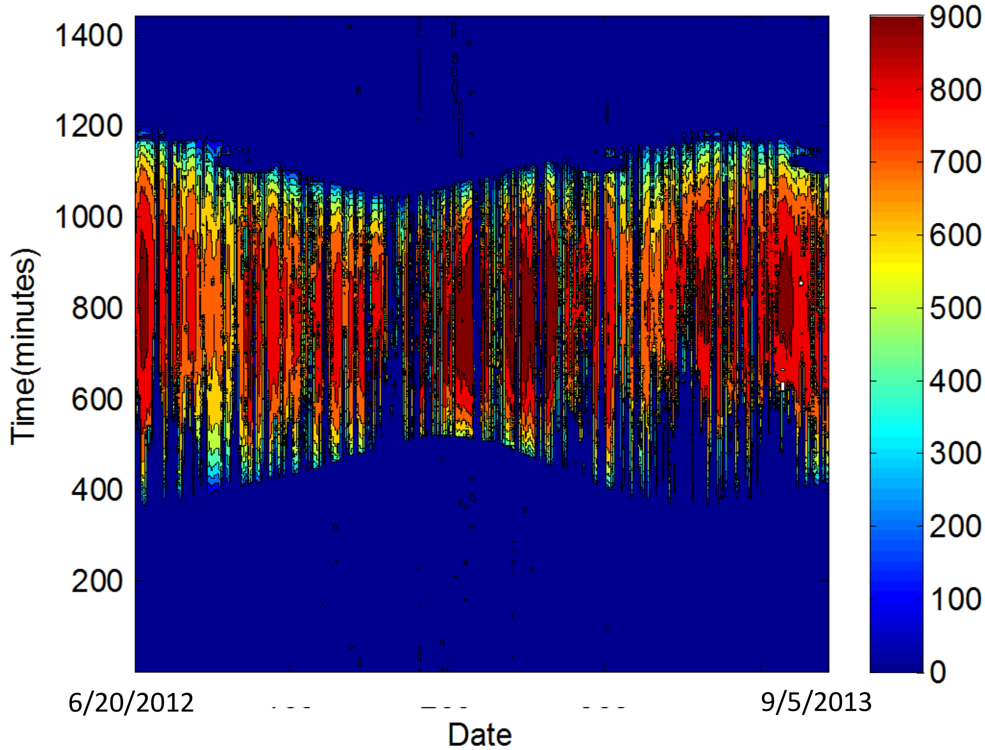

Figure 14. Direct Normal Irradiance from 6/20/2012 to 9/5/2013.

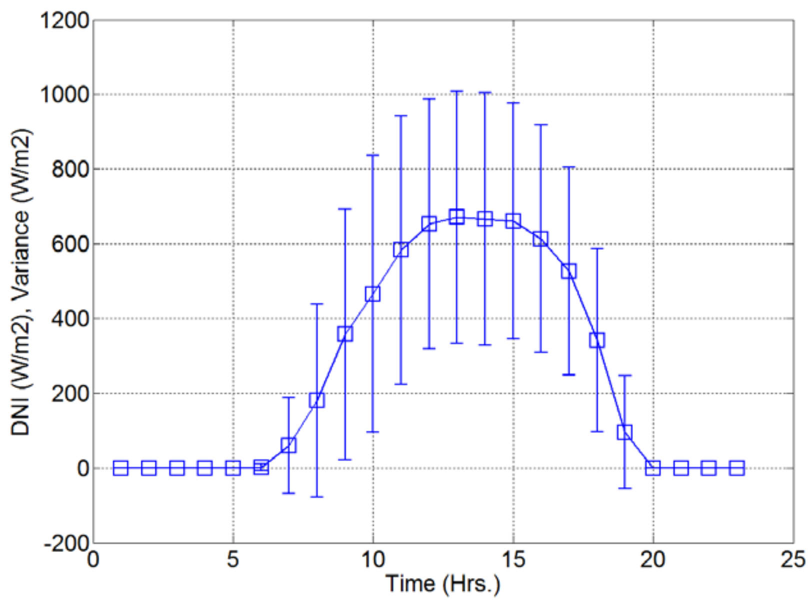

Figure 15. Maximum, Average, and Minimum Direct Normal Irradiance Values from 1/10/2012 to 5/31/2013.

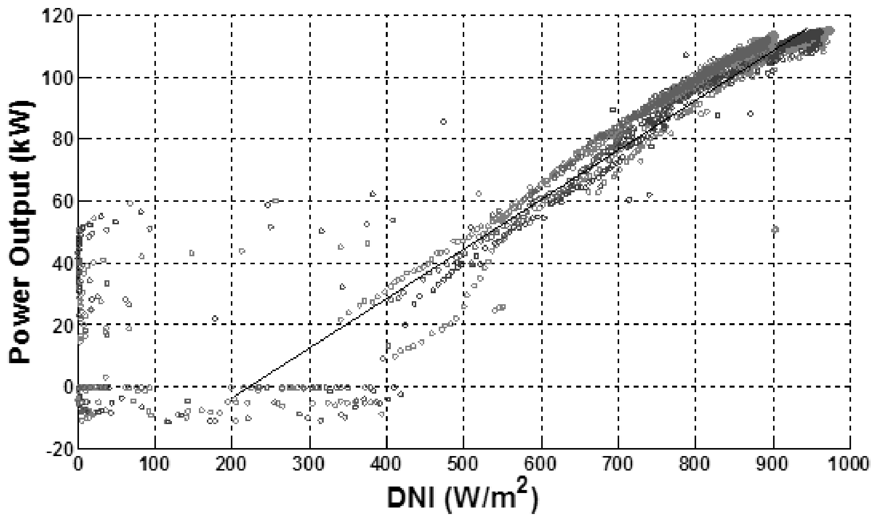

Figure 16: Power Output VS DNI.

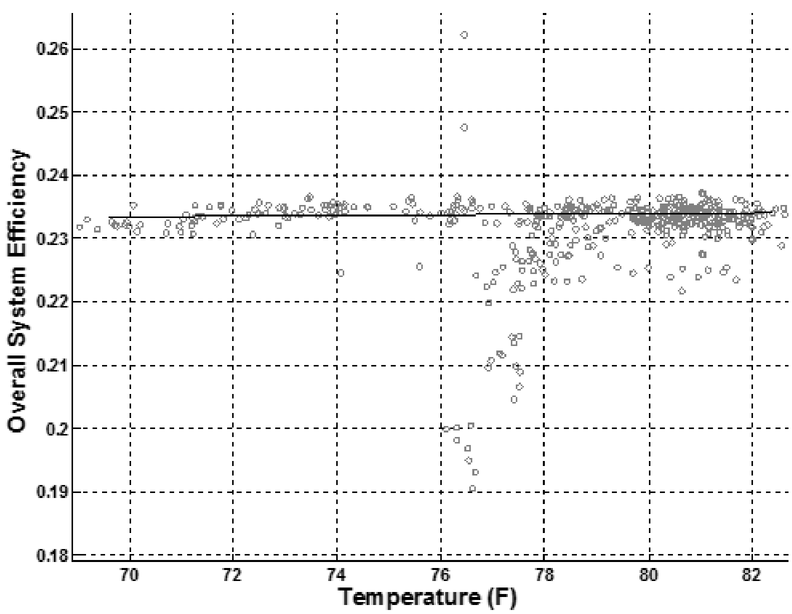

Figure 17: Overall System Efficiency VS. Ambient Temperature.

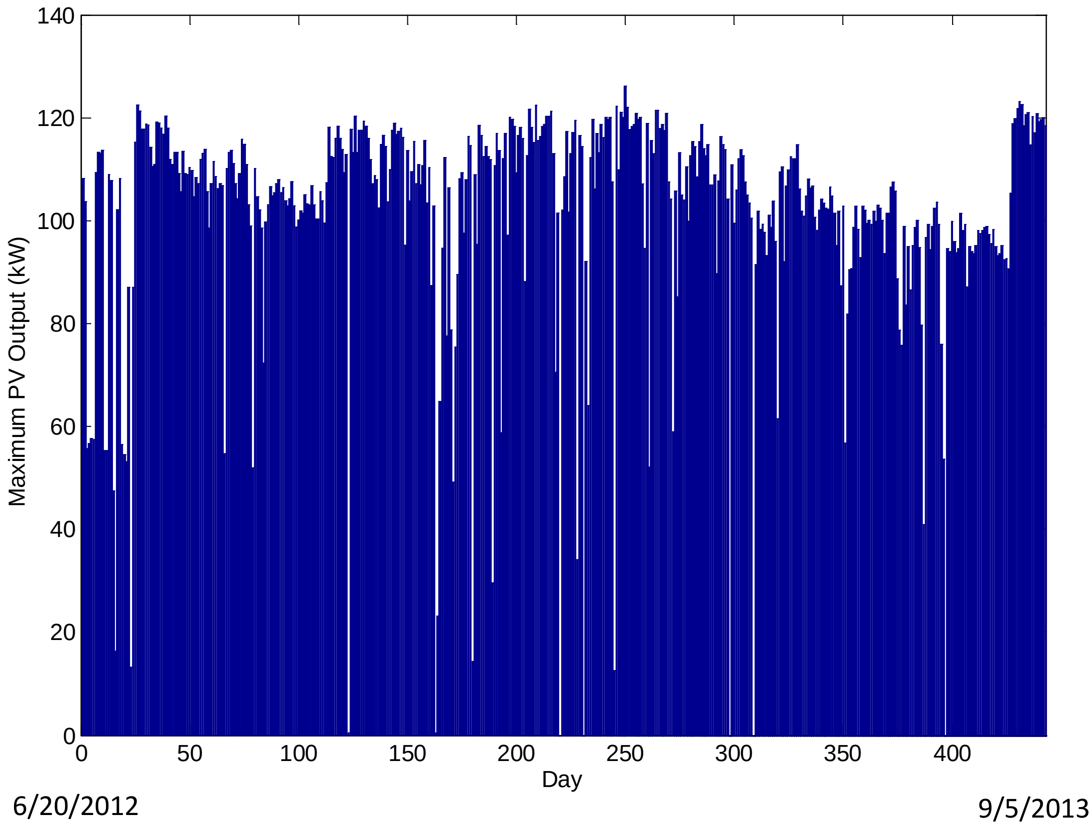

Figure 18: Maximum CPV Output from 6/20/2012 to 9/5/2013.

2.1.4.5 CPV Impact Assessment on UC-9 Using ETAP

The Amonix system was connected to the Anteater Recreation Center motor control center (ARC MCC) via 1100 feet of three 350 MCM[1] conductors in a 3-inch conduit. The ARC (see Abbreviations and Acronyms), in turn, was connected to the UCI substation switchgear via a 2 MVA 12 kV-to-480 V transformer (Z = 5%, X/R = 7.29) and 11,235 feet of cable (Z = 0.05078 /1000 ft, X/R = 1.482). Figure 19 shows the ARC/Amonix portion of the UC-9 one-line diagram.

[1] One thousand circular mils (cross-sectional wire area)

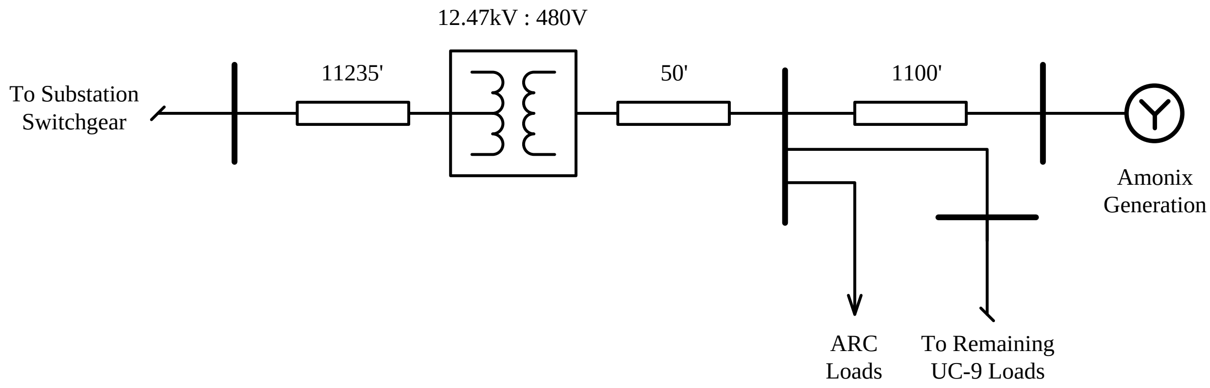

Figure 19: Amonix/UC-9 Oneline Diagram.

A load flow model was developed in ETAP. Baseline simulations were conducted and results were compared against field voltage measurements to verify the model. The ETAP model accepted substation voltage, ARC load, and Amonix power data as inputs, and outputs simulated voltage profiles of the ARC and Amonix busses. Due to the unavailability of direct 12 kV substation voltage measurements, the substation voltage profile was approximated by scaling the voltage profile measured at the Multi-purpose Science and Technology Building (MSTB), a nearby bus, to the 12 kV level. It was noted that throughout the UCI microgrid, recorded voltage profiles were nearly identical with the exception of a slight scaling factor, yielding the conclusion that any variation in 12 kV bus voltages were primarily due to utility fluctuations and not local effects. Figure 20 shows the voltage profiles of several UCI buildings on independent circuits. Additional 12 kV loads downstream of the ARC were also regarded as having negligible impact on local voltage profiles. In the UC-9 simulation, this included the Verano Place housing, Social Ecology, and Social Sciences loads. Voltage profiles downstream of transformer secondaries were, however, largely affected by local loads and generation. In Figure 21, measured voltage profiles at the ARC and at the Amonix terminals are shown. The local voltage rise seen at the Amonix terminals is attributed to the series impedance in the 1,100-ft cable connecting the panels to the ARC MCC. The voltage profile of the ARC MCC was strongly dependent on the substation voltage.

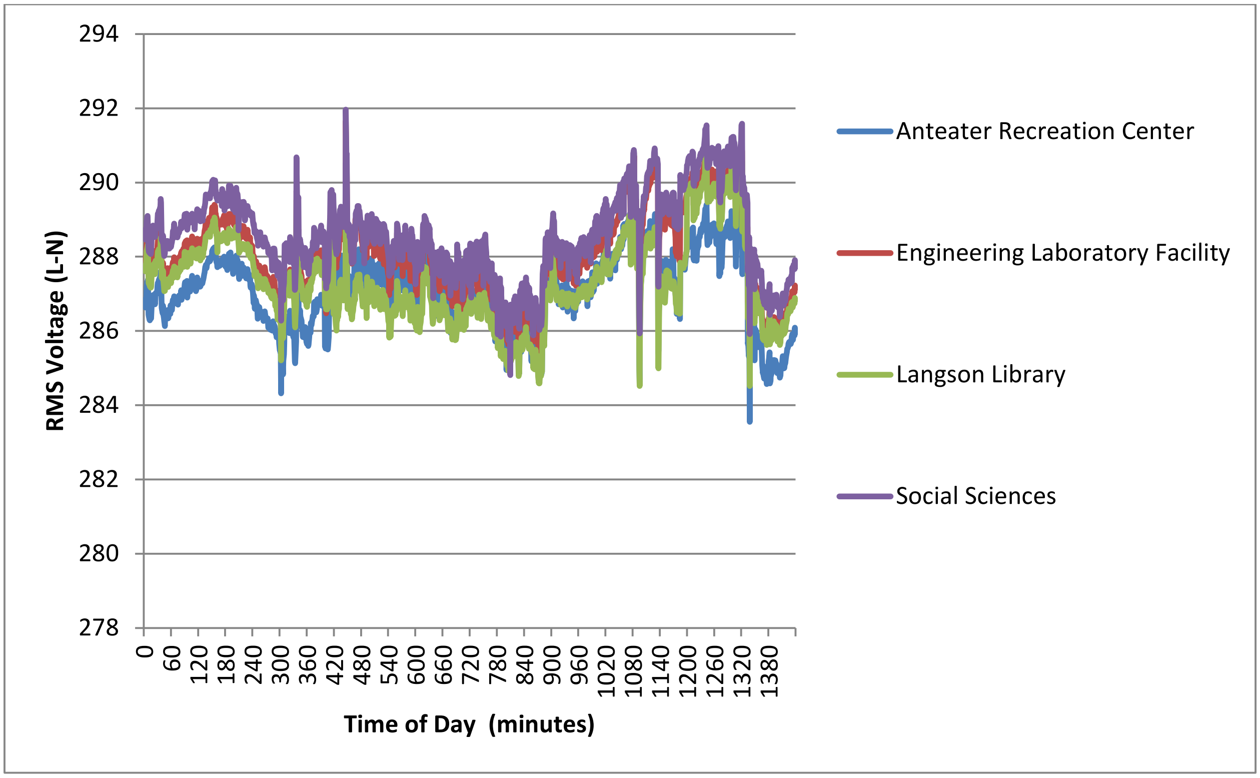

Figure 20: Voltage Profiles of Various UCI Buildings.

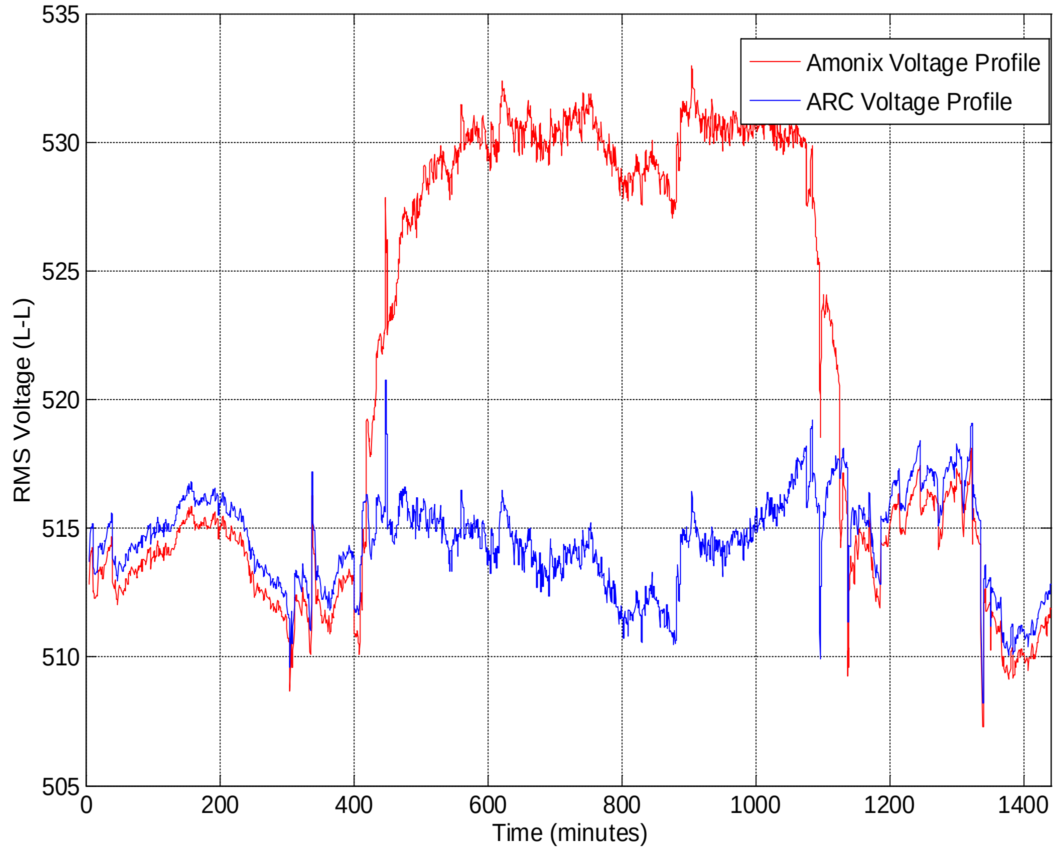

Figure 21: Amonix and ARC Measured Voltage Profiles. 8/28/2013.

Real and reactive power data were obtained directly from the MelROK system and entered into the model. ETAP simulations were then conducted to simulate varying penetrations of CPV on the UC-9 circuit. Comparisons of simulated vs. measured data are shown in Figure 22 and Figure 23.

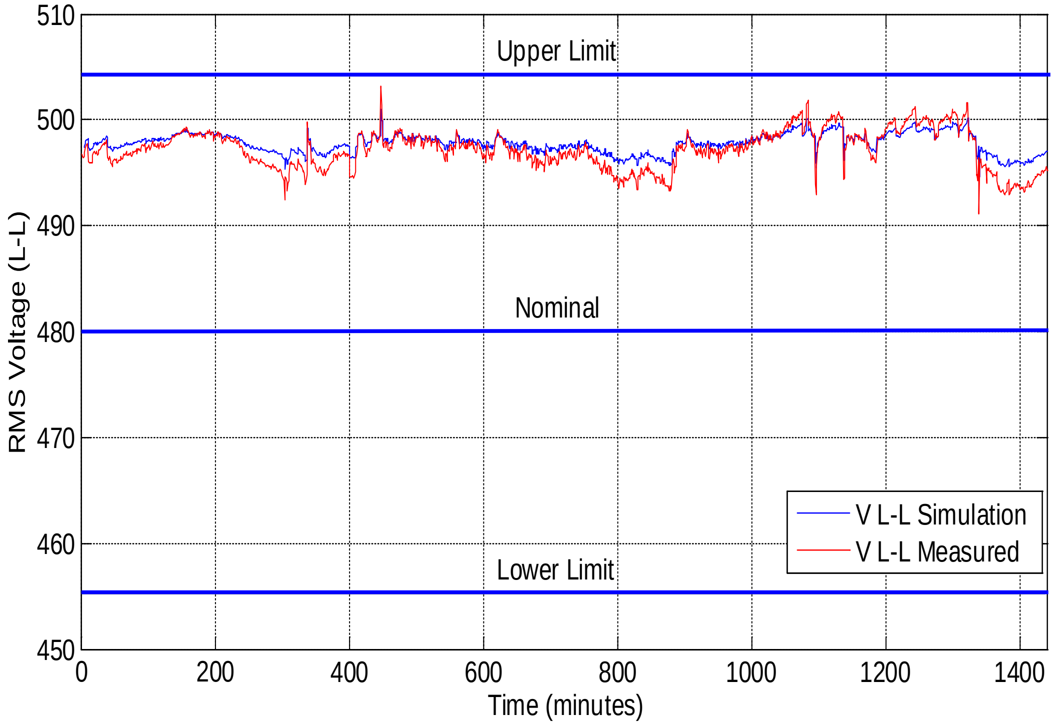

Figure 22: Baseline ARC MCC voltage profiles. 8/28/2013.

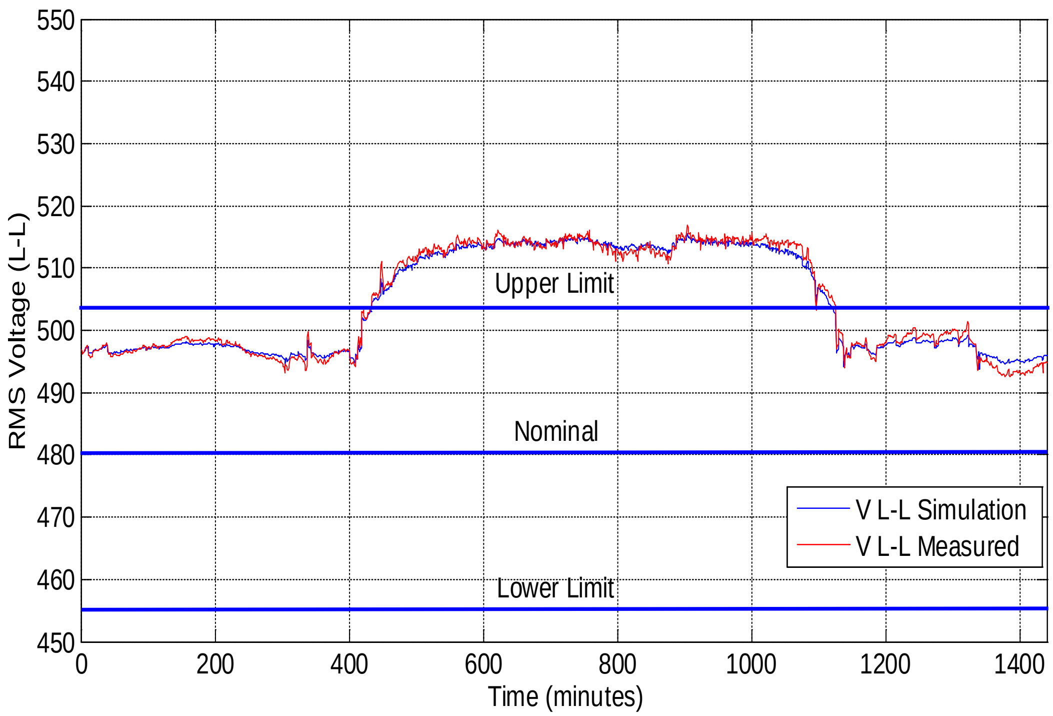

Figure 23: Baseline Amonix Voltage Profiles. 8/28/2013.

The addition of the dual Amonix CPV 7700 system resulted in significant load reduction on the UC-9 ARC circuit. At peak solar production, total load demand was reduced by up to 27 percent and reverse power flow would be achieved at approximately 3.5 times the baseline production (420 kW). Measured voltage profiles from the MelROK system showed a minimal voltage disturbance at the ARC bus, but a substantial voltage rise at the Amonix systems' inverter terminals. Additionally, above-nominal line voltages were noted throughout the UCI system (ANSI Range A utilization voltage limits are illustrated in Figure 22 and Figure 23). Though the voltage rise at the Amonix connection was due to local power injection, the high voltages at the ARC MCC and other UCI buildings were indicative of a campus-wide condition. Voltages increased at the ARC terminals due to power injection and decreased at the ARC MCC, due to reactive power effects which were attributed to the impedance between the ARC and the MCC, coupled with the unity power factor operation of the Amonix inverters.

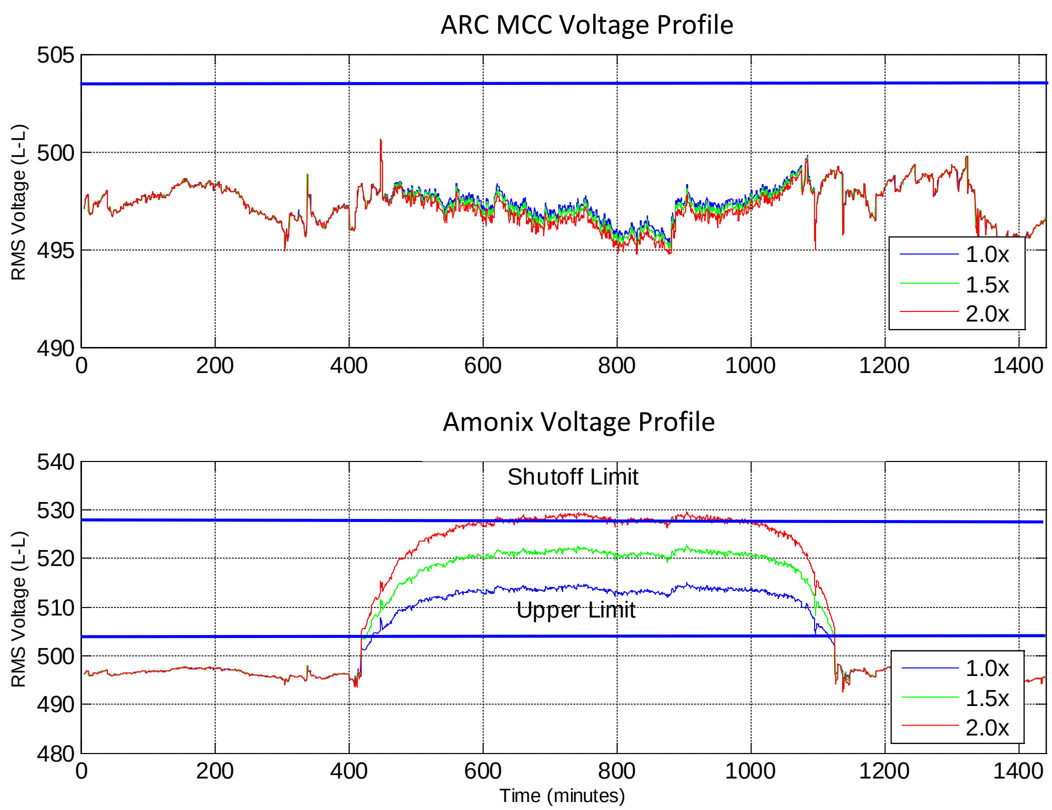

Figure 24. ARC and Amonix Simulated Voltage Profiles. 1.0x to 2.0x of Baseline Generation. 8/28/2013.

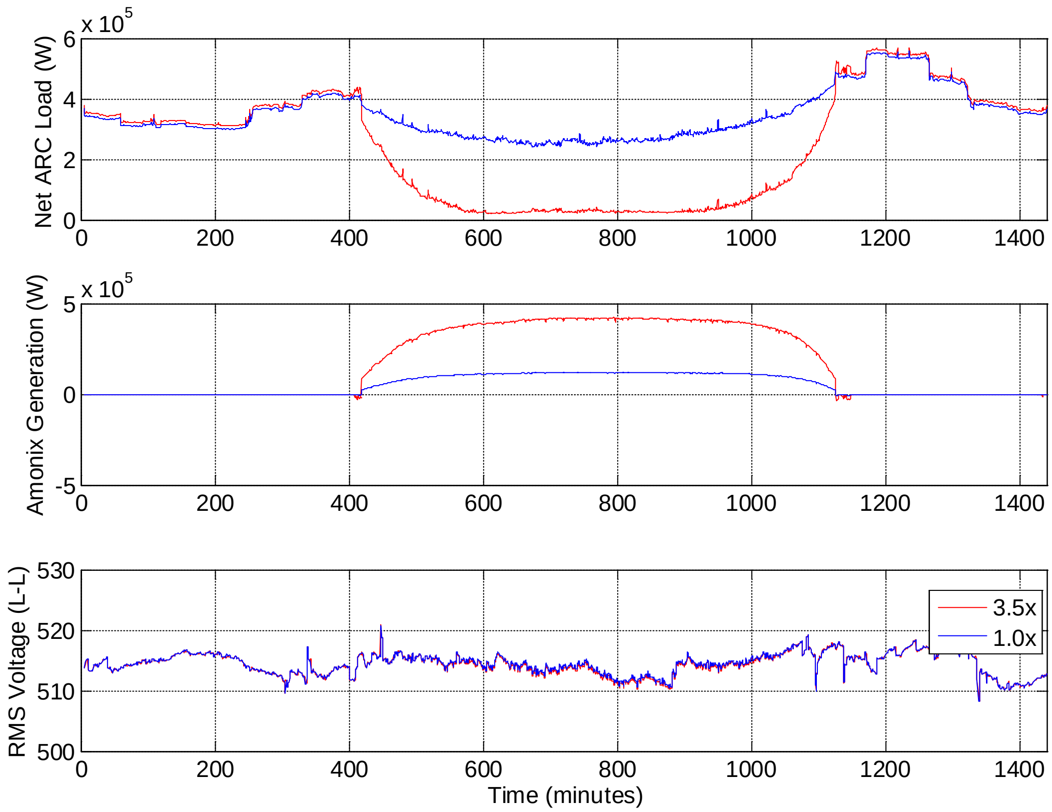

Figure 25: ARC MCC Reverse Power Flow Limit. 8/28/2013.

ETAP simulations show that a 120 kW (about 2 times baseline) *in situ* increase in CPV generation may be tolerated before inverter shutdown voltage limits are reached. Inverter safety limits (Figure 24) are programmed at -12%/+10% of nominal line voltage (422.4 to 528 V for 480 V L-L). The 350 MCM conductor was rated for an ampacity of 380 A, and allowed for approximately a 3.3 times baseline generation increase before current limits were reached. Local CPV power injection at the 480 V level up to these limits produced negligible effects at the ARC MCC, as shown in Figure 25. The injection of higher (up to 10 times baseline) power directly on the 12.47 kV bus upstream of the ARC MCC also produced negligible voltage effects, as shown in Figure 26.

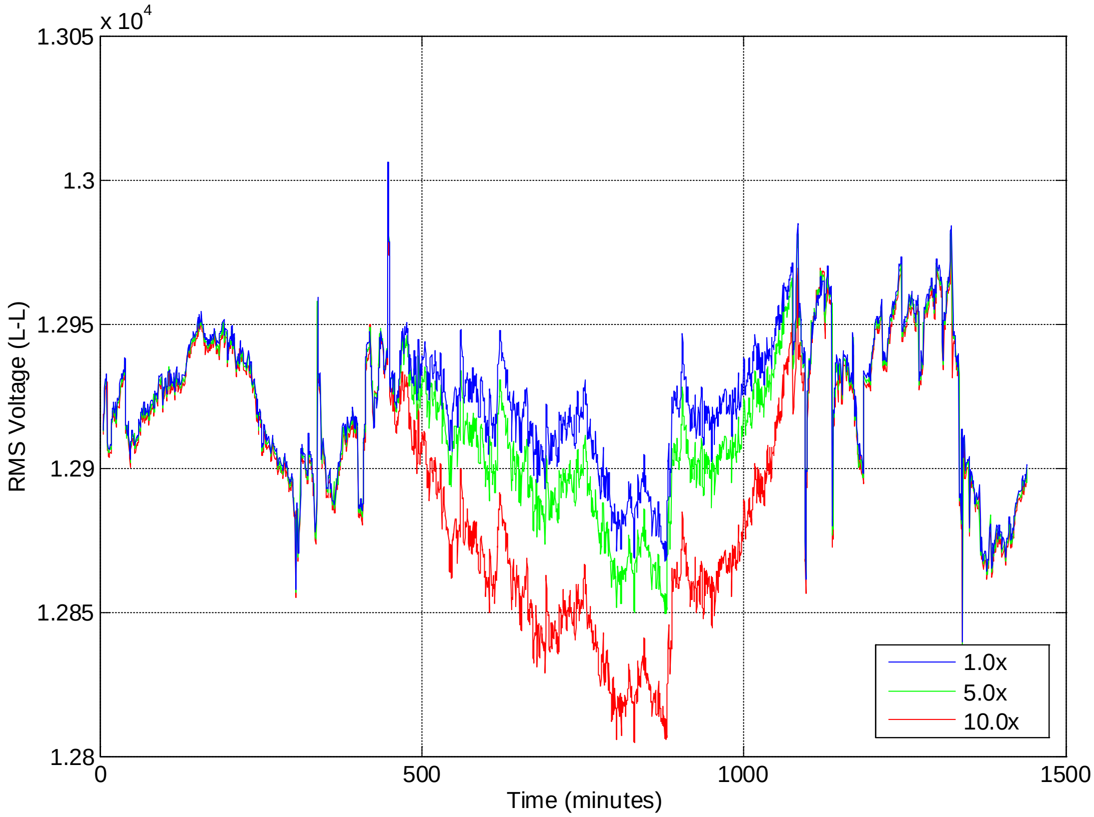

Figure 26: Upstream 12.47 kV Bus Power Injection Voltage Profile Effects. 8/28/2013.

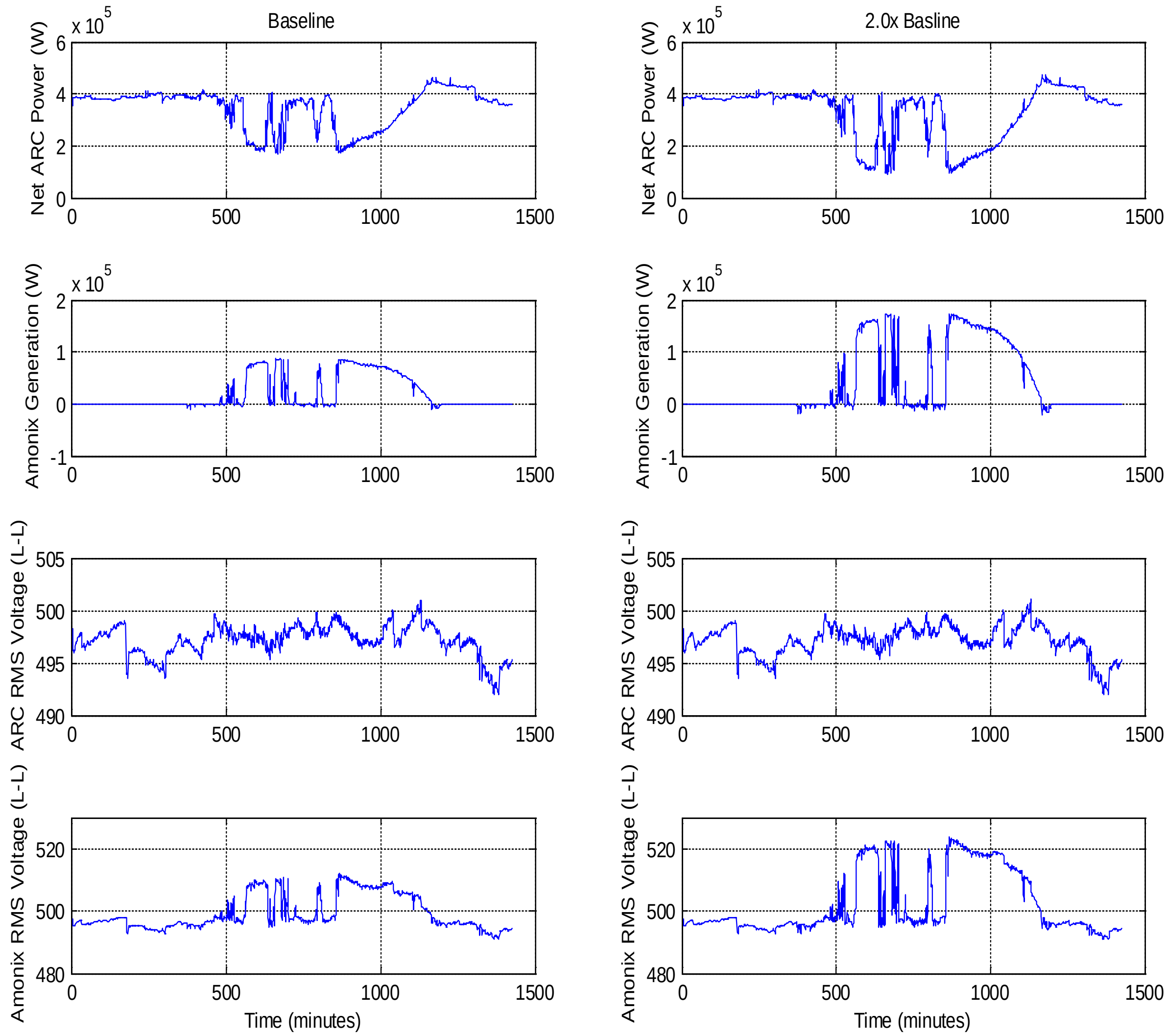

Figure 27: Simulation Results for a High Demand Day with Intermittent Generation. 7/5/2013.

Figure 27 shows simulation results for relatively high ARC load coupled with intermittent PV generation. The ARC MCC voltage profile tracked substation voltage, while the Amonix terminal voltage was dependent on real power injection. PV intermittency resulted in negligible effects beyond the ARC MCC bus.

2.1.5 Conclusions

The installation of 113 kW Amonix CPV on the UCI campus was concentrated on one circuit: UC-9. The 113 kW power plant consisted of two panels; these panels were monitored for 443 days at one-minute resolution, and monitoring continues. The average CPV system efficiency was measured to be 23.3 percent. The collected data were then used as input to load flow simulations using ETAP software. The circuit model developed in the ETAP software simulated the UC-9 circuit. This model was used to investigate the CPV penetration limits on the UC-9 circuit. Once the installed capacity of the CPV on the UC-9 circuit reached 420 kW, reverse power flow began to occur. However, before reverse power flow occurred, voltage limits at the Amonix bus were exceeded with only 240 kW installed CPV capacity. The voltage on the 12 kV side was only minimally affected by the CPV penetration. When the CPV capacity reached ten times the baseline installed capacity (about 1,200 kW), effects on the 12 kV side voltage become noticeable.

2.1.6 Coordinate with RESCO and SCE

With a grant from the California Energy Commission (CEC) for Renewable-Based Energy Secure Communities (RESCO), APEP developed an energy infrastructure (electric power, transportation, waste, and building) roadmap for the UCI community and a generic roadmap for California communities which outlines the criteria by which to maximize the deployment and utilization of renewable energy resources while satisfying reliability, enhancing and sustaining power quality, and minimize the levelized cost of electricity (LCOE). The roadmaps were based on pilot project experience, energy management analysis, and cost minimization. The CPV system data were relevant to both distributed and utility scale desert installations. Further, models of the UCI central plant, including a 13.5 MW turbine, and 8.4 million gallon cold water thermal energy storage tank were available for Subtask 2.3 of the RESCO project.

In addition to grid interconnection issues, the RESCO initiative evaluated the integration and energy management of solar technologies at both the distributed and transmission level. Particularly, APEP developed a set of tools to evaluate the deployment and operation of energy systems at both the transmission and distribution level to support increased penetrations of renewables.

Tasks 4a and 4b from the RESCO grant were supported by this CSI project. In completion of task 4b, a site was selected and prepared, and two Amonix concentrator solar photovoltaic (CPV) panels were installed. In support of task 4a, data were captured and archived regarding the operation of the panels.

In addition to the operation and performance of the panels, UCI's RESCO roadmap considered lessons learned during the contracting and installation periods for the CPUC grant. Understanding the effects from an operation point-of-view was the main goal, but understanding the challenges with permitting and installing a system like this was also very important.

Installation and analysis of these panels proved to be highly beneficial to the development and refinement of the UCI RESCO roadmap. As part of the RESCO program, the opportunity to improve system performance and reduce the system operating costs of UCI's central power plant by reducing the minimum electrical import was explored. Currently, the campus must import a specific percentage of its demand; otherwise, the gas turbine at the central plant trips off. Thus, to prevent trips, enable greater renewable capacity, and maximize the central plant's efficiency (higher load points yields higher efficiency), it was highly desirable to reduce or remove the minimum import constraint. This involves changing out equipment at the campus substation, which allowed for accidental export of electricity. If the cost of changing out the limiting equipment is less than the value of reducing the minimum import, then the campus should proceed with this activity.

2.2 Task 2: CPV Lifetime and Reliability Modeling

2.2.1 Background

Reliability is a major focus today for both PV and CPV as solar deployments routinely exceed tens of GW throughout the world. Reliability and lifetime validation is essential to secure major investment and financing of future CPV system deployments.

2.2.2 Objective

The objective for this task was to conduct accelerating testing in environmental chambers, to correlate the test data with field data, and to develop a method to evaluate the reliability and lifetime of CPV technologies.

2.2.3 Approach

Highly-Accelerated Lifetime Tests (HALT) began with using existing CPV qualification standards, since they validate initial operation in the field, typically assumed to be the first couple of years. The international CPV qualification standard (IEC 62108) includes environmental chamber testing requirements, for example, that cycles components for hundreds to thousands of cycles between high temperatures (e.g., 110^{o}C) and low temperatures (-40^{o}C), along with outdoor testing for several months. The HALT approach provided an alternative to fielding a new technology for 25 to 30 years before reliability and lifetime could be established. The HALT approach began with increasing qualification chamber testing by multiples of 2, 3, 4, etc., while observing “wear out” failures, separate from early “infant mortality” failures associated with inadequate design or poor quality assurance during manufacturing. Details of infant mortality failures, while proprietary to Amonix, were shared with NREL under a Cooperative Research and Development Agreement (CRADA) funded by Amonix and supported by this CSI RD&D award.

Amonix conducted HALT studies on cell packages based on IEC 62108 thermal cycling, and damp heat and humidity freeze qualification tests. Amonix shared its chamber failure data with NREL. See Figure 28 for examples of chamber failures. Details of the HALT studies are proprietary, but the results are summarized below.

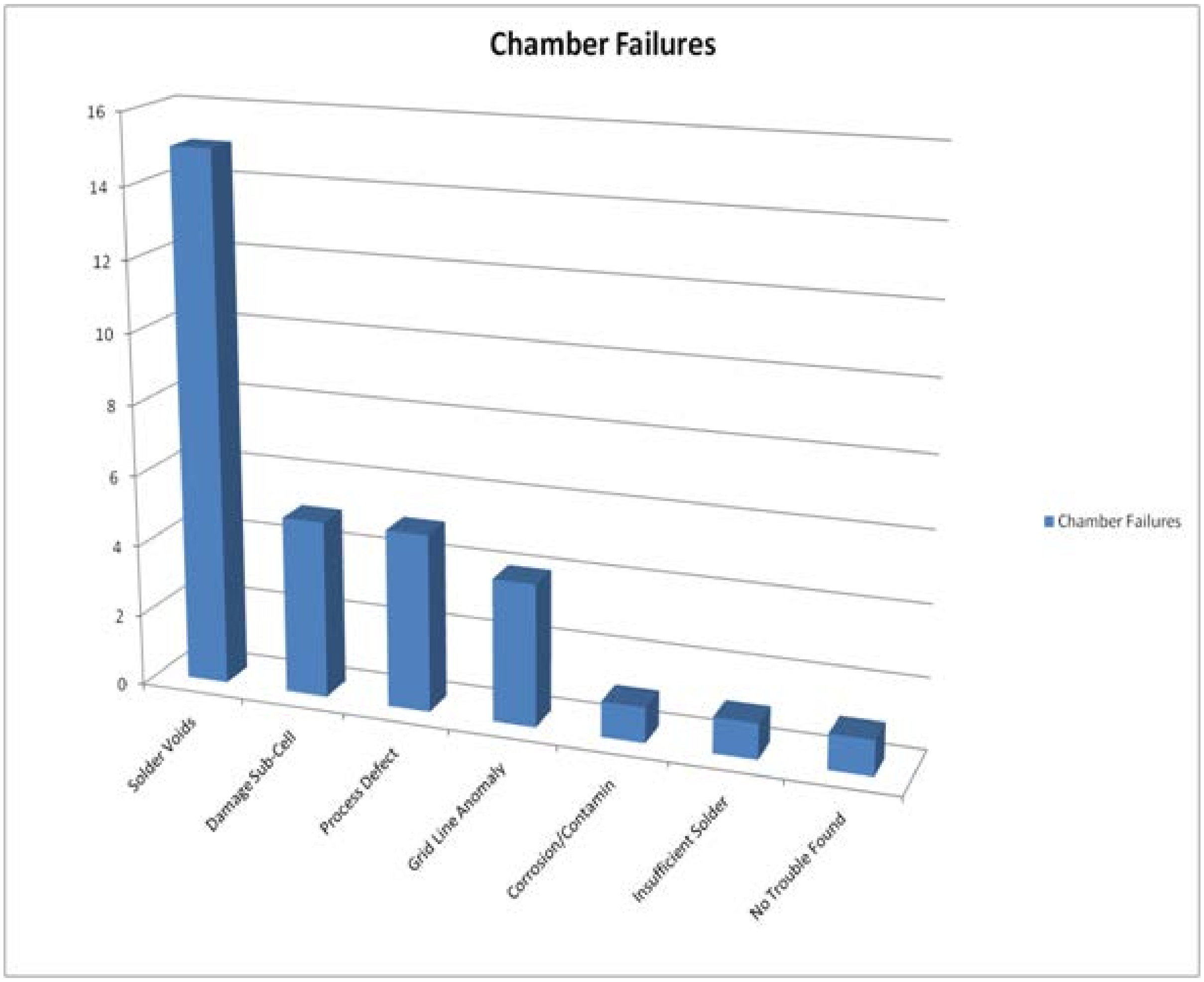

Figure 28: Number and Type of Chamber Failures

2.2.4 Results

2.2.4.1 Early Life Failures

Over the last two months of 2011 and the first two months of 2012, early life failures were increasing. The failures were found to be mostly Wet Insulation Resistance (WIR) related. See Figure 29. It was subsequently found that the RTV silicone used in the package process was inadequate to withstand the process design temperatures. A new silicone was identified and implemented.

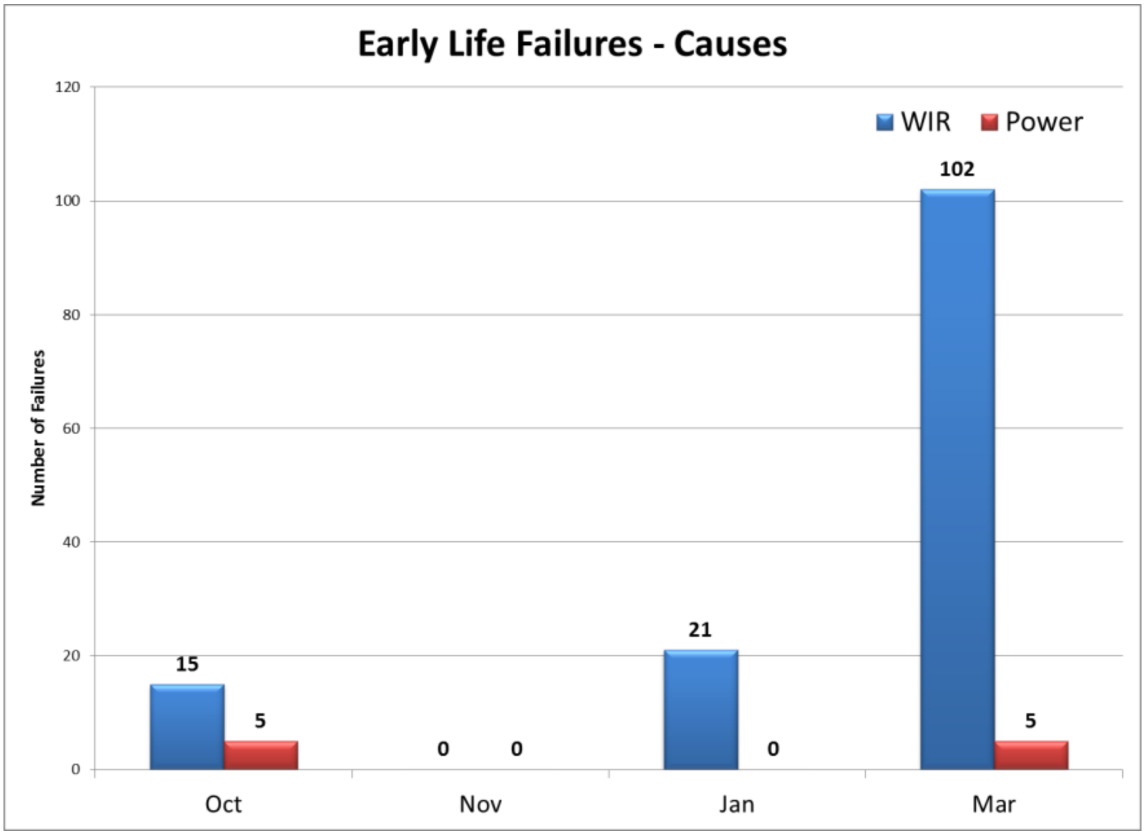

Figure 29: Early Life Failures were primarily due to wet insulation resistance and were corrected by a different silicone.

Four months of HALT studies for the IEC 62108 thermal cycling test, damp heat test, and humidity freeze test showed no failures for thermal cycling and manufacturing-related failures for the damp heat and humidity freeze testing. In summary, environmental chamber HALT failures were predominately related to manufacturing and were deemed early life failures, and not intrinsic life or “wear out” failures associated with long-term durability.

2.2.4.2 Correlate Field Data with HALT

The approach for this subtask was to document module failures during field tests of Amonix systems in order to correlate failures observed by Amonix with NREL HALT studies. In order to increase the probability of observing early failures that may portend longer-term failures, Amonix collected data from its 2011 field installations in California, Nevada and Colorado, followed by additional input from the UCI systems. Table 2 below provides highlights of the collected data for two different cell packages.

Date In Service	Pkg Type	Fail Mode	Fail Location	Type Of Test	Failure	Date Removed from Service
4/19/11	Berquist	Unknown	Nevada	Field Failure	Thermal Runaway	4/22/11
3/31/11	Berquist	Unknown	RMA-114/Solar TAC	Field Failure	Package Void	4/07/11
3/31/11	Berquist	Unknown	RMA-115/Solar TAC	Field Failure	No Trouble Found	4/07/11
3/31/11	Berquist	Unknown	RMA-116/Solar TAC	Field Failure	Package Void	4/07/11
3/31/11	Berquist	Unknown	RMA-117/Solar TAC	Field Failure	Insufficient Solder	4/07/11
3/31/11	Berquist	Unknown	RMA-118/Solar TAC	Field Failure	No Trouble Found	4/01/11
2/11/11	Ceramic	EL Anomaly	UNLV	Field Failure	No Trouble Found	2/17/11
2/22/11	Berquist	Unknown	RMA-129/Solar TAC	Field Failure	Mfg.Process Defect	2/23/11
12/23/10	Berquist	Open Ckt.	Cal Poly (CPP)	Field Failure	Cracked Die	1/28/11

Table 2 Electrical field failures for two types of cell packages, known as Berquist and Ceramic. Each failure resulted in lower cell electrical performance and, if the analysis identified the trouble, was correlated with a specific electrical failure mechanism.

Failure analysis is the process that determines the root cause of the failure. Each failure was verified and then analyzed to the extent that the cause of the failure and any contributing factors could be identified. The analysis methods used ranged from a simple investigation of the circumstances surrounding the failure to a sophisticated laboratory analysis of all failed parts. Failure analysis began once an event report was written and sent to the Reliability and Quality Department. It ended when the Failure Analysis team sufficiently understood the root cause so the Quality Department could develop corrective actions.

The Failure Analysis Process included:

1. Review, in detail, the field service reports, or Level I Failure Analysis Reports.
2. Capture historical data from the database of any related or similar failures.
3. Assign owners for action items.
4. Obtain the failed items for the Level II Failure Analysis.
5. Perform a root cause analysis or investigation.
6. Write a failure analysis report summarizing the root cause findings.

All reports were kept in a database for reference of failure analysis investigations in the future.

2.2.4.2.1 Failure Analysis at Amonix Field Installations

Table 3 shows an example of a Failure Analysis Monthly Summary for the examinations that AMONIX's Failure Analysis Department performed for one month. This example shows failures found for both modules and cells at Amonix projects located in California, Arizona, New Mexico and Colorado. The Amonix R&D engineering and reliability engineering (REL ENG) departments in Seal Beach, California requested some of the analyses. Discussions following the table summarize the data found during these examinations.

FA No.	Failure Mode	Failure Mechanism	Customer/Site
FA2012-030	N/A	N/A	R&D ENG.
FA2012-031	Module Leakage	Module Seal Fracture	REL ENG.
FA2012-032	Module Leakage	Module Seal Fracture	REL ENG.
FA2012-033	Not Specified	N/A	R&D ENG.
FA2012-034	N/A	N/A	N/A
FA2012-035	N/A	N/A	N/A
FA2012-036	Low Cell Performance	TBD	UASTP (Arizona)
FA2012-037	Low Cell Performance	TBD	JUWI (California)
FA2012-038	Low Cell Performance	TBD	HATCH (New Mexico)
FA2012-039	Cracked Lenses	TBD	SolarTAC (Colorado)
FA2012-040	Burnt Cell Packages	TBD	ALAMOSA (Colorado)

Table 3 Example Failure Analysis (FA) Monthly Summary.

A total of 11 examinations were performed in one month. As a result of these 11 examinations, there were a total 187 samples that underwent failure analysis testing. The most common failure mechanisms were insufficient thermal contact for the cell packages (which included recessed substrates, improper torque, flashing issues, etc.), module seal fractures, and module moisture intrusion.

The extensive review of field data at all of Amonix projects installed in 2011 concluded that almost all early failures were associated with issues of quality assurance and manufacturing process compliance. This subtask then focused on field data from the two UCI systems. One system was an early 53-kW unit moved from a previous installation in the Arizona Public Service territory, which came to UCI with some "mileage" on it. The second system was a 60-kW system with 7,560 solar cell packages prepared especially to study the failure of solder contacts to the solar cells having different percentage voids. A void is an incomplete area coverage of the solder on the solar cell's back contact.

2.2.4.2.2 Failure Analysis at UCI Installation

The Amonix 60-kW system at the UCI campus was deployed in early 2012 with packages containing varying ranges or 'bins' of solder void percentages. The goal was to better understand the effects of die attach void areas in the Amonix system under fielded conditions.

There is a thermally-based threshold at which a difference in temperature between finite areas of a multi-junction solar cell can set up a thermal feedback mechanism that will eventually damage the cell. Voids in the die attach are a major contributor to this effect. A significant amount of work has been done in the past to understand this problem. This work was done to further that effort, exploring an optimized value for the Amonix system; this failure mechanism is non-linear, multi-faceted and difficult to model. More importantly, field conditions contributed to a large number of factors that were not as easily captured in laboratory tests, but which could contribute to this problem. DNI levels, concentration level, alignment, reflective secondary optical element flux enhancement, void size, void shape, and void position were a few other factors.

The current manufacturing specification established at Amonix contains an *overall void percentage* and a *single largest void percentage*; the single largest void percentage is of the most concern. The field test theorized that the failure from thermal runaway occurs in a short period of time, assuming that worst case conditions existed. Therefore, given a long enough exposure with a large universe of cells, all of the variables germane to this problem would come together to create the worst case conditions and demonstrate a statistically significant threshold below which failures would not occur. This procedure provided an optimized manufacturing specification for Amonix.

Amonix historical test data on the void percentage question are described below. Three tests were done by Amonix. A related test done by NREL on a similar CPV cell package was also included for thoroughness.

A thorough test must include a wide range of variables that all contribute to an optimized value. These variables include:

- The void shape, or length of thermal path, is not typically captured by a generic percentage.
- Void location may be important.
- The point focus primary lens and the reflective secondary optical element for the Amonix system may lead to solar flux densities larger than what might be expected from the geometric concentration ratio alone, especially at the edges under normal alignment variation.
- DNI levels (and to a small extent ambient conditions) may also play into this problem.

The initial tests done below are progressively more inclusive, but only Test 3 was expected to capture all of the potential variables to set a specification robust enough for a 25-year threshold.

Test 1: Single void bins for single package test on the outdoor single package tester (600X-900X). A statistically significant amount of packages of various void percentages were placed on-sun for a short amount of time to determine any infantile failures due to thermal runaway. This was done with two different lens sizes representing 600X and 900X geometric concentrations.

Potential deficiencies:

- Well-aligned and short exposure time only does not capture non-uniform image movement on the cell.
- Relatively small number of packages that does not represent normal manufacturing variations in shape and position.

Test 2: Receiver plate level testing on the outdoor module tracker (600X-900X). Identically-sized bins were put on a full receiver plate, and the plate was placed on an outdoor tracker for several hours to capture normal tracking variations over the day. Longer exposure time and normal tracking variability were accounted for.

Potential deficiency:

- Limited number of packages to obtain the full variation of void size and positions.

Test 3: Array level testing using packages of varying percentage voids at a higher concentration and longer exposure (7700-60 @ 600X). Relatively large universe of cell packages (7,560) captured a wide variety of voiding positions and shapes, along with long exposure times with normal tracking and DNI variability. This was the purpose of the Amonix 60-kW system at UCI.

Test 4: NREL modeling and confirmation of single void percentage. NREL developed an FEM model.

Results of these tests are summarized as follows:

- Test 1 uncovered no single package failures under either concentration level with short term exposure up to the largest void tested.
- Test 2 also showed no difference under either concentration level for two receiver plates (30 packages each). This lack of failures under 900X suggested that testing at a lower concentration level of 600 times Test 3 would not yield any new information.
- Test 3 results are described in detail in the next section.
- NREL's study (Test 4) approached the thermal runaway problem with an FEM on a typical multijunction cell, and then verified the model through empirical testing. The results show a runaway at 3.5 A/cm^2 with a 2.5 area percent void, corresponding to on-sun failure.

2.2.4.2.3 Solar Cell Void Testing at UCI Installation

More than 5,000 cells from different single void bins ranging from 0.5 percent to 1.75 percent were placed at random in a system installed at the UCI campus. They were allowed to operate for a full year before diagnostics on any failures occurred. The number of packages of each bin varied somewhat due to the number available from manufacturing yield. The goal was 1400 packages for each bin, and this was met for the bins above 1.0-1.75%. The bins below 1% had less than 1000 packages each, but the minimum number of packages was 854. This is deemed to be acceptable in retrospect for two reasons: 1) the concern over bins with voiding of less than 1% did not materialize. 2) 854 packages were a statistically significant number.

After a year, a filtering system was used to diagnose failed packages using ”top down” data from module, string, and plate performance. The assumption was that a cell which failed due to thermal runaway would result in a zero voltage cell. Measurements of the module currents and string V_{oc} were taken. Lower performing units were further explored down to the plate level and then failed packages were returned to Seal Beach for analysis. Failed cells were categorized by void bin, and failures attributable to solder voids were established as a worst-case threshold.

Fifty-six string V_{oc} measurements were taken to find low voltages (open circuit conditions). Each MegaModule® string set was taken within one minute, although different module readings may have been affected by changes in ambient conditions. The data (Figure 30) showed only a few relatively low V_{oc} strings, and one string (on MM 2) at zero volts.

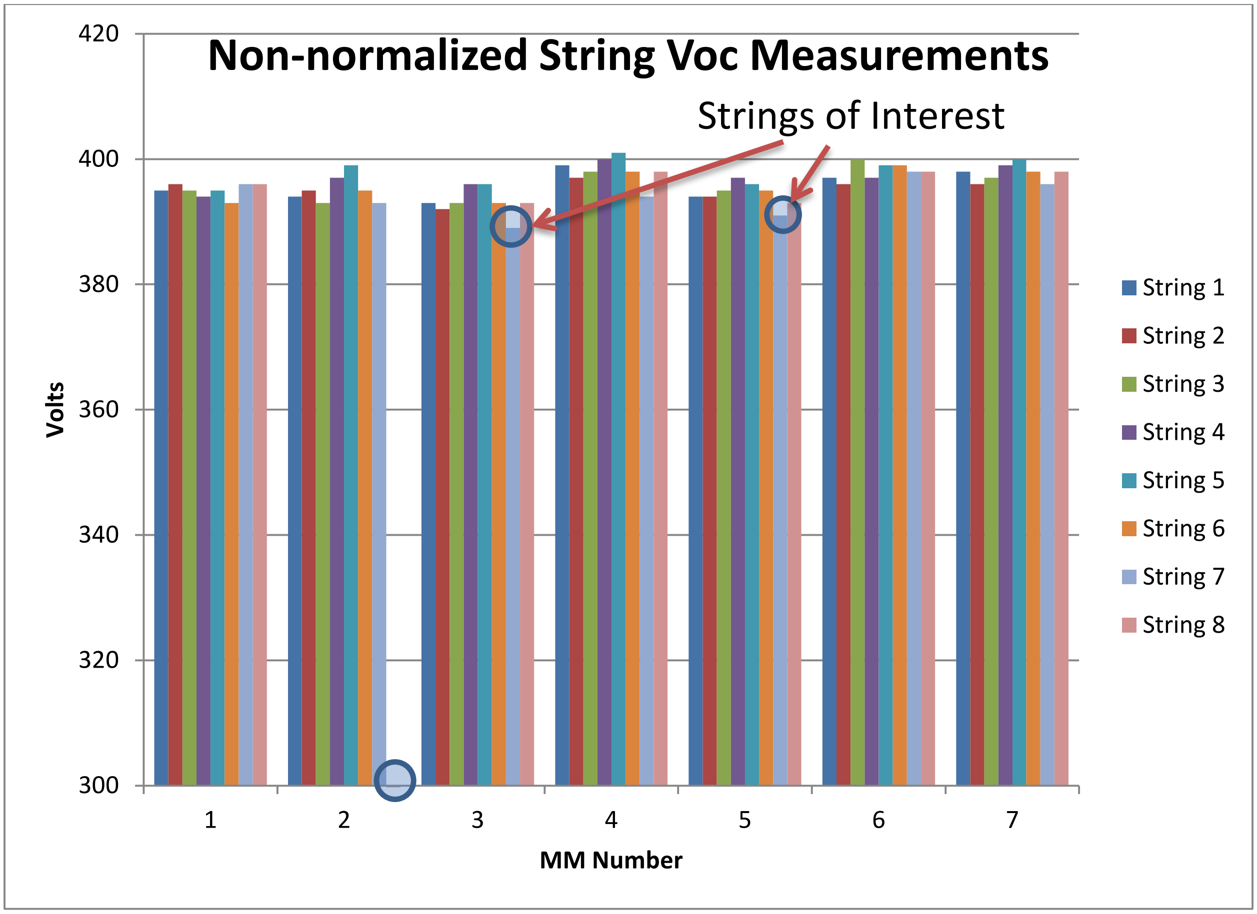

Figure 30: Array String Open Circuit Voltage Data for UCI MegaModules (MM)

The two lower voltage strings and a control string were measured at the plate level to find a dead cell. The results indicated the lower voltage appeared to be due to normal variation in V_{oc} readings between plates, and not a zero voltage cell. Fig. 31 is a chart of the plate voltages on the two lowest strings, along with a control string for comparison. None of the plates showed a voltage delta larger than two volts, suggesting all of the packages were contributing voltage.

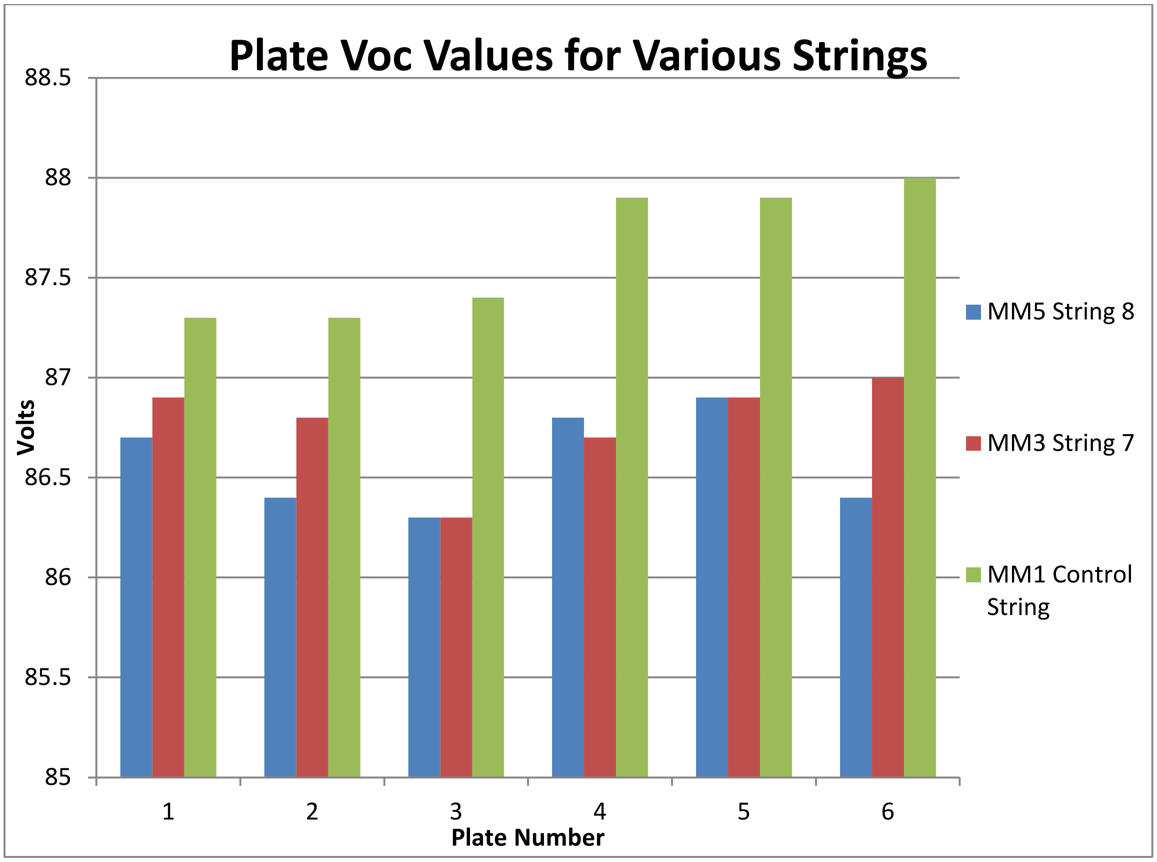

Fig. 31: Intra-string Plate Open Circuit Voltages

The damaged plate which exhibited zero volts was returned to the lab. The failure was attributed to one package with an open circuit due to a faulty solder joint on the lead, and is pictured below in Figure 32.

Fig. 32: Failed Solder Joint in copper lead

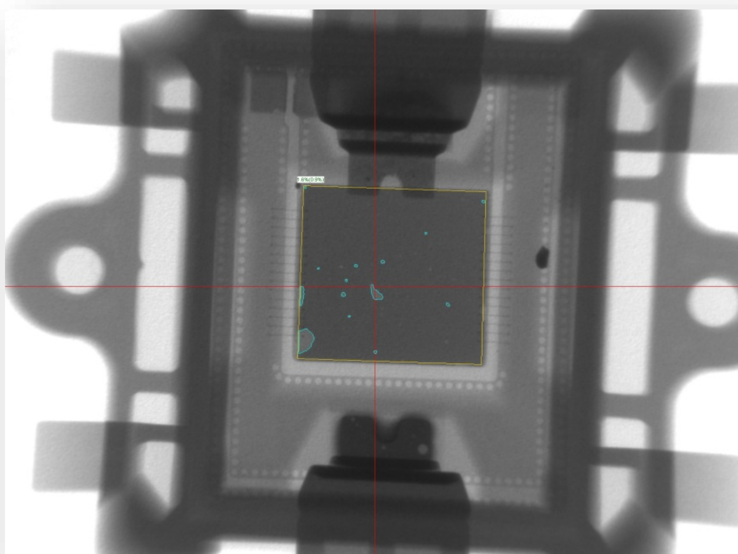

Fig. 33: X-Ray image of open lead Package. Single Void % = 0.9%

The X-ray image (Figure 33) does not indicate any anomaly in solder voids, and the cell passed an electroluminescence test, suggesting the cell would have operated properly on sun if the copper lead to the cell package hadn't failed. Amonix observed no failures for the voids tested on the UCI installation.

In conclusion, all four of the tests performed showed similar results and suggest there was little chance that some unknown factor had not been addressed by the four approaches. The NREL failure void percentage was slightly higher than those seen at Amonix, but when factors such as the uneven flux distribution of a Fresnel system and test differences were accounted for, the results appeared to be similar.

The single largest void percentage bins in the field test ranged from 0.5 percent to 1.75 percent. This was chosen to try to capture the upper bound, based on knowledge at the time. The fact that no failed packages were discovered indicates the upper bound may not have been found. Although possible that it was higher than this, previous tests indicated that it would not be far from this value. Data from less-rigorous testing does indicate that packages would begin to fail between 1.5 percent and 2 percent. It is unfortunate that an optimum threshold for this system was not found, but it seems safe to assume that no failures for an entire year would make the true value greater than or equal to the 1.75 percent single largest void bin.

2.2.4.3 Develop Lifetime Prediction Model for CPV Solar Cells (Supported by CSI Match Funding from the U.S. Department of Energy)

NREL was engaged to research how to correlate measured weather data with quantitative accelerated testing in order to predict the lifetime of the attachment of the concentrator's solar cell. The cell attachment (or die-attach) layer accumulates damage during service in the field due to the differential strain between the solar cell and its substrate. Swings in temperature due to clouds and diurnal interruptions contribute to damage that can be modeled and accelerated. By correlating physical damage with calculated damage, the model may be refined to predict lifetime for the die attach from meteorological data.

The thermal fatigue model is succinctly described in the following conference abstracts. These papers are available in full on the CSI RD&D website.[2]

Silverman, T. J., N. S. Bosco, et al. (2012). "Relative lifetime prediction for CPV die-attach layers." *Proceedings of the 2012 IEEE International Reliability Physics Symposium*.

Abstract: In concentrator photovoltaics (CPV) cell assemblies, a large-area die-attach layer is subjected to thermal cycles, leading to thermomechanical fatigue. This causes cracking and the eventual failure of the CPV cell by thermal runaway. We define a damage metric representing lumped progress toward failure, and present a numerical model for computing the accumulation of damage for arbitrary transient temperature conditions. The model is applied to a particular design with a solder die-attach layer. We show that accelerated-test thermal cycles with higher ramp rates cause more damage, both per cycle and per unit time. Outdoor exposure to one entire year in two geographic locations is also simulated, revealing that a year of exposure in Golden, Colorado is equivalent to 1.4 years of exposure in Oak Ridge, Tennessee.

[2] http://calsolarresearch.ca.gov/funded-projects/71-improved-cost-reliability-and-grid-integration-of-high-concentration-photovoltaic-systems

Bosco, N., T. Silverman, et al. (2012). Simulation and Experiment of Thermal Fatigue in the CPV Die Attach. *International Conference on Concentrating Photovoltaics (CPV-8)*, Toledo, Spain.

Abstract: FEM simulation and accelerated thermal cycling have been performed for the CPV die attach. Trends in fatigue damage accumulation and equivalent test time are explored and found to be most sensitive to temperature ramp rate. Die attach crack growth is measured through cycling and found to be in excellent agreement with simulations of the inelastic strain energy accumulated. Simulations of an entire year of weather data provides for the relative ranking of fatigue damage between four cities as well as their equivalent accelerated test time.

Bosco, N., T. Silverman, et al. (2012). On The Effect of Ramp Rate in Damage Accumulation of the CPV Die-Attach. *Photovoltaic Specialists Conference (PVSC), IEEE*.

Abstract: This paper details progress in the development of a lifetime test protocol to this point. It was found that the thermal fatigue model accurately predicts the amount of physical thermal fatigue damage accumulated in the CPV die attach across a large range of temperature ramp rates, as confirmed by experiment. The rate of damage accumulation dramatically increases with increasing temperature ramp rate. The significance of this work is a confirmed route to enable a short thermal cycling sequence that represents a lifetime's value of service, since years of field damage can be modeled by high rates during a relatively short test period. This modeling result is the crucial element supporting the development of an international durability standard that can predict a technology's lifetime.

2.2.4.3.1 An Outdoor Shutter Experiment for Accelerated Lifetime Testing

Correlating similar failures, observed in both HALT and the field deployments, along with refinements of the thermal fatigue model, provided the best foundation for a lifetime prediction analysis. This subtask integrated the results from these subtasks to develop a lifetime prediction model for a key component of a CPV system, specifically the cell package and its die-attach layer. An additional set of validating experiments involved periodically blocking sunlight with a shutter (Figures 34 and 35) to exaggerate very damaging days due to a thick, passing cloud cover.

Figure 34: One set of validating experiments will involve periodically blocking sunlight with a shutter enables to exaggerate very damaging partly cloudy days. Causing cell failure in this way creates an experimental connection to the model that can support model-based absolute lifetime prediction.

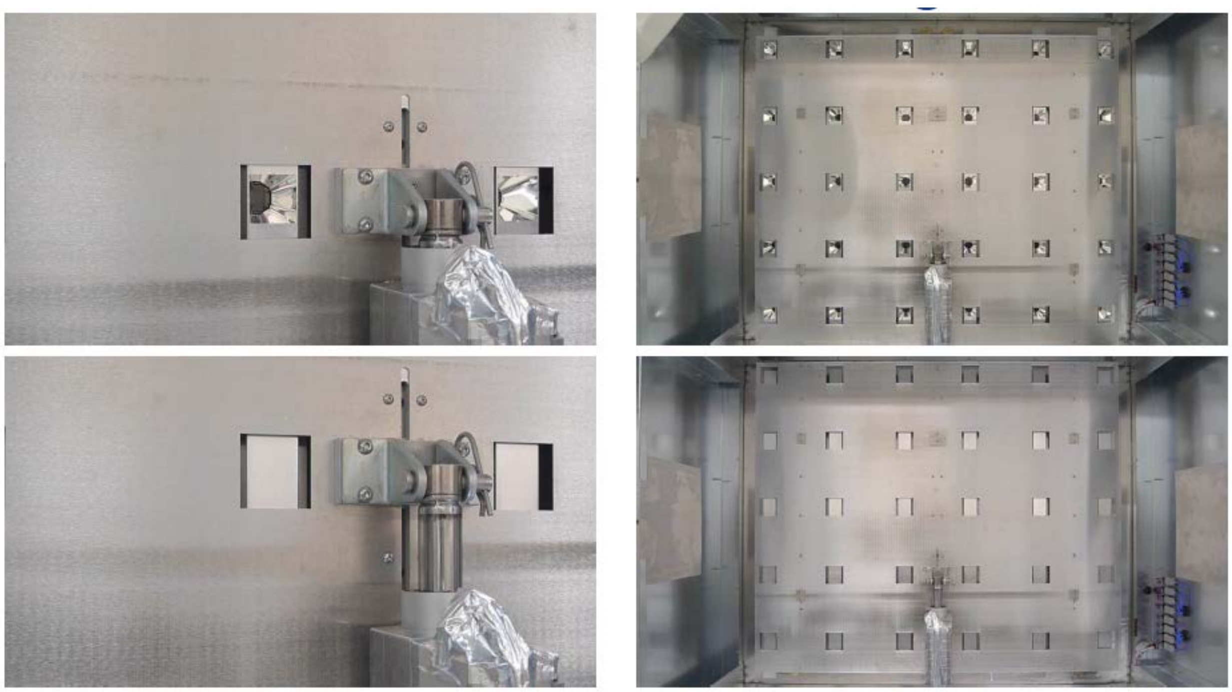

Figure 35: Three Amonix mini-modules were prepared with shutters over each cell and the modules were deployed in Phoenix, Arizona at TUV PTL.

The shuttered modules were placed in service and initial data was collected. An example of the real-time data available for these modules is presented below in Figure 36: the periodic change in cell temperature and module open-circuit voltage is affected by the shuttering action. The analysis will help adjust the FEM so that an accelerated chamber test can be designed which represents a desired lifetime of service. Data collection was not completed at the close of the CSI award, but NREL expects to continue data gathering after the shutter experiment is moved to its Outdoor Test Facility in Golden, Colorado.

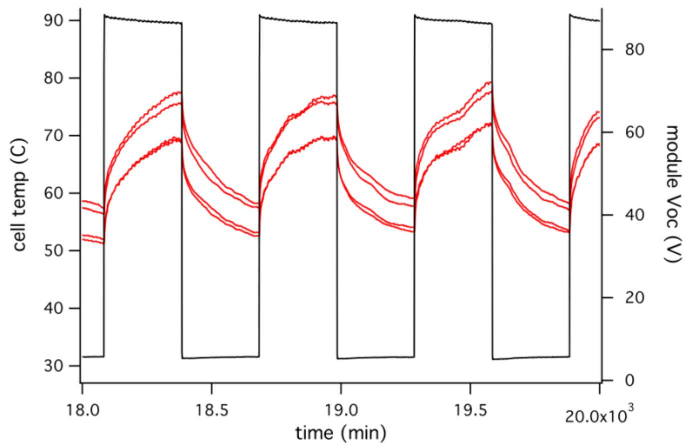

Figure 36: Example data collected from the shutter experiment.

2.2.4.3.2 An International (IEC) Standard for Predicting CPV Lifetime

The thermal cycling results continued to show promise as a lifetime test protocol and resulted in a proposed test protocol as a thermal cycling durability test for CPV modules. NREL prepared a draft IEC durability test standard for presentation and discussion at the IEC TC82 WG7 meeting on September 25 and 26, 2013 in San Jose, California. The proposal was submitted to the International Electrotechnical Commission (IEC), the international standards body for PV and CPV technologies. Since CPV power plants are relatively new and haven't operated for 25 or 30 years, this IEC standard, even in its draft form, will provide a useful and important bankability tool for minimizing risks associated with requirements for a 25- to 30-year lifetime. In November 8, 2013, IEC headquarters in Geneva accepted the draft CPV lifetime international project to be circulated for international vote by IEC's PV and CPV experts. The international ballot approved the project and IEC Geneva allocated IEC 62925 to identify the draft standard.

The title, scope and justification for the IEC standard are:

Title: Thermal Cycling Test for CPV Modules to Differentiate Increased Thermal Fatigue Durability

Scope: The purpose of this International Standard is to define a test sequence that will quickly uncover CPV module failures that have been associated with field exposure to thermal cycling for many years. This standard was specifically developed to relate to thermal fatigue-related failure mechanisms for the assemblies submitted to test. IEC 62108, the CPV module qualification test, already includes an accelerated thermal cycle sequence in one leg of the testing. However, the parameters of that test only represent a qualification level of exposure expected to be on the order of a few years. This test procedure applies more stress and will provide a route for comparative testing to differentiate CPV modules with improved durability to thermal cycling and the associated mechanical stresses.

Justification: The IEC 62108 "Concentrator photovoltaic (CPV) modules and assemblies – Design qualification and type approval" defines IEC requirements for the design qualification of concentrator modules for long-term operation in open-air climates. This standard, IEC 62925, will supplement IEC 62108 by providing tests that differentiate thermal fatigue durability of CPV modules for deployment in a larger range of applications and climates.

3.0 Technology Transfer and Outreach

The technology transfer and outreach activities targeted the following expert audiences:

- the international CPV expert community,
- the international utility R&D community and
- the international CPV standards community.

The results were documented in one pending international CPV standard and eight conference presentations/proceedings. The International Colloquia on Environmentally-Preferred Advanced Power Generation (ICEPAG) was organized by UC Irvine and provided a forum for presentations, as well as an opportunity for utility R&D attendees to visit the UCI CPV systems. UCI also hosted site visits and presentations for Electric Power Research Institute (EPRI) program managers and a Department of Commerce African Trade Mission.

The IEC standard is pending further review, balloting and international approval by the entire IEC solar photovoltaic energy systems Technical Committee 82 (TC82) that includes the 85 CPV experts from 18 countries belonging to the IEC CPV Working Group 7 (WG7). IEC 62925 Edition 1, "Thermal cycling test for CPV modules to differentiate increased thermal fatigue durability," submitted and approved for further development and IEC publication in 2015.

3.1 Conclusions

Two principal R&D tasks answered the following questions:

1. What are the key integration barriers to installing and operating Amonix CPV systems in a distributed grid? This is an important question, because CPV has the potential for lower costs and greater greenhouse gas emission reductions than conventional PV technologies. However, CPV's integration into a distributed grid could be hampered by its daily electricity production profile, which is different from that of conventional PV systems. Electrical systems researchers and engineers answered this question by analyzing CPV's electrical characteristics while operating in a distribution grid. No major barriers were discovered and after three years of operation, the two Amonix CPV systems continue to operate successfully in the UCI distribution grid.
2. How can the long-term durability of CPV, a relatively new technology in the solar marketplace, be assured so consumers may expect 25 years of reliable operation? Researchers and engineers correlated field failures and weather data with accelerated environmental testing in order to predict the lifetime of the solder attachment of the CPV cell. The quality of the solder attachment was determined to be critical to the lifetime of the CPV cell package. Based on this solar cell lifetime research, the researchers developed an international CPV durability standard for adoption by the International Electrotechnical Commission (IEC). This is the first lifetime reliability standard for CPV.

3.2 Results

The answers to the questions above have provided benefits to the state of California. The project exhibited no major barriers to CPV's distribution grid integration and no intrinsic issue with CPV's long-term reliability. These two results are consistent with lowering CPV's levelized cost of energy (LCOE). Task accomplishments are prioritized and summarized below:

- Amonix manufactured two CPV systems, operationally rated at a total of 113 kW AC, specifically for this project and installed them in UCI's distribution grid where they have operated successfully for over three years.
- NREL developed a thermal fatigue model to predict CPV solar cell lifetime. The model became the basis for an international CPV durability standard IEC 62925. This is the first international lifetime reliability standard for CPV.
- UCI's APEP developed a central power plant and CPV dynamic models for system operation. Their models were used to investigate the CPV penetration limits on the UC-9 circuit. Once the installed capacity of the CPV on the UC-9 circuit reached 420 kW, reverse power flow began to occur. However, before reverse power flow occurred, voltage limits at the Amonix bus were exceeded with only 240 kW installed CPV capacity. The voltage on the 12 kV side was only minimally affected by the CPV penetration. When the CPV capacity reached ten times the baseline-installed capacity (about 1,200 kW), effects on the 12 kV side became noticeable.
- UCI's APEP documented the interconnection and operation of CPV systems within the UCI energy system.
- Amonix and NREL conducted thermal cycling and humidity exposure of CPV solar cells in environmental testing chambers.
- Amonix categorized CPV solar cell failures in its southwestern U.S. field installations according to design, manufacturing, and lifetime (so-called "wear out") problems; failures caused by design and manufacturing dominated the findings. No "wear out" failures were found consistent with the expectation of long-life for the CPV cell packages.
- Amonix and UCI reaffirmed the importance of reaching out to the university residents for comments and approval before installing large CPV solar systems.
- Project results were publicly documented in six papers at international CPV and PV conferences,[1,2,3,4,7,8,9] two international conference papers on Environmentally-Preferred Advanced Power Generation (ICEPAG),[5,6] and an approved IEC project for a new CPV durability standard.[10]

3.3 Recommendations

Two principal recommendations result from this work.

- The lifetime durability standard, IEC 62925, developed by NREL is based on modeling of thermal fatigue of the CPV cell contact. The next step is to confirm modeling results with long-term correlation with field failures over period of several decades. While hundreds of thousands of cell packages were deployed at Amonix project sites in southwestern US in hopes of finding a correlation between the tests in IEC 62925, the duration of the project was not adequate to make such a correlation. Reliability R&D

requires long-term support to compile 10, 20, and 30 years of field failure monitoring in order to correlate failures with those of accelerated environmental chamber testing specified for IEC 62925. While solar companies may come and go, government agencies such as DOE, the CPUC, and the CEC are better positioned to support these decades-long monitoring studies.

- For the near-term, additional integration studies for both distribution and transmission grids are urgently needed to support the ambitious CSI goal for installing 3 GW of new solar electricity by 2016. CPV, with an energy payback similar to wind systems, has the intrinsic potential to rapidly meet this goal. However, market entry of innovative PV technologies such as CPV presents a large CPV industry hurdle in today's growing and rapidly-evolving PV marketplace. The PV marketplace has seen significant change in the past few years due in part to global shifts from a PV panel supply-constrained market to an overabundance of PV panels back to a nearly balanced market.

3.4 Public Benefits to California

Amonix has been based in California since its creation in 1989. Benefits to California include the manufacture of one of the 7700 power plants and all multijunction cell packages in California. The high-efficiency multijunction cells were manufactured in Sylmar, California by Spectrolab, a wholly-owned subsidiary of Boeing.

Experience gained from this installation can guide similar CPV projects in California. While financial agreements, environmental approvals and project surprises are well-known delays to conventional PV and CPV system developers, CPV installations can trigger strong community reactions unless the developers take the time and effort, as UCI did, to survey nearby residents and obtain their approval.

Developing models for CPV generation within this distribution grid will enable evaluation of benefits and issues for CPV installations in other California distribution grids.

Part of the good stewardship of ratepayer funds is coordination of UCI funding for related projects supported by two different CEC programs. Another benefit is the addition of CPV performance data to CEC's RESCO project for the development and refinement of the UCI RESCO roadmap and the development of a set of tools to evaluate the operation and deployment of energy systems at both the distribution and transmission level to support increased penetrations of renewables.

As solar technologies become more prevalent in California, reliability becomes more important. While reliability is ultimately validated by studies in the field, a durability standard can provide a lifetime protocol for testing CPV, an emerging solar technology, within a research plan that could be beneficial for all PV technologies.

Development of a thermal fatigue model is a critical step towards a CPV lifetime prediction model. Even conventional flat-panel PV technologies lack a lifetime prediction model and can benefit from this CSI/DOE/Amonix project.

CPUC's California Solar Initiative was acknowledged within the international CPV standards community for its support of cutting-edge reliability research.

3.5 Publications

1. "Relative Lifetime Prediction for CPV Die-Attach Layers," *Proceedings of the 2012 IEEE International Reliability Physics Symposium*, T. Silverman, N. Bosco and S. Kurtz, 2012.

2. "Simulation and Experiment of Thermal Fatigue in the CPV Die Attach," Presentation at the *8th International Conference on Concentrator Photovoltaic Systems (CPV-8)*, Toledo, Spain, N. Bosco, T. Silverman and S. Kurtz, 2012.

3. Bosco, N., T. Silverman, et al. (2012). "On the Effect of Ramp Rate in Damage Accumulation of the CPV Die-Attach," *Photovoltaic Specialists Conference (PVSC), IEEE*.

4. "A Study on the Impact of High-Penetration Distributed Generation Inverters on Grid Operation and Stability," Presentation at the *9th International Conference on Concentrator Photovoltaic Systems (CPV-9)*, F. Gu, J. Brouwer and Samuelsen, 2013

5. "Large Transmission Scale CPV Deployment," Presented at the *2012 International Colloquium on Environmentally Preferred Advanced Power Generation (ICEPAG)*, R. McConnell, 2012.

6. "Concentrator PV: A Breakthrough for a Historic Solar Technology," Presented at the *2011 International Colloquium on Environmentally Preferred Advanced Power Generation (ICEPAG)*, R. McConnell, 2011.

7. "Modeling Thermal Fatigue in CPV Cell Assemblies," *IEEE Journal of Photovoltaics*, Vol. 1., pp 242-247, N. Bosco, T. Silverman and S. Kurtz, 2011.

8. "CPV Cell Infant Mortality Study," Presentation at the *7th International Conference on Concentrator Photovoltaic Systems (CPV7)*, N. Bosco, C. Sweet, T. Silverman and S. Kurtz, 2011,

9. "Quantifying the Thermal Fatigue of CPV Modules," *AIP Conference Proceedings*, Vol. 1277, pp. 225-228, N. Bosco and S. Kurtz, 2010.

10. Draft Standard IEC 62925 Edition 1, "Thermal cycling test for CPV modules to differentiate increased thermal fatigue durability," pending publication in 2015.