Low-Cost High-Concentration Photovoltaic Systems for Utility Power Generation

U.S. Department of Energy
Technology Pathway Partnerships
DOE Award DE-FC36-07GO17042

Final Technical Report

April 2012

This material is based upon work supported by the Department of Energy under Award No. DE-FC36-07GO17042.

Executive Summary:
Under DOE's Technology Pathway Partnership (TPP) program, Amonix, Inc. developed a new generation of high-concentration photovoltaic systems using multijunction technology and established the manufacturing capacity needed to supply multi-megawatt power plants built using the new Amonix 7700-series solar energy systems.

For this effort, Amonix collaborated with a variety of suppliers and partners to complete the tasks below. Subcontractors included: Evonik/Cyro; Hitek; the National Renewable Energy Laboratory; Raytech; Spectrolab; UL; University of Nevada, Las Vegas; and TÜV Rheinland PTL.

Task	Description	Phase
1	Multijunction Cell Optimization for Field Operation	II-III
2	Fresnel Lens R&D	I-III
3	Cell Package Design & Production	I-III
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Amonix's TPP addressed nearly the complete PV value chain from epitaxial layer design and wafer processing through system design, manufacturing, deployment, and O&M. Amonix has made progress toward achieving these reduced costs through the development of its 28%+ efficient MegaModule®, reduced manufacturing and installation cost through design for manufacturing and assembly, automated manufacturing processes, and reduced O&M costs.

Program highlights include:

- Optimized multijunction cell and cell package design to improve performance by > 10%.
- Updated lens design provided 7% increased performance and higher concentration.
- 28.7% DC STC MegaModule efficiency achieved in Phase II exceeded Phase III performance goal.
- New 16" focal length MegaModule achieved target materials and manufacturing cost reduction
- Designed and placed into production 25 MW/yr manufacturing capacity for complete MegaModules, including cell packages, receiver plates, and structures with lenses.
- Designed and deployed Amonix 7700 series systems rated at 63 kW PTC ac and higher.

Based on an LCOE assessment using NREL's Solar Advisor Model, Amonix met DOE's LCOE targets: Amonix 2011 LCOE 12.8 ¢/kWh (2010 DOE goal 10-15); 2015 LCOE 6.4 ¢/kWh (2015 DOE goal 5-7).

Amonix and TPP participants would like to thank the U.S. Department of Energy Solar Energy Technology Program for funding received under this program through Agreement No. DE-FC36-07GO17042.

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TPP Overview

Project Title: Low-Cost High-Concentration Photovoltaic Systems for Utility Power Generation

Covering Period: May 14, 2007 – December 31, 2011

Date of Report: March, 2012

Award Number: DE-FC36-07GO17042

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Project Objective& Summary:
The principal objective of this project was to meet DOE's Levelized Cost of Electricity (LCOE) goals for 2015 and enable Amonix to successfully compete in large-scale utility markets with its High Concentration Photovoltaic (HCPV) systems. To accomplish this objective the project consisted of tasks leading to reduced material costs, system performance increases, improvements in reliability, and cost reductions due to high-volume manufacturing.

During the award period of performance, Amonix developed and placed into volume production its 7700 series multijunction HCPV system, with substantially improved performance and lower cost than previous silicon-based Amonix products. Product performance and reliability were evaluated at multiple sites and, concurrently, Amonix supplied HCPV systems for commercial projects, including a 30 MW project at Alamosa, CO. The product has been certified to IEC 62108 and is listed by the California Energy Commission on their eligible product list.

Budget

Budget Period	Start	Finish	DOE Funding	TPP Cost Share	Total
1	05/14/2007	06/30/2008	$2,223,930	$2,223,930	**$4,447,860**
2	07/01/2008	12/31/2009	$7,066,901	$8,508,580	**$15,575,481**
3	12/31/2009	12/31/2011	$6,314,800	$7,297132	**$13,611,932**
Total			$15,605,631	$18,029,642	**$33,635,273**

**Final cost share may exceed negotiated amount based on final expenditures.*

Project Background:
Amonix was founded in 1989 to develop High-Concentration PV systems using proprietary silicon cell technology. By 2008, Amonix had demonstrated a world-record 27.6% efficient silicon concentrator cell, developed the sixth generation of its system, installed over 700 kW, manufactured more than 500,000 cell assembles, and licensed its technology to Guascor Fotónwhich installed 12.3 MW of silicon-based HCPV technology in Spain.

With this project, Amonix undertook the development of its 7th generation technology, including 25 MW/yr of manufacturing capacity. Initially, Amonix planned to continue development of high-efficiency silicon cells, including procuring and equipping a silicon cell foundry, while performing research on III-V multijunction cells for use in the new HCPV system. Market conditions and rapid progress on multijunction cell technology led Amonix, with the support of the DOE stage gate review panel, to focus all of its Phase II and III efforts on the multijunction cell technology. The deployment of the first multijunction7700 product, rated at 53 kW AC PTC, occurred in the first quarter of 2009.

With the help of its TPP accomplishments, Amonix raised a $129.4 million of Series B financing round led by Kleiner, Perkins, Caulfield & Byers. Subsequently, Amonix applied for and won a $5.9 million tax credit from the Recovery Act for a new MegaModule®manufacturing facility in North Las Vegas, Nevada capable of producing 150 MW/year of the MegaModules for the 7700 product. Amonix was also selected to supply its HCPV systems for a 30 MW (AC) project in Alamosa, Colorado. Construction began in 2011, with completion expected in the second quarter of 2012.

To meet the increased demand for Amonix products, development of manufacturing capacity was accelerated using non-TPP funds and was moved from Amonix's Seal Beach, CA facility to facilities operated for Amonix by Flextronics in Milpitas, CA (cell packages) and North Las Vegas, NV (MegaModules). Phase III TPP funding was redirected from manufacturing capacity towards deployment and monitoring of additional systems to focus on establishing and improving product performance and reliability.

Technology Background and Nomenclature:
The Amonix 7700 product developed under this award is a High-Concentration PV system, shown in Figure O-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 the 10' x 49' rectangular steel frame; 36 lens parquets including 30 lenses each, and 36 receiver plates, to which are mounted 30 cell packages. The cell packages include the multijunction solar cell bonded to a die attach, electrical contacts, and a secondary concentrator. To support testing and research, representative samples informally called mini-modules are fabricated. These include a single receiver plate and lens parquet with 30 cells with a frame constructed of the same materials as the MegaModule.

The project was reorganized at the beginning of Phase II into tasks which generally correspond to the various manufacturing and assembly steps, as shown in Table O-1. This is the task structure followed in this report. Work performed during Phase I is presented in the context of the Phase II and III task structure.

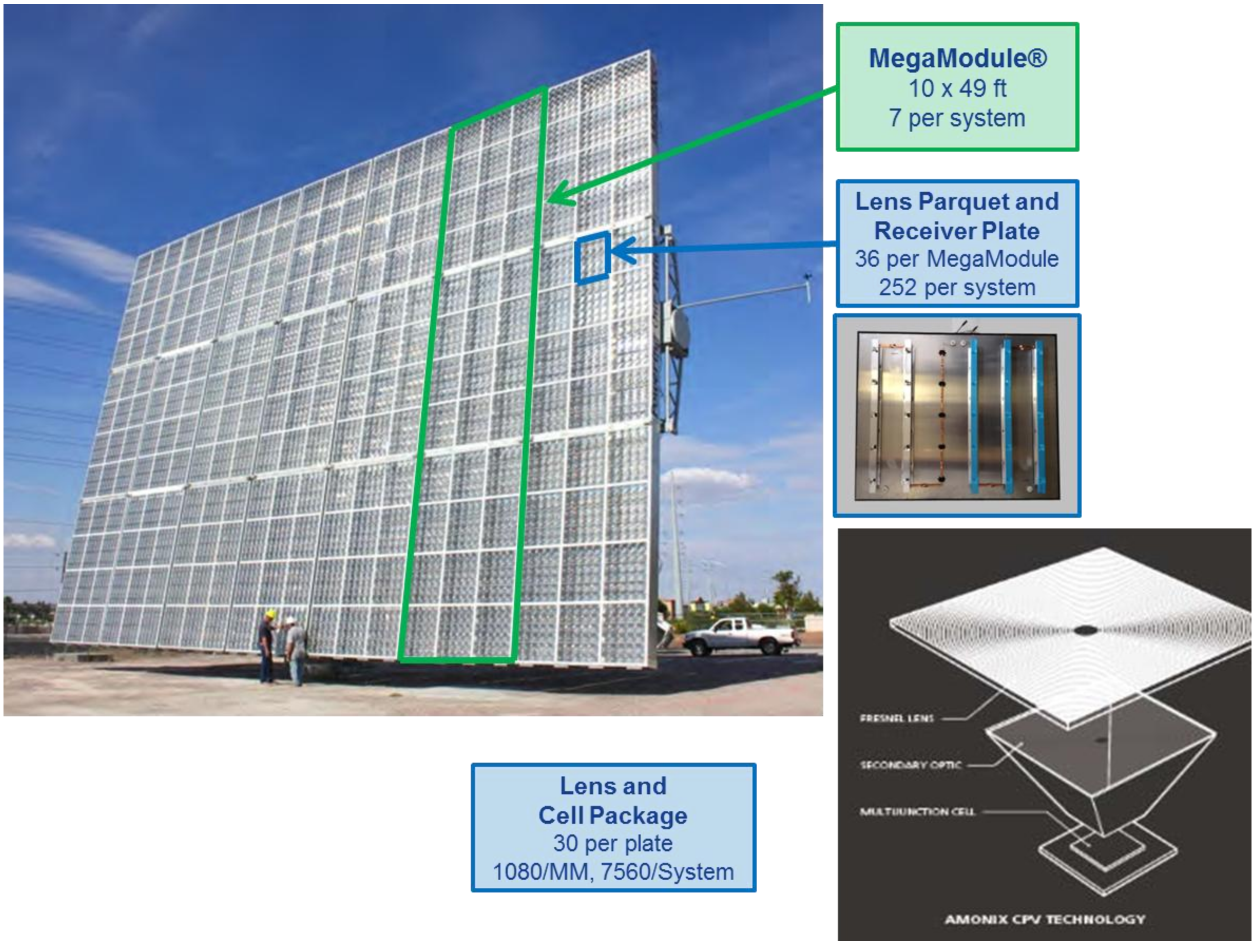


Figure O-1: Amonix 7700 High-Concentration PV System.

Table O-1. Task structure.

Design, Manufacturing, and Installation Tasks			Support Tasks	
1	Multijunction Cell Optimization for Field Operation		**4**	Standards Compliance and Reliability Testing
2	Fresnel Lens R&D			
3	Cell Package Design & Production			
5	Receiver Plate Production		**11**	Field Testing
6	MegaModule Performance			
7	MegaModule Cost Reduction			
8	Factory Setup and MegaModule Production		**12**	Solar Advisor Modeling and Market Analysis
9	Tracker and Tracking Controller			
10	Installation and Balance of System (BOS)			

Task 1: Multijunction Cell Optimization for Field Operation
TPP Task Participants: Amonix, Spectrolab *Phases II & III*

Task Objective: Optimization of III-V multijunction cells for use in Amonix MegaModules

Highlights:
- Developed a multijunction cell performance model that showed excellent agreement with measured field performance.
- Developed a new target spectrum for cell design to improve performance by 4%.
- Optimized cell and package design to improve performance by > 10%.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase II	
✓	C	Demonstrate positive correlation between cell modeling and field data.	Complete. Documented in quarterly report to DOE.
✓	C	Design review of cell and anti-reflective coating (ARC) coating options.	Complete. Technology transferred to Spectrolab in Q1 2011. In production Q1 2012.
		Phase III	
✓	SG	Demonstrate design that increases cell current by 2%. (Baseline: current from cell with vendor grid lines optimized for AM 1.5 and 25°C).	Complete. Cell design transferred to Spectrolab for production. Cell sent to NREL.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
Optimization for field operation in Amonix HCPV systems is critical to this project's success. At the beginning of the project, multijunction cells received from vendors had been optimized for performance under the AM1.5 direct solar spectrum at 25°C. In this task, Amonix pursued increases in performance through changes in cell and gridline design to accommodate the variable spectrum, intensity and temperature conditions present in field operation of the Amonix 7700 system.

Phase II
During Phase II, outdoor cell Light Current Voltage (LIV) testing and spectroradiometric measurements were performed at outdoor test facilities in Torrance, CA and Las Vegas, NV to support cell power and energy production modeling, development of a new target spectrum, and prototyping of a new cell design optimized for the new target spectrum.

<u>Multijunction Parameter Cell Model</u>:Amonix developed a multijunction parameter cell model to support evaluation of power and energy production. The model incorporates hourly temperature, aerosol optical depth, and opaque cloud cover data to go beyond maximum power calculations and estimate daily energy generation. Model development was supported by outdoor cell Light Current Voltage testing and spectroradiometric measurements at outdoor test facilities in Torrance, CA and Las Vegas, NV.

The multijunction cell model demonstrated strong correlation with field data from operation of an Amonix 7500 concentrator fielded at the University of Nevada, Las Vegas (UNLV) (see task 10).

The multijunction parameter cell model was also modified slightly to correct limitations in the TMY3 database for cloud cover data. The opaque cloud cover data were normalized so that the resulting output from the NREL SMARTS model[1] yielded a direct normal resource consistent with measurements at the given location. The parameter model was then updated and used to generate peak power and annual energy predictions for five locations.

Target Spectrum:The AM1.5 direct (G173-03) reference spectrum typically used to design and test multijunction cells are an imperfect match for concentrating PV systems. A parametric model was used to determine a new target spectrum. Analysis of conditions in Alamosa, CO; Las Cruces, NM; Las Vegas, NV; Palmdale, CA; Tucson, AZ; and Denver, CO yielded the target spectra shown in Figure 1-1. Despite significant differences in latitude, elevation, temperature, and cloud cover, the spectra measured in these locations are quite similar suggesting a single target spectrum can be used and that cell designs will not need to be changed for different locations.

The difference between the target spectrum and the reference standard of more than 5% suggests that a significant increase in annual energy output may be obtained by tuning the top subcell and middle subcell designs to a new spectrum.

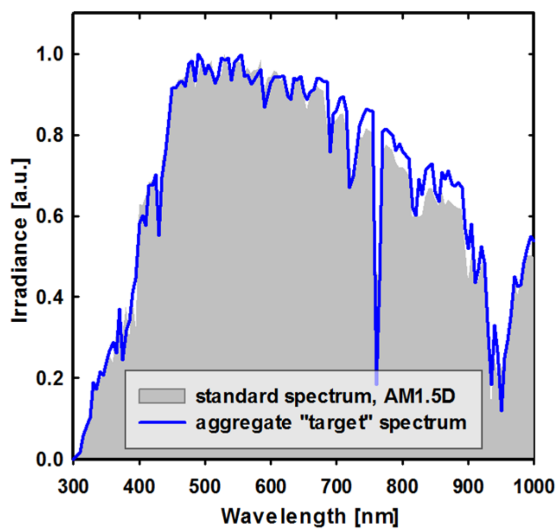


Figure 1-1. Target spectrum compared to the ASTM-G173 (direct) reference standard. The target spectrum is based on data from Alamosa, CO; Las Cruces, NM; Las Vegas, NV; Palmdale, CA; Tucson, AZ; and Denver, CO.

Optimized Cell Design:Amonix followed a two-step process to optimize cell designs for the Amonix concentrator. Data on the target spectrum were provided to Spectrolab where changes were made to improve cell performance by modifying the epitaxial structure. Amonix also built a clean room facility for solar wafer processing and packaging in their Torrance, CA facility, as shown in Figure 1-2. This 15 MW line enabled Amonix to make improvements in their solar cell efficiency using proprietary solar cell finishing processes (see Figure 1-3). Optimization of the solar cell design and wafer processing increased mean current (and power) by ~2% as shown in Figure 1-4. These improvements are independent of epitaxial design.

[1]Myers, D. R.; Gueymard, C. A. (2004). Description and Availability of the SMARTS Spectral Model for Photovoltaic Applications. Kafafi, Z. H.; Lane, P. A., eds. Organic Photovoltaics V: Proceedings of SPIE Conference, 4-6 August 2004, Denver, Colorado. SPIE Proceedings Vol. 5520. Bellingham, WA: SPIE (The International Society for Optical Engineering) pp. 56-67; NREL Report No. CP-560-37294.

Figure 1-2. Amonix wafer processing facility in Torrance, CA.

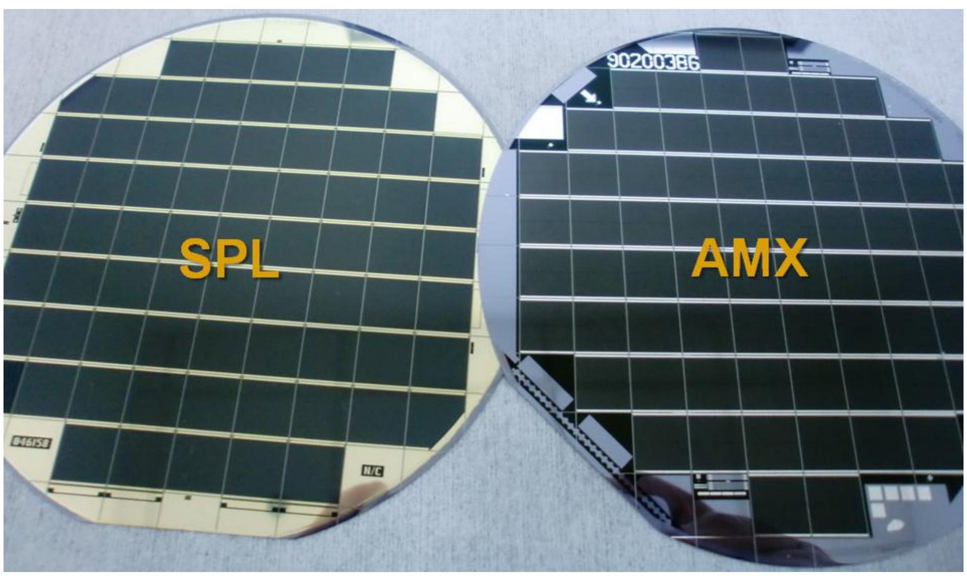
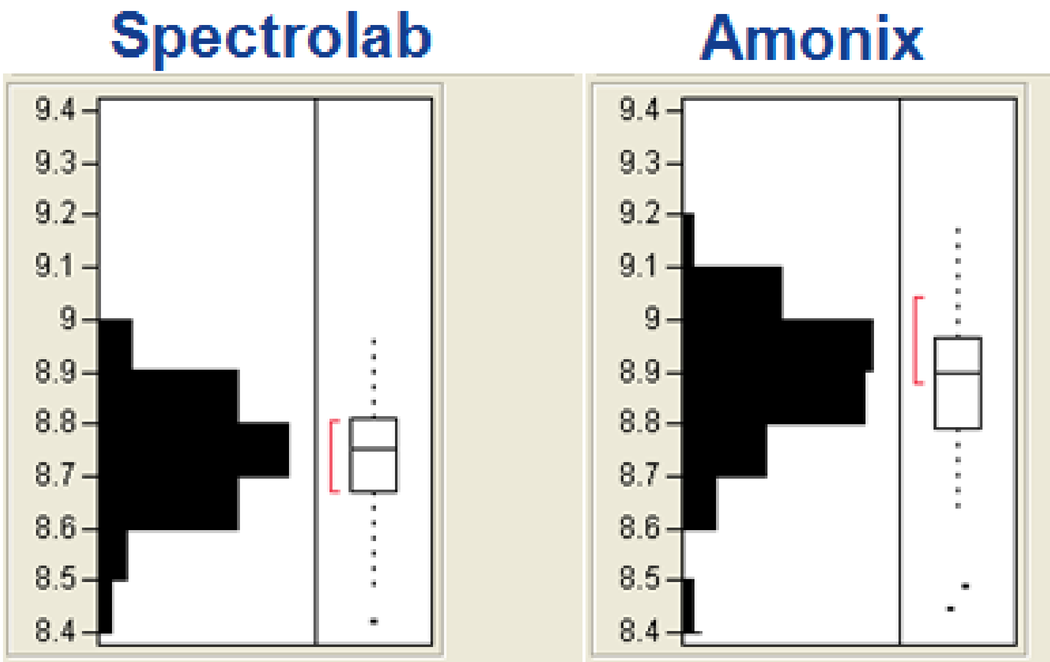


Figure 1-3. Darker anti-reflective coating produced by Amonix.



Quantiles

	Spectrolab		Amonix
100.0%	maximum	8.9749	9.199
99.5%		8.9749	9.199
97.5%		8.94907	9.0951
90.0%		8.87886	9.0309
75.0%	quartile	8.8101	8.9662
50.0%	median	8.7529	8.8963
25.0%	quartile	8.6727	8.7924
10.0%		8.58172	8.6345
2.5%		1.99975	5.7271
0.5%		0.013	0.00838
0.0%	minimum	0.013	0.00838

Moments

	Spectrolab	Amonix
Mean	8.558	8.6619116
Std Dev	1.1949355	1.199857
Std Err Mean	0.1090822	0.1099907
Upper 95% Mean	8.7739936	8.8797232
Lower 95% Mean	8.3420064	8.4441001
N	120	119

Figure 1-4. Outdoor test results showing ~2% Increase in median power.

Phase III

Multijunction Parameter Cell Model:The multijunction parameter cell model was improved to provide daily summaries and take into account system-specific soiling profiles. During the first five months of 2010, the difference between measured and predicted cumulative energy generation was <1%.

Optimized Cell Design: A pixelated cell was developed to allow measurement of cell current which indicates the incident flux distribution within the cell aperture area, as shown in Figure 1-5. Use of multiple pixelated cells on the concentrator enables quantification of flux distribution over time and as a function of the elevation angle, wind load, temperature, etc. Pixelated cells can also be used to monitor temperature distribution across the cell area. Based on the data provided by the pixilated cell, the Amonix cell was re-designed to better match the intensity distribution that exists under the Gen3 Fresnel lens (see task 2). The spacing between gridlines (pitch) was reduced and the cell made smaller. Figure 1-6 shows the resulting improvement with respect to the 2010 baseline (Spectrolab) design as demonstrated in outdoor testing. This resulted in a median efficiency improvement of ~0.7% absolute (~2.3% relative).

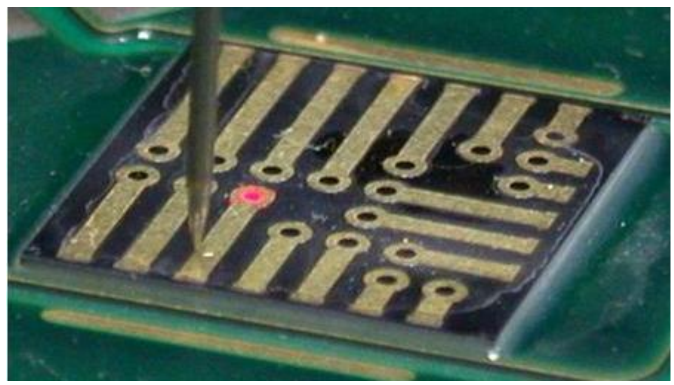


Figure 1-5: Pixelated test cell.

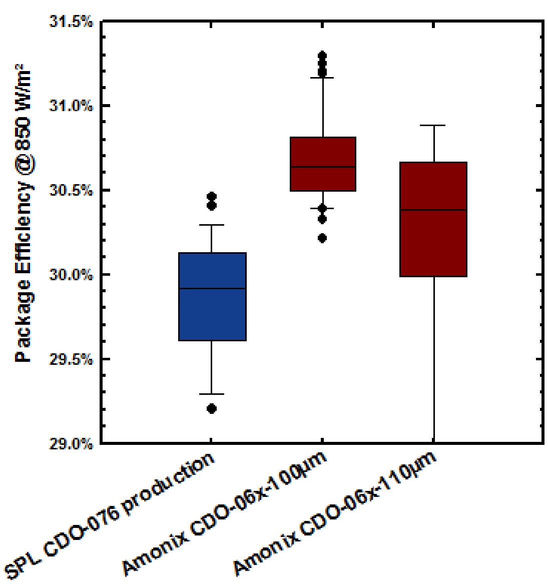


Figure 1-6: Performance improvement from cell optimization.

One of the wafer processing improvements made was a wafer process design that allows for metal gridlines with an aspect ratio greater than one, as shown in Figures 1-7 and 1-8. This reduces obscuration of the incident light for a given gridline pitch.

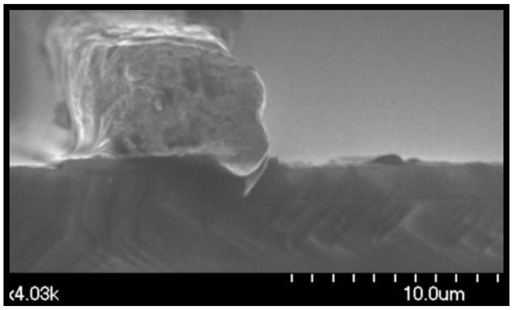


Figure 1-7. Cross section of a gridline for the wafer process fielded in 2010.

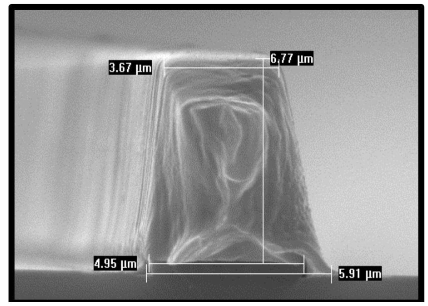


Figure 1-8. Cross section of a gridline with the improved Amonix wafer process.

Amonix transferred the optimized CDO-06x design and associated wafer process improvements to Spectrolab. In production, these transfers increased cell performance 1.5% (relative) with respect to the baseline cell design.

These changes, along with changes at the cell package level (see task 3),have led to substantial increases in package efficiency, as demonstrated in outdoor testing at the package level, as shown in Figure 1-9. The Amonix cell package uses a cover glass to protect the front surface of the cell to enhance reliability. Texturing of the cover glass was investigated as a means to divert incident light away from the metal gridlines on the cell surface and thereby increase cell current. An increase in current of more than 3% was obtained. Textured cover glass was not incorporated in the 7700 system but is planned for the next generation Amonix system.

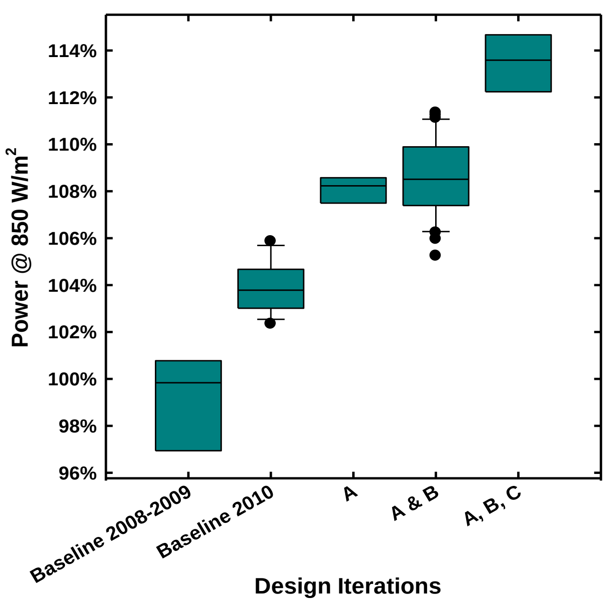


Figure 1- 9. Design improvements demonstrated at the package level in outdoor testing.

Task 2: Fresnel Lens R&D
TPP Task Participants: Amonix, Evonik/Cyro Phases I, II & III

Task Objective: Optimize Fresnel lens for use with multijunction cells.

Highlights:
- Lens design updated for multijunction cells, with 7% increased performance and higher concentration.
- Lens qualification was completed and the lens was placed in production.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	C	Modify/update the design of the Fresnel lens and secondary optical element to increase system performance.	Initiated discussions with new lens designer and supplier; lens subcontracts in negotiation. Completed in Phase II.
✓	C	Test optical efficiency and tracking tolerance of a single piece lens with updated design for multijunction cells.	Postponed. Completed in Phase II.
		Phase II	
✓	C	Demonstrate Fresnel verification system.	Complete.
✓	C	Complete improved Fresnel design.	Complete.
		Phase III	
✓	C	Contract for improved lens design prototype production.	Complete.
✓	C	Field demonstration of improved Fresnel performance.	Complete.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
The primary optical element used by Amonix to concentrate sunlight is an acrylic Fresnel lens, which is made from an acrylic lens film laminated to a structural layer of acrylic. Previous generations of lenses were designed for silicon cells and were not yet optimized for use with multijunction cells. Under this task, Amonix optimized the design for the multijunction cells and researched cost reduction options.

Phase I
Amonix began modification of the design of the Fresnel lens and secondary optical element for use with multijunction cells. As compared with silicon cells, multijunction cells are more sensitive to intensity and spectral non-uniformity (chromatic aberration) and the short-wavelength absorption of acrylic. New lens patterns designed to improve spectral and intensity uniformity were fabricated and evaluated on test equipment built to confirm that manufactured lenses perform as designed. Test results were reported in Phase II.

Amonix also explored various means of reducing lens cost such as a one-piece lens; alternative materials, such as glass and silicone; and, with Evonik, a thermal method of bonding the lens film to the substrate. Amonix concluded that the current structure offers the best combination of manufacturability and cost. Amonix also sought to diversify its supply base by qualifying multiple vendors as reported below.

Phase II

Amonix completed Gen 2 and Gen 3 designs of a new single-element Fresnel lens optimized for multijunction cells and had prototypes fabricated by multiple vendors. A laser mapping system was developed and used to evaluate lens performance, as shown in Figure 2-1.

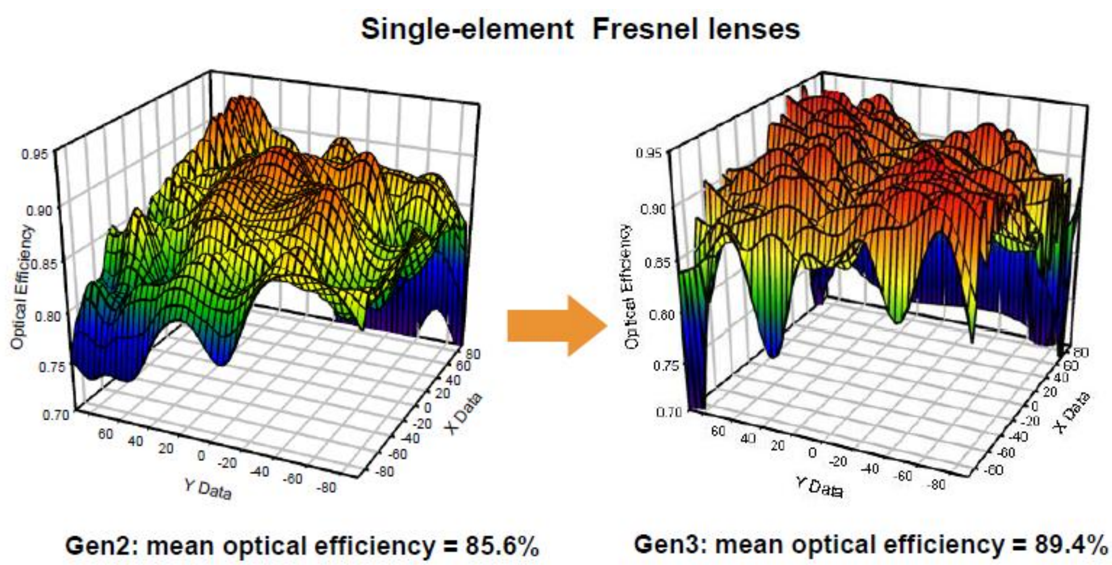


Figure 2-1. Laser maps of Fresnel lenses.

Subsequent outdoor performance tests confirmed the ~7% boost in power expected from the improved lens design. This power boost exceeded the requirements of the Amonix technology roadmap. The Gen3 lens design also provides a focused beam which enables higher (mean) concentration >600x when coupled with a smaller cell and secondary optical element (SOE).

Phase III

Amonix developed a lens qualification program that included thermal cycling and UV testing of the Gen 3 lens at NREL. Performance testing was conducted with new cell packages designed for the higher concentration of the Gen 3 lens design. Performance of the Gen 3 design was established and the design was placed in production.

Task 3: Cell Package Design & Production
TPP Task Participants: Amonix Phases I, II & III

Task Objective: Develop 25 MW/year production line for multijunction cell package.

Highlights
- Design and development of IEC 62108-compliant multijunction cell package.
- Design and development of 25 MW/Yr cell package assembly line.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	C	Modify the silicon cell package design and cell package assembly station to accommodate multijunction cells.	Two designs in progress. One offers higher performance and the other offers increased manufacturability.
✓	C	Fabricate and field test prototype multijunction cell/packages on single plate modules.	Field testing performed.
✓	C	Design, fabricate, and procure automated equipment for cell package assembly.	Delayed by transition to multijunction cells. Completed in Phase III.
		Phase II	
✓	C	Final review to select two candidate designs.	Complete.
✓	C	Production tooling design review.	Complete.
✓	SG	Selection of final production package design/process based on performance, process, and latest HALT analyses.	Complete.Reported to DOE (Quarterly Reports).
		Phase III	
✓	C	Report HALT results on deployed cell packages.	Complete.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
The purpose of the cell package is to provide a robust housing for the multijunction cell, including mechanical support and encapsulation, thermal management, electrical leads, and secondary optics. This task includes the design and testing of the package and of the automated manufacturing line, beginning with a pilot line and expanding to 25 MW/yr production capacity.

Phase I
Consistent with the initial project objective of bringing the silicon-based HCPV system to volume manufacturing, the initial cell package design was for silicon with a relatively simple projected transition to multijunction cells. In the initial investigation, a limitation arose in seamlessly moving from silicon to multijunction cells: the process that worked relatively well in low volume complicated the steps necessary to assure void free soldering. Amonix modified the cell package and assembly station designs to accommodate multijunction cells and identified three potential designs based on the criteria of cost,

performance, manufacturability, and reliability. Of the package options, two were selected for further research. Package “A” offered increased manufacturability while Package “C” offered higher performance, as shown in the figure 3-1.

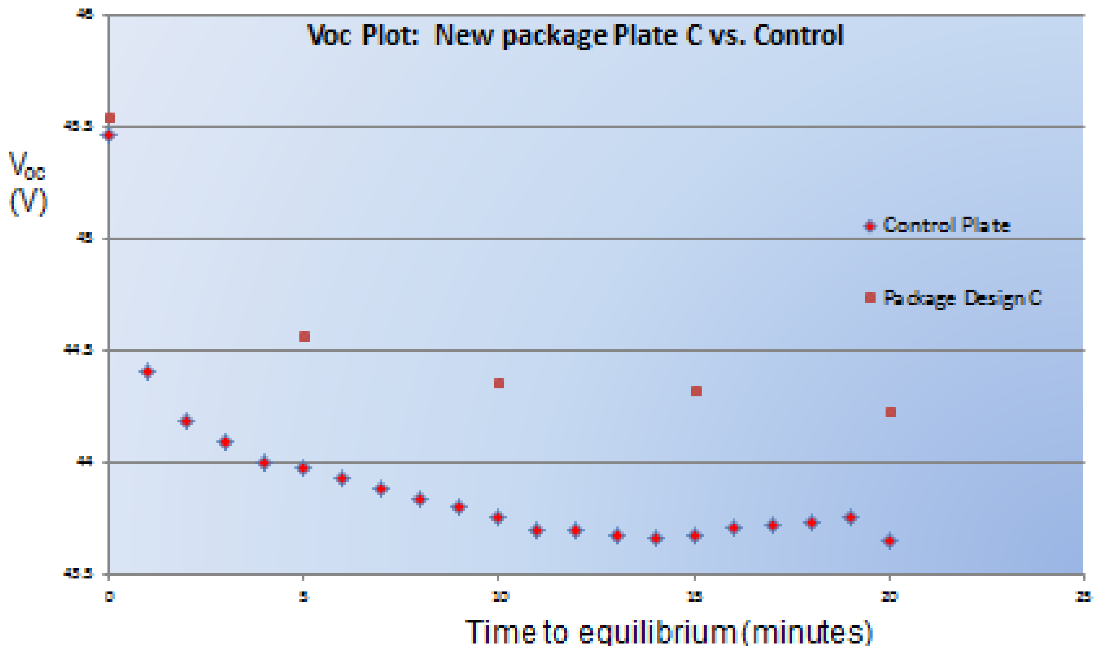


Figure 3-1: On-sun thermal performance, package option C.

Development and procurement of automated cell package assembly equipment began during Phase I, including internal development of assembly stations for passivation and flash testing. Discussions were held with prospective equipment vendors to finalize the assembly process, vendors were selected, and purchase orders were initiated.

Phase II

Review of two cell package designs from phase I resulted in hybrid cell package design to meet performance and manufacturability criteria, as follows. The approach to package design focused heavily on utilizing industry standard equipment for both cost purposes as well as support. The process for the multijunction attach is at the upper end of normal process capabilities, with the desire to use a fluxless-voidless process being more stringent than many typical semiconductor applications warrant. Additionally, the current levels involved put the application in the power semiconductor industry, which, when combined with the limited number of cell providers with locked in materials, limited the choices of processes to make the package. Some changes were required in the hybrid package design to find materials that not only worked in the application, but also met the requirements for UL listing.

During Phase II, the design was sent to automation equipment vendors to closely verify the capability of their machines to achieve the desired results. Vendors were selected based on previous Amonix experience with the vendors, product performance, and cost. Highly Accelerated Life Tests (see task 4) were then carried out to verify product performance, using the IEC 62108 test battery as a foundation. Among the tests performed were damp heat, humidity freeze, and thermal cycle. The initial test series both validated portions of the design and identified the need for a design change. That change was implemented, leading to successful completion of the tests, and selection of a final production package, shown in Figure 3-2, was made.

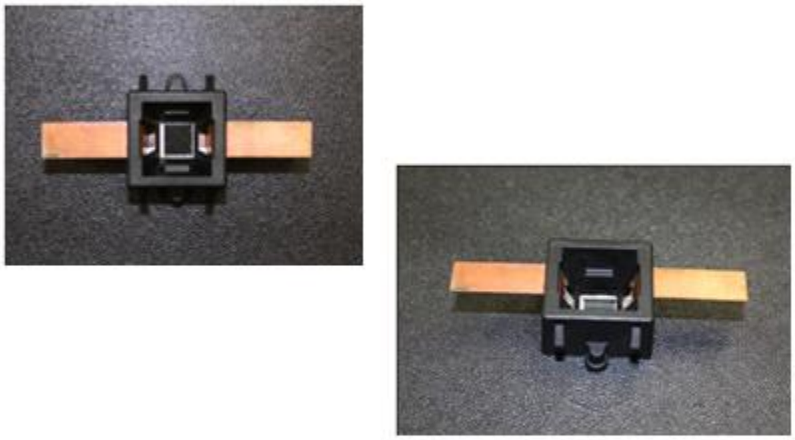


Figure 3-2. Cell package without secondary optics.

Phase III

The HALT testing that was performed in Phase II was done at an outside facility. In Phase III, HALT testing of the cell packages was expanded with the purchase of a bank of environmental chambers to enable in-house testing, up to a full backplate with 30 cell packages. The goal was to use multiple iterations of the test to failure, if possible, to uncover weaknesses in the design and perhaps get insight into ultimate lifetime.

Additional HALT testing, pilot production, and field testing provided insight into design and production weaknesses that affected reliability, yield, and/or production capacity. Design and process changes were made to meet project goals, including bringing the process line to 25 MW capacity. For example, attachment of silver tabs for the cell connection was moved to an automated wire bond application. The wire bond tool displaces a more cumbersome manual process of tab welding with a more reliable wire bond process. Another addition to the line was a spectrally precise flash tester used for better accuracy. The internally developed model was used as a “go-no-go” unit that used reference cells under an untuned spectrum for testing validity. This new model increased the accuracy of the test by tuning the spectrum to AM1.5D. The improved accuracy and repeatability allows for better binning in production and can also be used in R&D development.

Prototype runs of thousands of packages were used to evaluate and improve the manufacturing process at Seal Beach, as shown in Figure 3-3. All activities were completed on this task and the task was closed in the 3rd quarter of 2010. The process line was ultimately moved from the Seal Beach facility to a facility operated for Amonix by Flextronics in Milpitas, CA.

Figure 3-3. 25 MW/yr cell package assembly line, Seal Beach CA.

Task 4: Standards Compliance and Reliability Testing
TPP Task Participants: Amonix, NREL, TÜV Rheinland PTL, UL Phases I, II & III

Task Objective: Assure product reliability and safety through standards certification and accelerated life tests.

Highlights:
- MegaModule certified as eligible solar equipment under California Solar Initiative.
- MegaModule IEC 62108 certification tests completed.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	SG	Redesigned 16" Si module passes all relevant aging tests as listed in the draft IEC concentrator standard.	Si IEC test conducted. Multijunction module certified to IEC 62108 in Phase III.
		Phase II	
✓	C	Complete HALT plan.	Complete.
✓	C	Complete preliminary HALT screening of candidate packages.	Complete.
✓	C	Acquire listing for California Solar Initiative program.	Complete.
✓	C	Complete component level testing for IEC 62108.	Completed in Phase III.
		Phase III	
✓	C	Compile reliability data on first 7 MegaModule systems.	Amonix routinely compiled field reliability from SolarTAC. Reported to DOE (Quarterly Reports).
✓	SG	MegaModule passes IEC 62108 and UL 8703 tests.	MegaModule passed IEC 62108 tests at TÜV-PTL in Tempe. Completed UL 8703 tests except for damp heat, which is in progress.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
Ensuring that Amonix's products are reliable and meet the requirements of standards such as IEC 62108 is critical to achieving success in the marketplace. Testing to demonstrate reliability is done in three parts. Highly-Accelerated Life Testing (HALT) and qualification testing were performed under this task, while fielded system testing was performed under task 11. This task also supports the collaborative development of international CPV standards through the International Electrotechnical Commission (IEC).

The focus of HALT testing is the cell package. Multijunction cells on germanium substrates have different thermal, mechanical and chemical properties than silicon cells, so the packaging of these cells must be demonstrated to survive such conditions as thermal cycling, concentrated ultraviolet light, vibration and humidity. Development of accelerated life test procedures was done in-house as well as in collaboration with TPP partners NREL & Spectrolab.

Qualification testing was conducted through Underwriters Laboratories and other Nationally Recognized Testing Laboratories. Special compliance tests (e.g. California Solar Initiative listing) were also performed. Note that Amonix's MegaModule is much too large to be subjected to qualification testing at traditional test laboratories. To support laboratory-scale qualification testing, Amonix prepared ~1 m^2 mini-modules, which include a single receiver plate of 30 cells, a lens parquet, and a frame of the same design as the MegaModule. Final qualification testing of a full MegaModule incorporated in an Amonix concentrator was performed by witness testing conducted at the Amonix test site at UNLV.

Phase I

Screening of materials to ensure that they met the requirements of IEC 62108 began in Phase I. Figure 4-1 shows examples of the IEC 62108 testing of candidate fast-cure adhesives for fastening the lens parquet to the MegaModule that led to identification of an appropriate adhesive (proprietary).

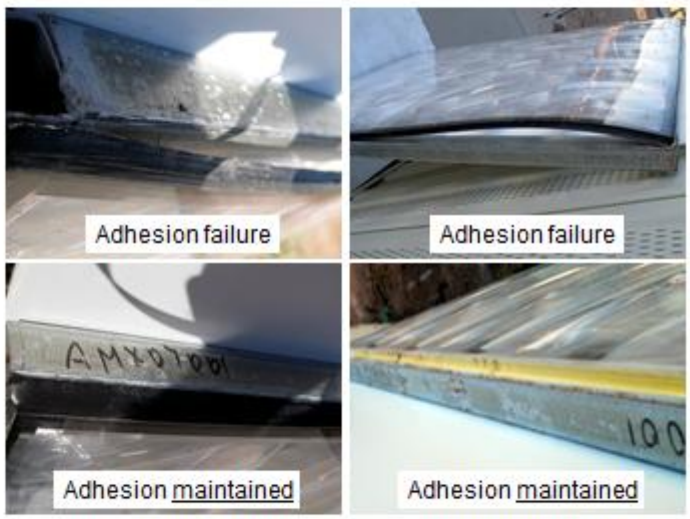


Figure 4-1: IEC 62108 testing of fast-cure adhesives for lens attachment.

Phase II

Highly-Accelerated Lifetime Testing: HALT testing is used to provide assurance of long-term reliability in the field. HALT builds on correlation of failure data from decades of field deployment with stress tests derived from qualification standards such as IEC 61215 "Crystalline silicon terrestrial photovoltaic (PV) modules—Design qualification and type approval", IEC 61646 "Thin-Film terrestrial photovoltaic (PV) modules—Design qualification and type approval" and IEC 62108 "Concentrator photovoltaic (CPV) modules and assemblies—Design qualification and type approval." For example, thermal cycling has been considered a useful stress test from the earliest days of PV. In all three IEC qualification standards, the thermal cycling test consists of 200 thermal cycles from -40° to +85°C. These tests were used to guide development of Amonix HALT plans since thermal cycling and related qualification tests provide confidence in cell packaging, somewhat independent of solar cell material. HALT testing of cell packages performed at NREL included thermal cycling, damp heat, weather-o-meter (UV plus 60°C and 60% RH), and humidity freeze tests to examine reliability of a non-production AR coating on the cover glass as well as the reliability of the package assembly including cover glass, solder, substrate, chip, etc. Additional HALT testing was performed on the multijunction cells. These tests provided information both on design elements that passed the design criteria and those needing further iteration or redesign. The successful designs that resulted from the testing are reflected in the summaries of the relevant design tasks.

Standards Testing: The MegaModule is both an environmental enclosure, protecting the multijunction cells and secondary optical elements from the moisture and soil, and an electrical enclosure containing the cells and associated conductors. To achieve UL-listing without requiring extensive materials testing requires that enclosure materials, especially polymers, be identified that are UL-recognized materials that still meet both performance and cost requirements. Some materials incorporated in the initial 7700 designs, such as the MegaModule condensation drains and air filtration, were replaced in consultation with UL to meet all of these requirements. IEC 62108 and UL draft 8703 testing were performed at UL labs in San Jose, California and TÜV Rheinland PTL labs in Tempe, AZ.

CEC/CSI listing: In addition to the goal of passing IEC 62108 and UL 8703 tests, Amonix also sought to meet the requirements to be included in the eligible California Solar Initiative (CSI) product list overseen by California Energy Commission (CEC) engineers. Required tests were performed at TÜV Rheinland PTL laboratories in Tempe, Arizona against a selected set of environmental and safety tests that were negotiated with and approved by CEC engineers. The tests came principally from IEC 62108 and the draft UL 8703 safety standards.Testing was completed and CEC listing was obtained on December 1, 2009. See http://www.gosolarcalifornia.ca.gov/equipment/other.php.

International CPV standards development: This task also supports the collaborative development of international CPV standards through the International Electrotechnical Commission (IEC). The Amonix task leader chairs the CPV Working Group, WG7, within the IEC PV Technical Committee, TC82. During Phase II, IEC members were working on the following draft standards and technical specifications:

- CPV power rating version of IEC 61853 power rating standard for flat plate modules,
- An IEC technical specification for a system acceptance test,
- An IEC technical specification for an energy performance rating using average performance,
- CPV safety standard following IEC 61730,
- An IEC technical specification for a tracker test protocol,
- A multijunction cell qualification standard,
- Edition 2 of IEC 62108 (Edition 1 was published in December 2007).

Amonix contributed system performance data to support development of the CPV energy performance rating standard. Figure 4-2 shows data that were collected under Task 11 on an Amonix 7500 system installed at UNLV.

Phase III

During Phase III, Amonix added staff and intensified its reliability testing. The detailed results of reliability tests leading to design changes and improvements are beyond the scope of this report. Final designs are discussed in the relevant tasks in this report. Highlights from reliability testing are briefly described here.

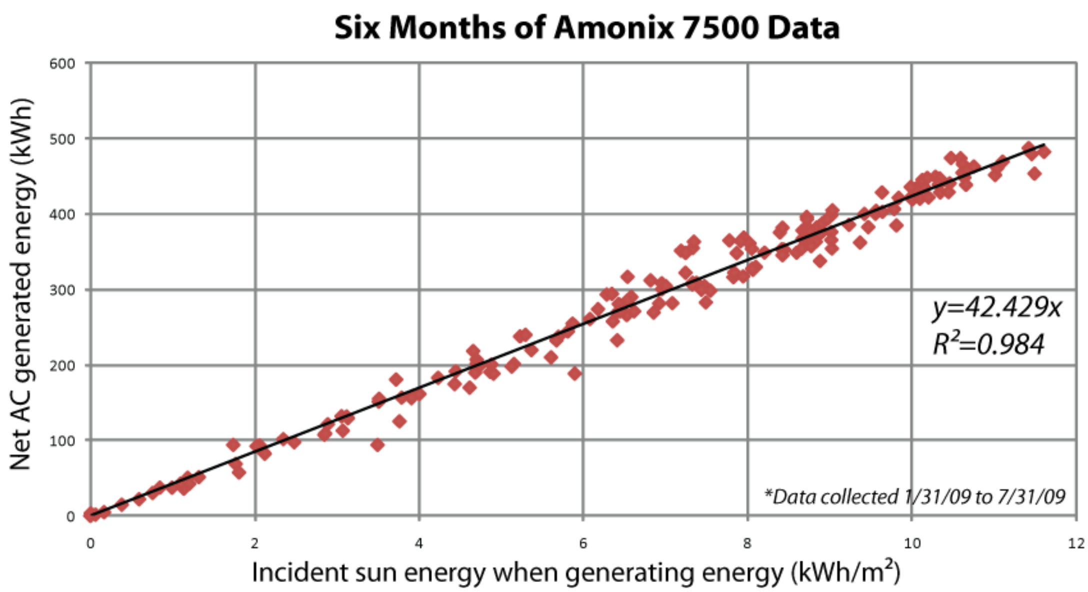


Figure 4-2. Net AC generated energy.

Highly-Accelerated Lifetime Testing: Testing was complete and described in a final, proprietary CRADA report by NREL. These verified performance on the following design elements:

- Protected cell package,
- Solder bonds that attach the concentrator cells to the package assemble,
- Lens material.

Standards Testing: All testing, including full MegaModule witness testing at UNLV, was completed and the Amonix system 7700 MegaModule passed all tests required for IEC 62108 certification. As shown in Table 4-1, those tests included preconditioning, thermal cycle, humidity freeze, damp heat, temperature test, and outdoor exposure.

Table 4-1. IEC 62108 certification status as of January 25, 2012.

7700-53 IEC				
Test	Current Status Pass/Fail	Status %	Forecast Closure (ECD)	Comment
Preconditioning	Pass	100%	Done	
Thermal Cycle	Pass	100%	Done	
Humidity Freeze	Pass	99%	12/13/11	Passed WIR and on Sun Testing; Pending Listing from Agency
Damp Heat	Pass	100%	Done	
Mechanical Load	Pass	100%	Done	
Temperature Test	Pass	100%	Done	
Outdoor Exposure	Pass	100%	Done	
OVERALL % Complete:		99%		

In-House and Full System Reliability Testing: Under the third phase of the TPP, Amonix emphasized system level reliability testing with continued work at UNLV and installation of 13 systems at SolarTAC in Denver, CO. Data were also analyzed from other Amonix projects, such as the 2 MW system installed in Tucson, Arizona. Field data are analyzed to understand system performance and reliability in real-world conditions, as illustrated below.

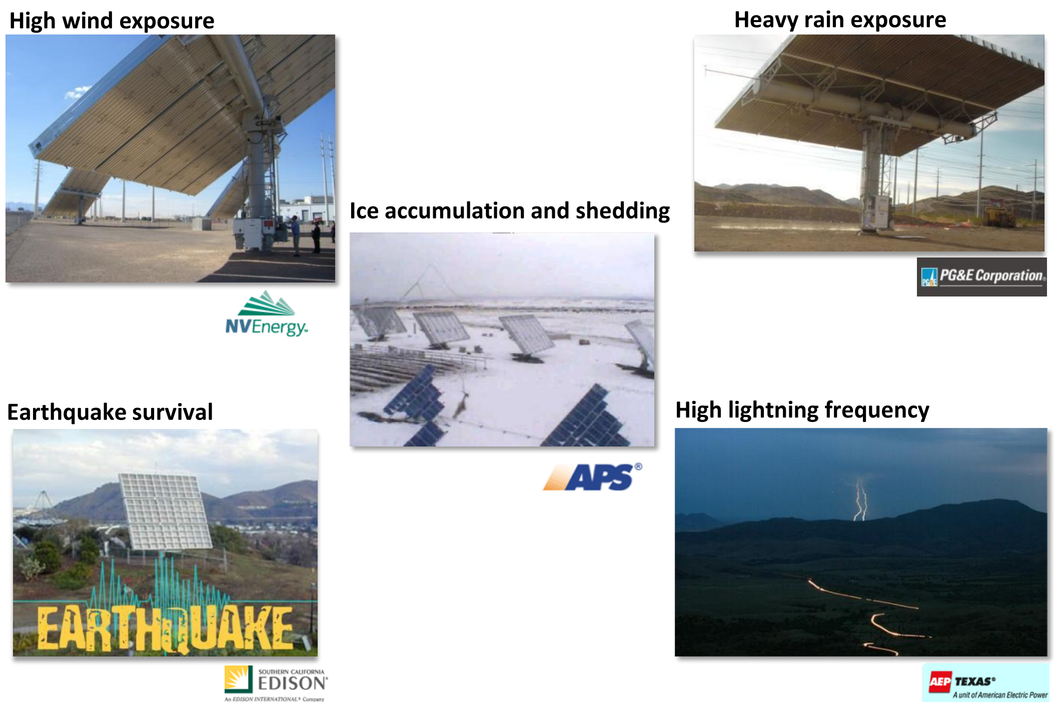


Figure 4-3. Improving reliability through field testing in real world conditions.

Amonix also established in-house test capability in the following areas:

- Developed and implemented hail impact test capability.
- Developed and implemented adhesive to lens compatibility test capability.
- Purchased environmental chambers capable of testing mini-modules for Damp Heat, Humidity Freeze and Thermal Cycle.
- Implemented adhesion strength test capability.
- Identified and purchased accelerated UV tester for material evaluation.

Testing completed by Amonix and its contractors also included:

- MegaModule transportation by highway and rail,
- Accelerated lens aging to evaluate transmission and hazing,
- Module drain system,
- Software quality and reliability.

International CPV standards development: Amonix continued as lead for the CPV Working Group, WG7, within the IEC PV Technical Committee, TC82. During Phase III, IEC members completed the following draft CPV standards and technical specifications:

- IEC 62670-1: draft Concentrator Rating Standard consisting of two rating conditions: a concentrator standard operating condition (CSOC) rating defined using 900 W/m^2 direct normal irradiance, an AM1.5D reference spectral irradiance distribution, 20 °C ambient temperature, and wind speed of 2 m/s. A second condition is a concentrator standard test condition (CSTC) rating defined using 1000 W/m^2 direct normal irradiance, an AM1.5D reference spectral irradiance distribution, and 25 °C cell temperature.

- IEC 62670-2: draft CPV energy rating standard based on the results of this task (see Figure 4-2) and similar measurements made at other labs including NREL and ISFOC.

- IEC 62688: draft IEC CPV safety standard having some elements of the draft US CPV safety standard, UL 8703. UL is now participating in the development of this IEC safety standard while TÜV Rheinland PTL is the designated project leader for the safety standard.

- IEC 62727 TS: draft IEC tracker technical specification that will be the basis for developing a draft tracker standard.

- IEC 62787: draft CPV cell qualification standard for both bare cells and packaged cells.

Task 5: Receiver Plate Production
TPP Task Participants: Amonix Phases I, II & III

Task Objective: Setup a high-volume, high-yield receiver plate assembly line.

Highlights:
- The receiver plate design was updated and improved for the multijunction cell package and to lower materials and manufacturing cost.
- A 25 MW/yr receiver plate assembly line was developed, validated, and placed into production.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	C	Design, fabricate and procure automated equipment for receiver plate assembly.	In progress. Completed in Phase II.
		Phase II	
✓	C	Qualify vendors for automating each process step in pilot line and order equipment.	Completed during Phase III.
		Phase III	
✓	C	Take delivery of and program equipment for full production line.	Complete.
✓	C	Complete design specifications and drawings for increased automation.	Complete.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
In receiver plate assembly, cell packages are mechanically and thermally mounted to a plate and interconnected electrically. Cooling fins are attached to the plate to dissipate thermal energy to the environment. The plate is modular and can be removed from a MegaModule, if necessary.

In this task, a pilot line was setup and a capacity analysis performed to find the bottlenecks for expansion to the full 25 MW production line. Once the process parameters were optimized, expansion into full production proceeded by addition of equipment, personnel and shifts to reach the capacity goal of 25 MW.

Phase I
The first phase of the project focused on the development of a receiver plate assembly process for the silicon solar cell. The initial design was for silicon, with a simple projected transition to the multijunction cell. In the initial investigation process for the transition, as in the package assembly case, a limitation arose in moving the silicon technology to the multijunction technology. One process step, ultrasonic welding of the package interconnect, was not compatible with the multijunction cell properties for high yield. Brazing was found to be an acceptable alternative that enabled establishment of a pilot-scale automated plate assembly line.

Of the original seven receiver plate assembly steps, Amonix found that two of the steps could be combined, reducing the number of assembly steps to six. During Phase 1, Amonix identified automation pathways and prepared purchase orders for equipment for three of the steps. Two of those orders were issued during the phase.

Performance was improved by incorporation of a new thermal interface material between the cell package and the receiver plate. Results of on-sun testing of this material are shown in Figure 5-1.

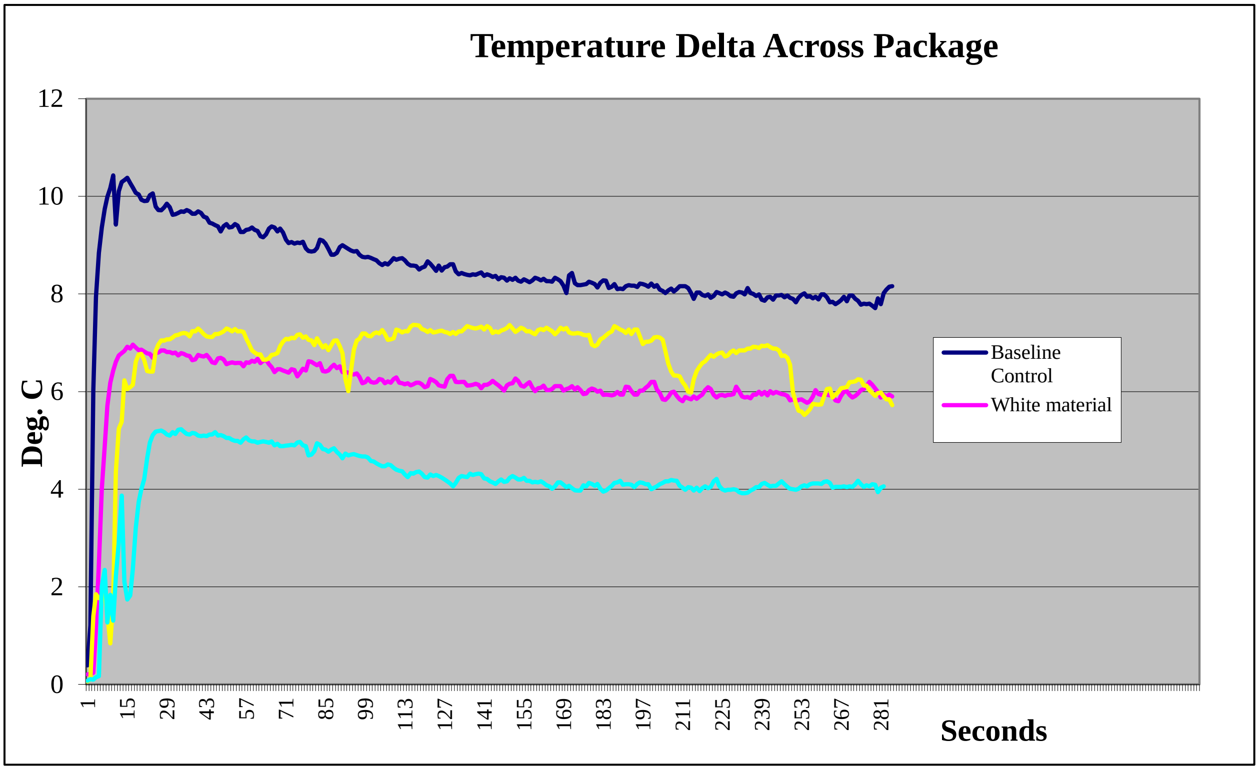


Figure 5-1: On-sun testing of candidate thermal interface material.

Phase II

Amonix continued process design, testing, procurement, and operation of the pilot receiver plate assembly line. An automated fastening machine was purchased to assemble both cooling fins and cell packages to the plate in medium volume. An alternative means of fastening the cooling fin to the plate was identified, as shown in Figure 5-2. The clinch fastener offered both a cost savings and a higher throughput, subject to final testing results.

The clinch attachment of the cooling fin to the receiver plate was then further refined and tested on-sun. Figure 5-3 shows the results of on-sun testing of the receiver plate with two versions of the clinch method of attaching the cooling fins to the receiver plate. While clinching enables an inexpensive powder coating process, the thermal performance was inferior, so it was decided to continue use of the existing fastener (the control in Figure 5-3).

Figure 5-2. Alternative cooling fin fasteners: simple fastener (left), clinch (right).

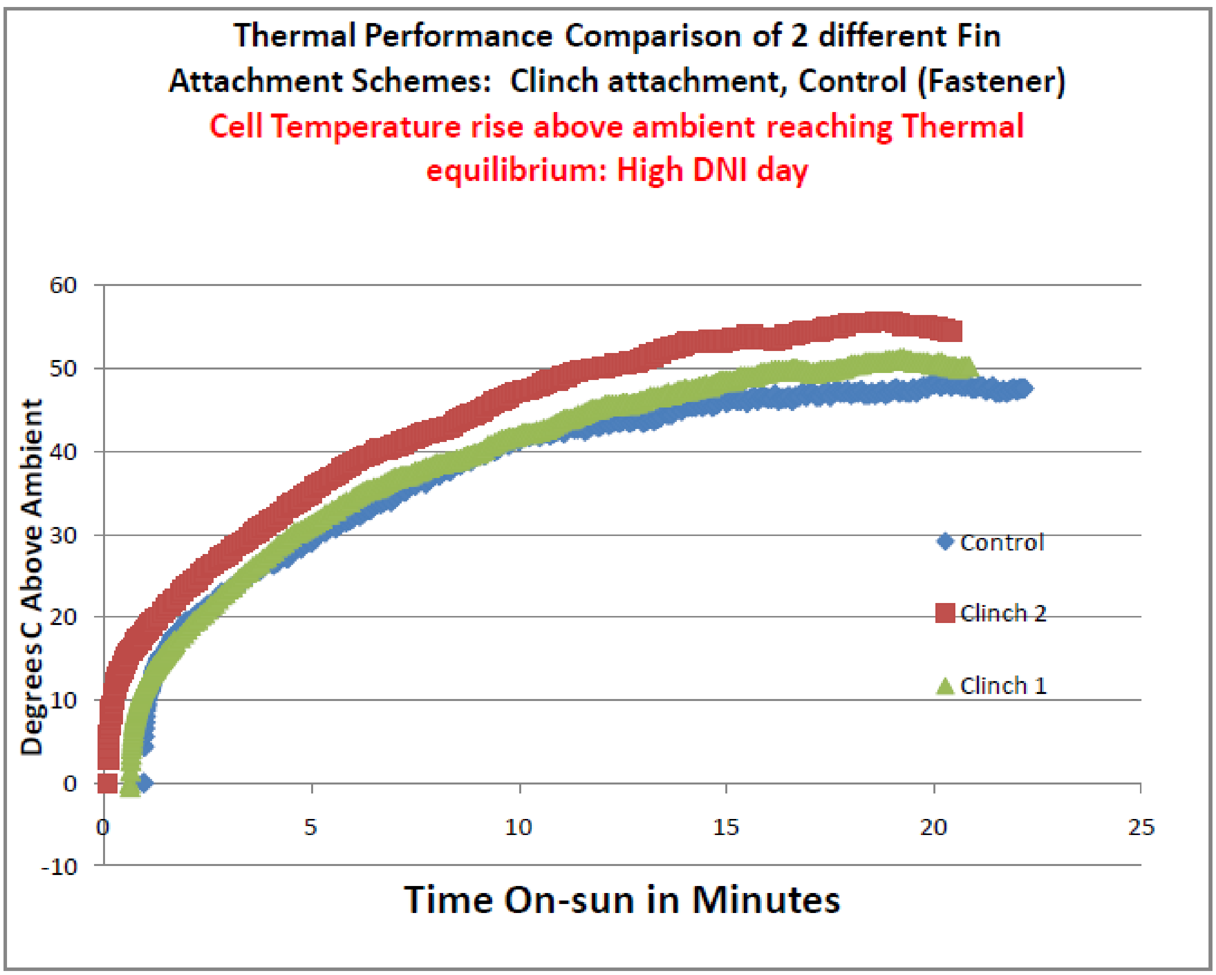


Figure 5-3. On-sun test of alternative fin attachments.

Two proposed processes for interconnecting the cell packages on the plate were explored. Both passed the technical specifications for interconnecting the packages on the plate. The one chosen for implementation was a cleaner, faster and ultimately less expensive process.

Receiver plates were fabricated on the pilot line using the automated equipment that was purchased through Phase II. Figure 5-4 shows the pilot line as of the end of Phase II.

Figure 5-4. Receiver plate assemble pilot line at the end of Phase II.

Phase III

Amonix completed developing and refining automation of receiver plate assembly. Development including in-situ forming of the interconnects between cell packages, fastening of the cell packages to the receiver plate, and an automated system for fastening the cooling fins to the plate. Conceptual designs of two automation stations that were acquired for evaluation are shown in Figures 5-5 and 5-6. In the end, full automation of some steps was not cost-effective because of the cost and time required for equipment maintenance. In production, some steps are performed at lower cost by operators on simpler machines requiring less maintenance. These included the secondary optical element/sunshield attachment and the brazing step. A laser weld was considered for this latter step but the machine maintenance requirements were found to be excessive.

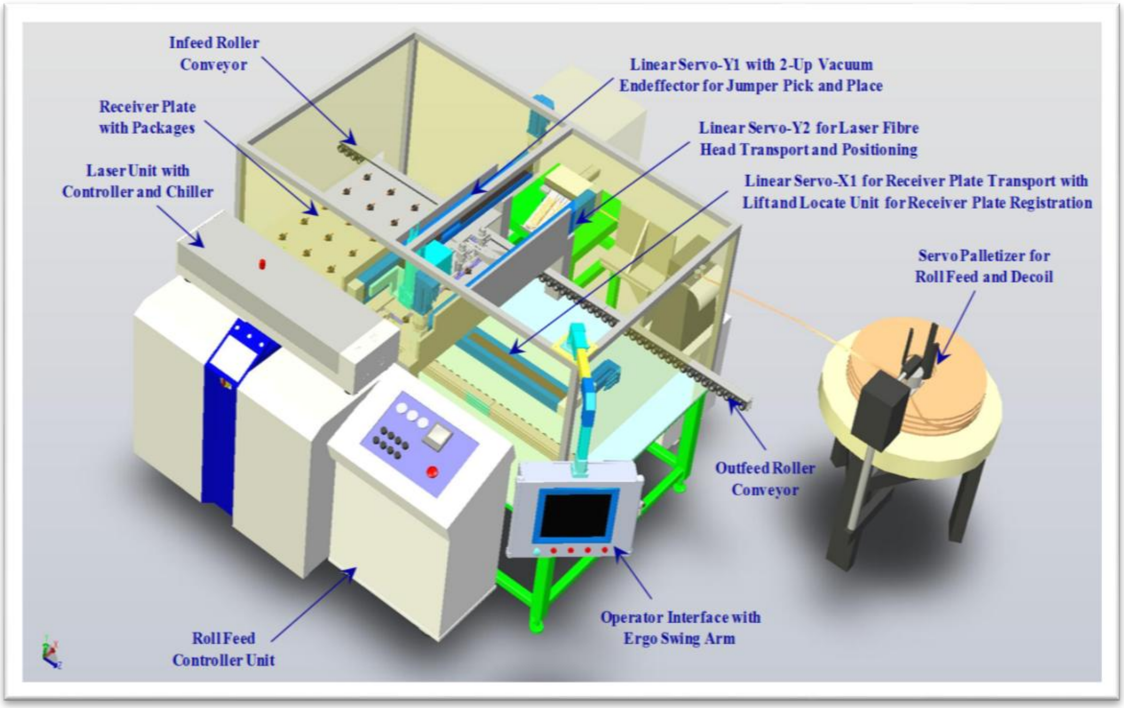


Figure 5-5. Laser welding automation tool.

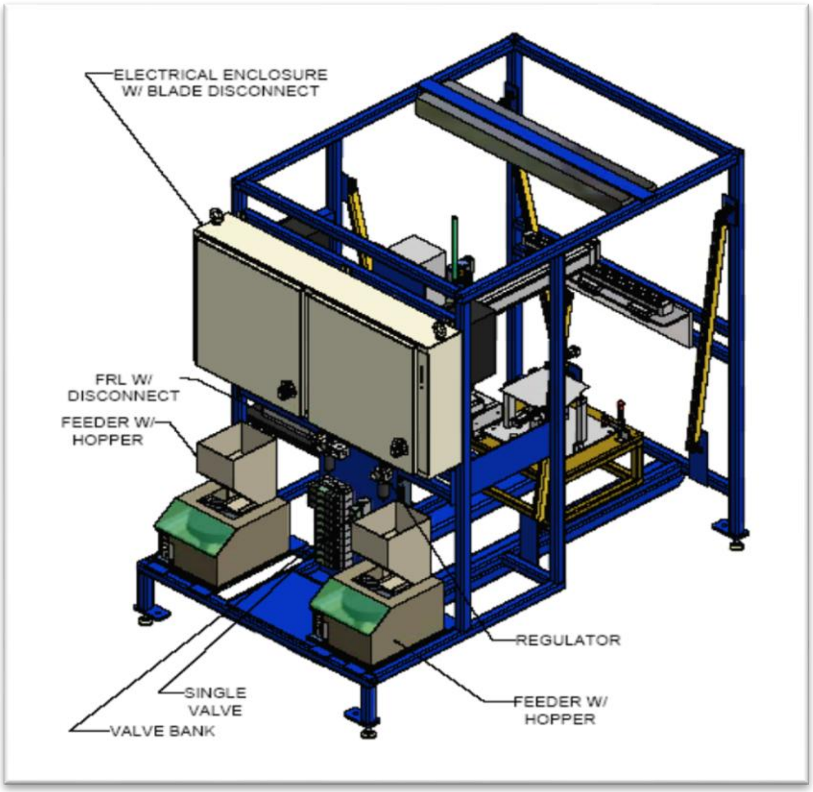


Figure 5-6: Plate package assembly station.

Following completion of initial production runs of the 25 MW/yr capacity receiver plate assembly line at Amonix's facility at Seal Beach, CA, the equipment was transferred to a North Las Vegas, NV production facility operated by Flextronics for Amonix.

Task 6: MegaModule Performance
TPP Task Participants: Amonix Phases I & II

Task Objective: Determine power and energy performance of plates, individual MegaModules and 7700 system.

Highlights:

- New 16” focal length silicon MegaModule exceeded baseline silicon MegaModule performance by 19%.
- Measured efficiency of 28.7% (STC) for multijunction MegaModule met Phase II and Phase II stage gates during Phase II.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	SG	Redesigned 16" Si MegaModule maintains or improves baseline module performance.	Field test by Sandia National Labs showed 19% improvement.
		Phase II	
✓	SG	Demonstrate 24% DC MegaModule efficiency (PTC).	Field test by Sandia National Laboratories showed 28.7±1.5% efficiency at STC, 26.9±1.4% at PTC.
✓	C	Year-to-date report on receiver plate performance.	Complete.
		Phase III	
✓	SG	Demonstrate 26% DC MegaModule efficiency (PTC).	Phase II field test by Sandia National Laboratories showed 28.7±1.5% efficiency at STC, 26.9±1.4% at PTC.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments

This task synthesizes field testing data from Task 11 and cell performance data from Task 1 to evaluate MegaModule performance and validate the receiver plate design. It is the receiver plate, with its cell packaging, heat transfer and circuitry, which is at the heart of the MegaModule performance.

Phase I

Figure 6-1 shows the installation of three different 16” focal length MegaModules installed on an existing tracker at UNLV. Also under test is a receiver cell plate with 24 multijunction cells installed in a 21” deep mini-module, adjacent to a baseline 21” focal length silicon MegaModule.

Personnel from Sandia National Laboratories test and evaluation group measured the performance of the 16” focal length prototype silicon MegaModule as well as the baseline 21” focal length silicon MegaModule. Sandia determined that, under Standard Test Conditions (DNI = 1000 W/m^2, Air Mass 1.5D, T_c = 25°C), the efficiency of the 16” prototype silicon MegaModule exceeded the output of the baseline 21” focal length silicon MegaModule by 19%. This exceeded the requirements of the Phase I stage gate milestone and validated the design of the 16” focal length MegaModule.

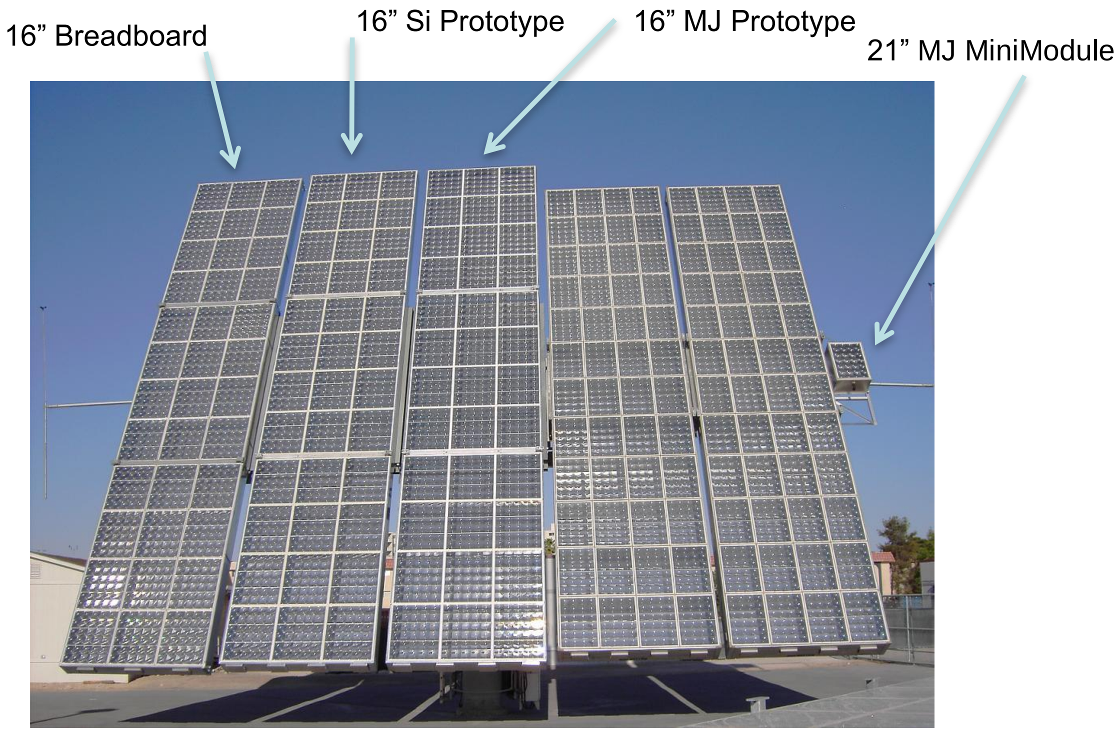


Figure 6-1: Prototype modules under test at UNLV.

The 7 kW multijunction mini-module shown to the right in Figure 6-1was deployed to support testing of the redesigned multijunction cell package and receiver plate modifications. As shown in Figure 6-2, the use of cell passivation (i.e. encapsulation) packaging showed promising results relative to a previously tested unpassivated cell both in initial and long-term performance.

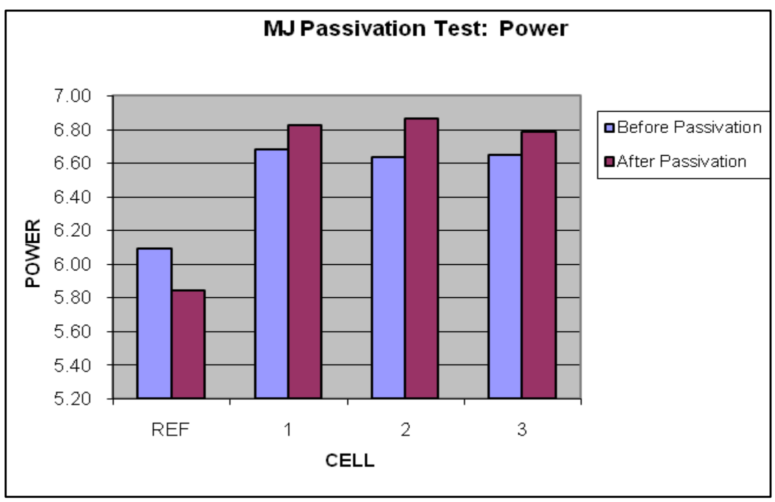


Figure 6-2: On-sun test results for passivated and unpassivated multijunction cells.

Phase II

The MegaModules shown in Figure 6-1 were replaced with a full complement of five multijunction Mega-Modules. One of these MegaModules was independently tested on-site by Sandia National Laboratories. Based on an area of 38.732 m^2, Sandia measurements of the MegaModule DC efficiency were 28.7±1.5% at Standard Test Conditions and 26.9±1.4% at PVUSA Test Conditions (DNI = 850 W/m^2, AM1.5D, T_a = 20°C, WS = 1 m/s), as shown in Table 6-1. This not only met the stage gate for Phase II but also the stage gate for Phase III.

Table 6-1: Prototype multijunction MegaModule test results measurements by Sandia National Laboratories.

STC Conditions (DNI=1000 W/m2, AM1.5D, 25C)							
Isc	Voc	Imp	Vmp	FF	Pmp	Ap Eff	
(A)	(V)	(A)	(V)		(W)	(%)	
33.75	420.1	30.31	366.4	0.783	11105	28.7	
±1.3	*±7.1*	*±1.3*	*±12.4*	*±.008*	*±599*	*±1.5*	
PVUSA PTC Conditions (DNI=850 W/m2, AM1.5D, Ta=20C, WS=1 m/s)							
Isc	Voc	Imp	Vmp	FF	Pmp	Tcell	Ap Eff
(A)	(V)	(A)	(V)		(W)	(°C)	(%)
28.93	394.0	26.17	338.8	0.778	8865	66	26.9
±1.1	*±6.7*	*±1.1*	*±11.5*	*±.008*	*±478*	*±5*	*±1.4*

Phase III

No further activity on this task occurred during Phase III because the stage gate was met during Phase II.

Task 7: MegaModule Cost Reduction
TPP Task Participants: Amonix Phases I & II

Task Objective: Implement further cost reductions for the MegaModule production line.

Highlights:
- Redesigned 16" focal length MegaModule achieves target materials and cost reduction.
- Redesigned 16" focal length MegaModule passes IEC 62108 certification tests.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	SG	Redesigned 16" MegaModule design yields combined materials, manufacturing and labor production cost reduction of 35% over baseline MegaModule structure.	Data delivered to Navigant Consulting for due diligence.
		Phase II	
✓	C	Weldments redesigned, performance (stiffness) verified.	Complete.
✓	C	Redesigned MegaModule components pass IEC qualification tests.	Complete. Certified to IEC 62108 in Phase III.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
Under this task, Amonix sought to reduce MegaModule cost by reducing material use and cost and assembly time and cost. The approach taken includes:
- Revision of the mechanical structure of the MegaModule to achieve necessary stiffness and strength, while reducing material weight and cost,
- Component cost reduction through design-for-fabrication,
- Alternative fabrication methods & components to reduce total assembly time and labor cost
- Revisions needed to comply with codes and standards, and
- Revisions made in response to problems discovered during field deployment of prototype MegaModules.

Phase I
One of the primary steps taken to decrease material usage was to reduce the depth of the MegaModule by changing the lens focal length from 21 inches to 16 inches. The previous Amonix MegaModules were 21 inches deep. Figure 7-1 illustrates some of the designs that were studied using finite element analysis. The analysis concluded that the 16 inch deep structure achieves sufficient mechanical bending-stiffness. In contrast, neither of the 12 inch deep alternatives exhibit sufficient stiffness, unless thicker steel sections are attached, which add material and labor costs. Compared to the original design, the 16 inch design uses less material and eliminated many fabrication assembly steps.

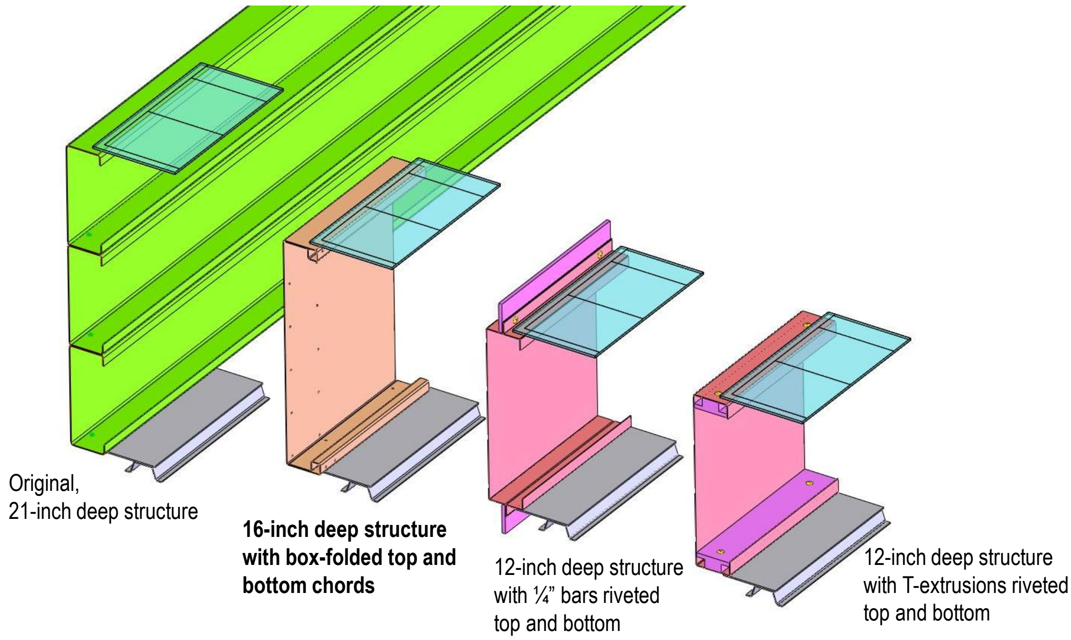


Figure 7-1: MegaModule design alternatives.

A significant cost savings and high performance was achieved through automated installation and alignment of the lens parquets on the MegaModule. Figure 7-2 shows the in-process development of one of the production robots that Amonix used for the alignment, placement, and adhesive-fastening of the Fresnel lenses to the MegaModule.

Figure 7-2: In-process development automation of lens alignment, placement, and adhesive-fastening.

Phase II

Modification of the MegaModule design continued during Phase II to reduce materials and manufacturing costs as well as to ensure compliance with IEC and UL requirements. Some of the key changes included:

- Optimized weldments in the central welded structure to reduce steel material content,
- Implemented a less expensive corrosion-protection method for the central welded structure by replacing the previous hot dipped galvanizing process with a high service-temperature, exterior-grade, zinc-loaded paint,
- Developed alternate MegaModule fasteners & methods to reduce assembly time,
- Selected and qualified a fast-curing lens-attachment adhesive and submitted it for UL certification (it is now a UL listed product),
- Shortened the height of the MegaModule's central welded structure to allow 5 MegaModules to be transported on a flatbed truck without violating DOT truck-height restrictions (see Figures 7-3 and 7-4),
- Made small revisions to some of the structural components in order to improve the MegaModule's resistance to water intrusion,
- Re-specified the MegaModule's condensation drains and air filtration components to meet UL requirements, while maintaining low cost.

Figure 7-3: The MegaModule's central welded frames serve two purposes, (1) to fasten each MegaModule to the sun-tracking structure and (2) for securing the MegaModules together for truck-transport.

Figure 7-4: By shortening the height of the MegaModule's central welded structure, the Series-7700 MegaModules can be stacked 5-high on a trailer, without violating DOT truck-height restrictions.

A key step in the automation of MegaModule assembly was the completion of the lens-alignment and installation robotic system shown in Figure 7-5. The MegaModule design and assembly process was validated through the fabrication and installation of 30 MegaModules. These MegaModules included several individual 7500- and 7700-series MegaModules installed at University of Nevada at Las Vegas, and (using non-project funds) Amonix 7500-series systems installed at the Southern Nevada Water Authority (see Figure 7-6).

Figure 7-5. Lens alignment & installation robot.

Figure 7-6. Amonix 7500-series systems installed at Southern Nevada Water Authority. These MegaModules incorporated a less expensive corrosion-protection design and easier-to-install fasteners.

During the final quarter of Phase II, a number of small changes were made to the MegaModule design to improve manufacturability and field assembly, as follows. Feedback from field installation (task 10) led to additional changes to the MegaModule's main mounting joints to improve leveling and bolting of the MegaModules. Feedback from field testing (task 11) led to some additional minor changes, such as the addition of weep holes to lateral structural members within the MegaModule. Standardized drawings, finalized bill of materials, and formal documentation were completed for all MegaModule components.

The MegaModule was then placed into production, completing this task. During Phase III, the production line was moved from Amonix's Seal Beach facility to a new production facility in North Las Vegas, Nevada. This production facility is operated for Amonix by Flextronics, a large contract-manufacturing company.

Task 8: Factory Setup and MegaModule Production
TPP Task Participants: Amonix Phases I& II

Task Objective: Implement all production lines and processes for capacity of 25 MW/yr.

Highlights:
- Receiver plate and MegaModule assembly automation designed and implemented.
- 25 MW production capacity achieved.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	SG	Plant and equipment design & plan for 7 MW production line is complete including selection of building, development of handling equipment, design of assembly fixtures and fabrication of shipping accessories.	Building selected and NEPA form filed. Plan complete and execution underway.
		Phase II	
✓	C	Commission MegaModule manual work unit equipment, tools, and fixtures.	Complete.
✓	C	Commission MegaModule semi-automated lens installation work unit equipment, tools, and fixtures.	Complete. Lens installation automated.
✓	SG	Validation of MegaModule semi-automated work unit.	Data delivered to Navigant Consulting for due diligence.
		Phase III	
✓	SG	Demonstrate production rate of 25 MW/year meeting 2010 cost target.	Production demonstrated at Amonix Seal Beach facility. Production transferred to Amonix/Flextronics North Las Vegas plant where 3 lines have a total production rate of 90 MW/yr.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments

Task Description:
The objective of Task 8 was to construct and equip the office and factory spaces required for production of the complete MegaModule, including an environmentally-controlled area for manufacture of the Amonix multijunction package and non-controlled areas for receiver plate subassembly and MegaModule finished goods assembly, as well as general maintenance, receiving, inventory, staging and shipping. MegaModule manufacturing includes all equipment required to transfer the raw materials into the line, perform the mechanical structural subassembly, transfer the structure into and out of the

manual or automated lens station where the lens supports and lenses are installed, and transfer of the MegaModule from the manual or automated station into the final assembly and staging/shipping area.

Phase I
Amonix began plant and equipment design to achieve high-volume production, including comparison of centralized and distributed production concepts; establishment of factory requirements to meet current production and location of facilities that meet the requirements; development of handling equipment: design and fabrication of assembly fixtures; and design and procurement of truck transport accessories.

Work completed included the search for and selection of suitable manufacturing space as well as the associated NEPA forms required by DOE. This plant can accommodate the cell packaging and receiver plate assembly lines discussed in tasks 3 and 5. Amonix also designed and developed assembly fixtures for the MegaModule and began work on automation of lens installation and alignment (task 7). The new plant is shown in Figure 8-1.

Figure 8-1: Amonix Seal Beach facility.

Phase II
During Phase II, construction of the Amonix Seal Beach facility was completed for production offices and factory spaces, engineering offices and labs, and administrative offices. The Seal Beach factory includes an environmentally controlled lab for multijunction package manufacturing and non-conditioned areas for receiver plate subassembly, MegaModule finished goods assembly, as well as general receiving, inventory, staging and shipping.

An initial manual MegaModule production line was installed and commissioned including the overhead crane system required to support both the manual and automated MegaModule production lines. Completion of an initial production run of 30 MegaModules (Figure 8-2) validated internal process capability.

Figure 8-2: First MegaModule production run.

A second production line was installed with the automated lens alignment installation unit (Task 7), and an initial production run was initiated during June, 2009 to validate internal process capability. Opportunities for MegaModule design and fabrication improvements were identified during equipment commissioning and initial production and were incorporated into the process design.

Amonix development of production and quality metrics began with preparation of initial documentation including a preliminary Amonix Quality Manual, preliminary and released standard operating procedures, work instructions, production line visual aids, workmanship standards, manual and ERP generated job order travelers, and quality control log sheets.

During the final quarter of Phase II, Amonix incorporated the equipment and process changes to the Amonix factory and MegaModule production line that were identified during the system verification in the last quarter of Phase II. Also achieved during the first quarter of Phase III was the completion and release of all manufacturing and quality process documentation including work instructions, workmanship standards, visual aids, quality checklists and test specifications. In addition, all bills of materials were completed and released to allow job order material tracking.

Task 8 was then closed in order to focus remaining project funds on quantifying and improving reliability (tasks 4 and 11). Task 8 completed its Phase IIstage gate milestone, provided the foundation for the DOE Manufacturing Investment Tax Credit awards, and set the stage for further manufacturing demonstrations using investor funding instead of DOE cost-shared funds.

Task 9: Tracking Systems
TPP Task Participants: Amonix, Hitek, Raytech Phases I, II & III

Task Objective: Verify Gen 1 tracker meets specifications, reliability goals, and cost target, and develop and verify a Gen 2 tracker, with 10% less material than Gen 1.

Highlights:

- Completed and fielded Gen 1 trackers for Amonix 7700 series system.
- Updated wind loads and performed computational fluid dynamics analysis to support design of Gen 2 tracker.
- Completed and fielded Gen 2 trackers for Amonix 7700 systems with lower weight, lower manufacturing and installation costs, and improved performance.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	C	Establish drive requirements and loads.	Complete.
✓	C	Complete and review drive design for seven-MegaModule system.	Complete.
		Phase II	
✓	C	Review of CFD analysis for nominal cases.	Complete.
✓	C	Completion of tracking controller acceptance testing.	Complete.
✓	C	Detail design review of Gen 2 tracker (10% weight reduction).	Complete.
✓	SG	Demonstrate successful operation of Gen 1 7700 tracker [Within 0.15 degrees tracking all day, 1.75 min stow, 9 to 90 degrees and + 180 degrees azimuth rotation].	Field Test by Sandia National Laboratories showed specification met except ±0.15° azimuth. Specification met in Phase III.
✓	C	Build and begin testing Gen 2 tracker.	Completed in Phase III.
		Phase III	
✓	C	Review of strain gauge field data and analytical analysis for Gen 2.	Complete.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
Task 9 supports the development and test of a new tracking system for the 7700 product. The first tracker supported initial 7700 series system deployment. A second generation tracker was built in Phase III following extensive design studies and benefited from the field experience with the Gen 1 unit.

Phase I
During Phase I, Amonix developed system requirements (see milestone table above) and, with Raytech, developed load designs (e.g., wind load when tracking and when stowed) for multiple sites andused this data to design a tracker and first generation (Gen 1) drive system for their 7700 CPV system. A contract

was placed with Hitek for a new tracking control system that will have lower cost, higher reliability, and additional operating features.

Phase II

The first Gen 1 hydraulic tracker was fabricated and installed for testing at UNLV, and tracking accuracy was characterized at UNLV by Sandia National Laboratories, as shown in Figures 9-1 and 9-2. Tracking accuracy was monitored with a pair of optical sensors which measure tracking error in elevation and in the direction which is perpendicular to elevation, which is called cross elevation. (Cross-elevation error may be converted to azimuth pointing error by dividing by the cosine of the elevation angle.) Note that the tracking error monitors measure relative error, which is the reason the data are shifted to create a mean of zero in the figures below. Amonix determined that these errors arose from several factors, including deflection in the azimuth drives, deflection in the coupling to the azimuth encoder, and the inability of the azimuth drive to rotate sufficiently fast at high elevation angles. The total energy lost was estimated at 5%, which while small, did merit corrective action.

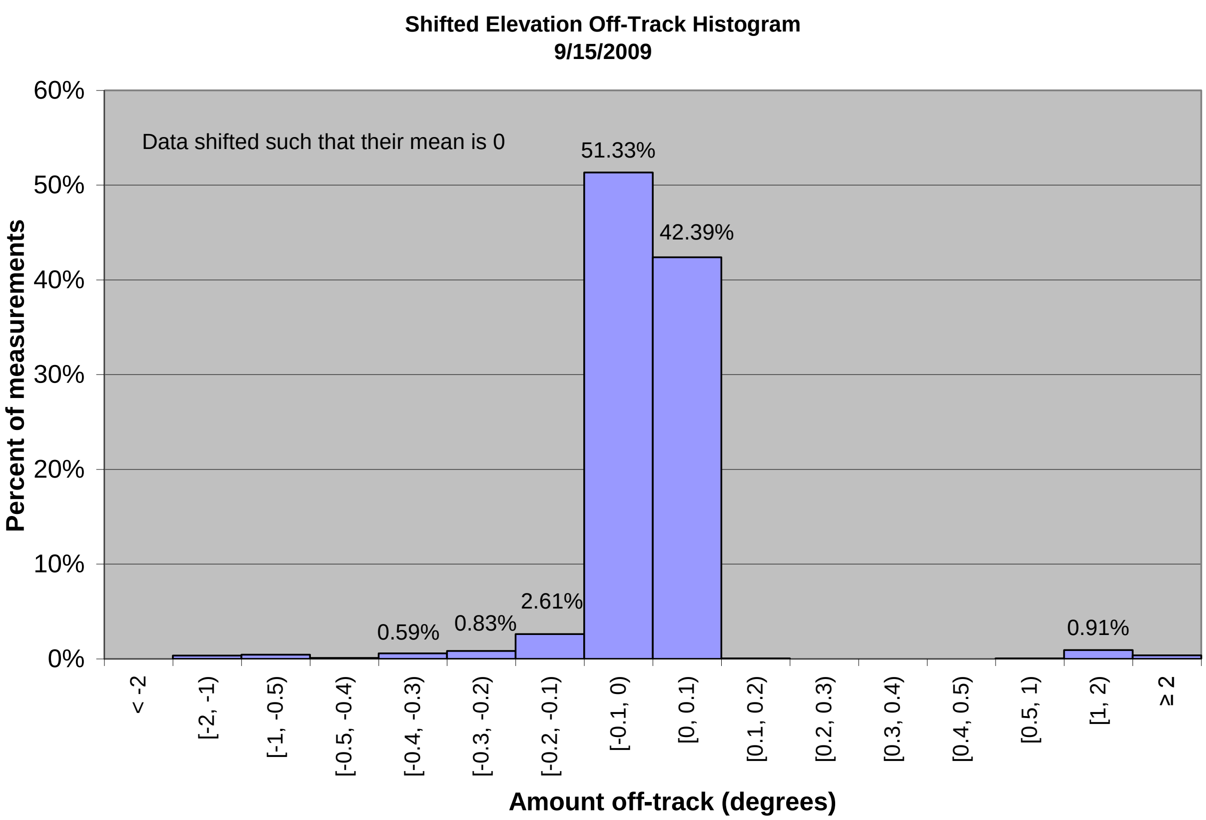


Figure 9-1: Histogram of elevation tracking errors for 9/15/2009.

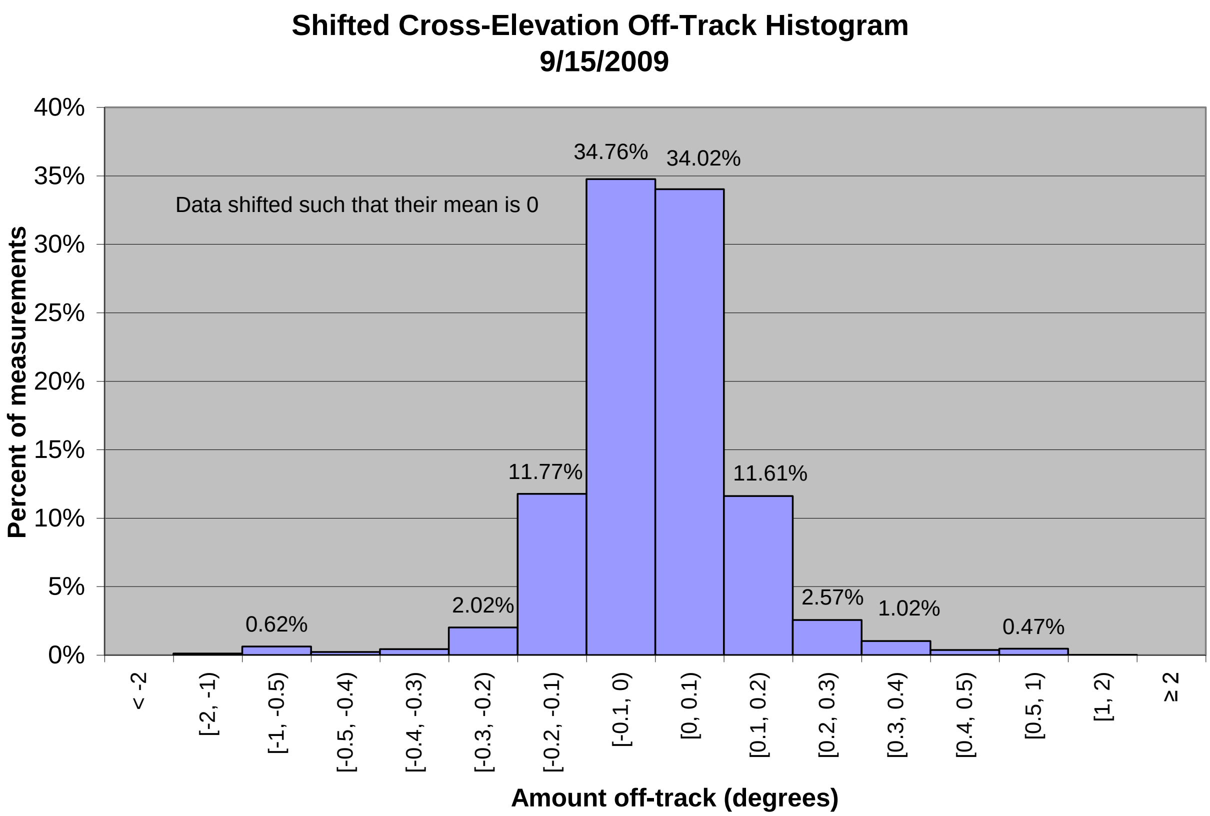


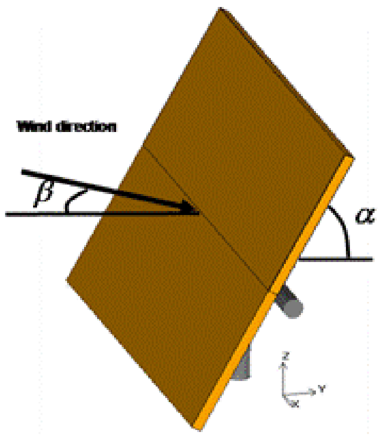
Figure 9-2: Histogram of cross-elevation tracking errors for 9/15/2009.

Outside the scope and funding of the TPP, an additional six unitswere installed at the Southern Nevada Water Authority (Figure 9-3) to provide additional O&M data. Installation and operation of these trackers provided input to design and deployment of the next generation tracking system.

Figure 9-3: Gen 1 tracking systems installed at Southern Nevada Water Authority.

The 2nd generation system was developed using more accurate quantification of loads, more accurate assessment of structural margins, and reduction of excess structural margins, with the goal of improving performance and reducing costs. This process included Computation Fluid Dynamics (CFD) analysis, Finite Element Analysis (FEA), drive head component testing, and field measurements of actual strain and deflection under load.

Design loads for the Gen 1 tracker were estimated using relatively coarse empirical relations from a widely known study by Dr. J. Peterka, et al. For the second generation tracker, detailed CFD calculations were performed following an analysis plan developed with the objective of obtaining more refined understanding of wind-induced forces with the system in various poses, at multiple wind angles and wind speeds (Figure 9-4).



Case	Wind Speed [mph]	α [o]	β [o]	γ [o]
A	30	40	180	0
B	30	83	65	0
C	30	83	0	0
D	90	0	90	-10
E	90	0	45	-10

Figure 9-4. CFD load cases.

The CFD analysis yielded fully developed 3D flow fields, with velocity and pressure visualizations (figure 9-5). Transient analysis revealed some Von Karman vortex shedding with long-periods (>8 sec); no oscillations in frequency ranges likely to excite structural resonances were found. Pressures acting on the structure were resolved into forces and moments acting at key locations on the structure.

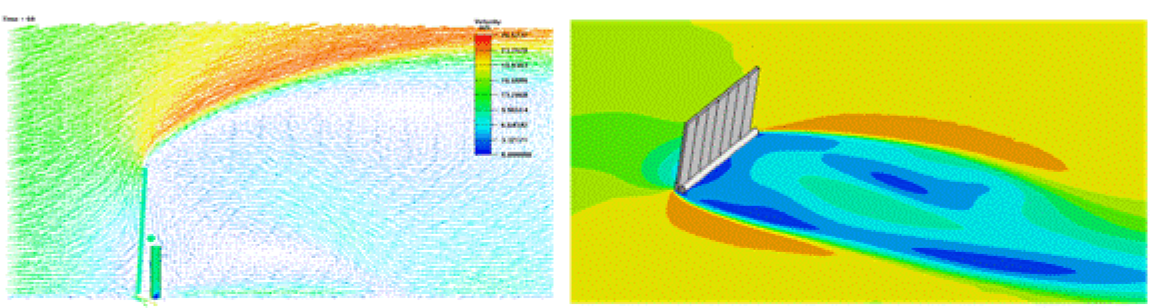


Figure 9-5. Sample flow visualization results for load case C.

Net steady state loads were compared to the original design loads. The premise that the original loads were overestimated held up in all 30mph cases. However, the Peterka method loads were much lower than CFD calculated loads in the 90 mph wind stow conditions that were studied (Load Cases D & E).

In developing the Gen 2 tracker, additional structural analysis was performed, as illustrated by the stress and deflection visualizations shown in Figures 9-6 and 9-7. This analysis and Design for Manufacturing and Assembly studies showed that, for the Gen 2 design, fabrication labor could be reduced 31%, part count 19%, and material weight 12% relative to the Gen 1 design.

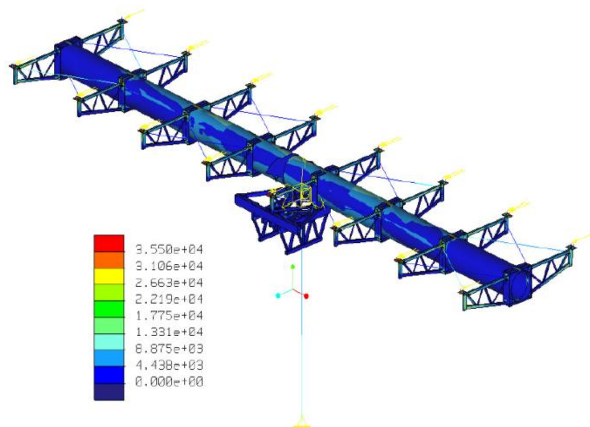


Figure 9-6. FEA output – low stresses under 90 mph winds.

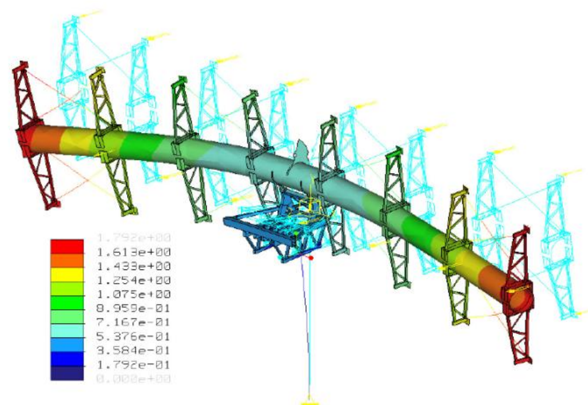


Figure 9-7. FEA output – low deflections under 30 mph winds.

Phase III

Amonix continued to improve both the fielded Gen 1 and the new Gen 2 tracking and control systems. Changes made to encoder linkages and the hydraulic controls for the Gen 1 tracker at UNLV improved tracking accuracy. As reported by Sandia, the retest of the system showed that “the elevation tracking error (monitor) indicated that over 99.9% of the errors were within the (specified) range of ±0.15°. The cross-elevation tracking error monitor found that 97% of the errors were within ±0.15°.”

Development of the lower cost, lower weight Gen 2 tracking system was completed and verified and a test system was installed at City of Industry, CA, as shown in Figures 9-8 and 9-9.

After completion of testing of the Gen 2 design, Amonix undertook a second iteration of cost reduction by redesigning the drive and torque tube outrigger weldments. This design was first implemented at California State Polytechnic University, Pomona. Additional units were installed at California State Polytechnic University, Pomona; at SolarTAC in Aurora, Co (Figure 9-10); and at University of California, Irvine. The SolarTAC environment provided additional cold weather requirements, which were relevant to the 30 MW commercial installation at Alamosa, CO.

Figure 9-8. New drive head installation at City of Industry, CA.

Figure 9-9. Installation of cost-reduced torque tube, pedestal and outriggers at City of Industry, CA.

Figure 9-10. SolarTAC site with 7700-60 units, Aurora, CO.

Task 10: Installation &Balance of System (BOS)
TPP Task Participants: Amonix Phases I, II & III

Task Objective: Develop installation techniques and Balance of System equipment that increase energy performance and reduce costs.

Highlights:
- Designed and deployed Balance of System(Wiring and Inverter) for Amonix 7500 and 7700 series systems.
- Developed and refined installation hardware for Amonix 7500 and 7700 series systems.
- Reduced time to install MegaModules and torque tube to 3 hours per system.
- Developed effective, lower water use lens washing system.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	C	Balance of System design/review.	Modeled wiring and inverter requirements; began soiling study. Completed in Phase II.
✓	C	Test Balance of System design.	Postponed to Phase II.
✓	C	Field installation process design/review.	Design and testing of installation hardware underway. Completed in Phase II.
		Phase II	
✓	C	Site design review for first 7700 system.	Complete.
✓	SG	Install and operate 7700 system.	Delayed 2 months after stage gate. Reported to DOE (quarterly report). Press release 10-27-2009.
✓	C	Installation fixtures and methods design review.	Underway, completed in Phase III.
✓	C	Report on washing and soiling study.	Complete. Reported to DOE (quarterly report).
		Phase III	
✓	C	Study of alternative inverter configurations.	Completed during Phase II.
✓	C	Design review of next generation installation equipment.	Complete.
✓	C	Review of installation equipment testing.	Complete
	C	Update of field soiling and washing study.	Complete. Reported to DOE (quarterly report).
✓	C	Deploy systems in three different locations.	TPP-funded systems installed at UNLV, SolarTAC, CalPoly-Pomona, City of Industry, and UC-Irvine.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
This task includes the design, fabrication, and testing of equipment for installation and Balance of System equipment that will reduce installation and operating cost. This investigation includes field

wiring and inverter configurations, Fresnel lens soiling reduction strategies, and various tools and methods to simplify field installation of the Amonix HCPV systems. Feedback on the installation process was obtained from various Amonix installations, including ones not funded with DOE or cost-share funds.

Phase I

During Phase I, Amonix initiated designed of the Balance of System for the 7700 system, including field wiring, to reduce cost and increase reliability. An electrical performance model of the silicon-cell receiver plate was developed for field wiring and inverter specifications, and model development for the multijunction configuration was initiated.

Work began on field installation process design and testing. Initial design of a MegaModule spreader bar for loading and unloading MegaModules was completed, and a lifting bracket was designed and tested during installation of a 16" deep MegaModule at UNLV. A conceptual design of a field assembly fixture for the drive system was completed.

A contract was placed with UNLV to investigate lens soiling rate, washing method, solutions, coatings, etc. and a test plan was prepared for evaluation of soiling rate and washing methods. Soling rate studies were begun at three sites.

Phase II

Design, deployment, and refining of installation hardware and processes proceeded as deployment of the MegaModules and Gen 1 tracking systems was performed. The first group of 5 MegaModules was installed using the new lifting hardware on an existing tracker at UNLV. Six 7500 systems, each including five MegaModules and a Gen 1 tracking system, were installed at Southern Nevada Water Authority, as shown in Figure 10-1. A time and motion study for unloading the MegaModules from the truck and installing them on the tracker-mounted torque tube was conducted. Excluding periods when high wind speed interrupted installation activities, the time required to install a set of five MegaModules on units 3-6 was 30±5 minutes, with the time declining as the crew gained experience.

Figure 10-1. Six series 7500 systems at Southern Nevada Water Authority.

The first 7700 system was installed at UNLV, using project funds. Figure 10-2 shows MegaModule installation underway at that site. For this installation, the service module was assembled at the factory and shipped to the site. The service module, shown in Figure 10-3, includes the inverter, AC interface box, hydraulic controller, tracking controller, conduit, etc. The service module is mounted to the tracker and rotates with the tracker in azimuth.

Figure 10-2. MegaModule being installed on the first 7700 system.

Figure 10-3. Service module assembled in factory and installed on the 7700 system at UNLV.

Two versions of the Solectria PV series inverter were fielded for these systems: the PVI 60 for the Amonix 7500 systems and the PVI 82 for the Amonix 7700 system. Both units are CSI eligible inverters and have an energy weighted efficiency rating of 95.5%. Multijunction PV devices have a very sharp power-voltage profile, and several software modifications were implemented by Solectria for use with Amonix MegaModules, including an improved filter to mitigate an overheating problem apparently related to the sharp power generation profile of the Amonix system. Discussions were held with Solectria and other inverter manufacturers to understand evolving trends in the industry and to familiarize suppliers with our specific needs. Of particular interest for the utility market is the need for inverters which can provide low voltage ride through and reactive power.

These seven installations established a baseline for assembly cycle time and labor required for each process step for the Gen 1 tracker and Balance of System. This installation experience brought better understanding of the true needs for specialized installation tooling. Some previously considered tools appear less useful than originally assumed, while some unanticipated needs for others emerged and were implemented later in Phase II. Among the specialized installation tools developed for these installations were:

- MegaModule lifting brackets and spreader bar,
- Torque tube ground assembly fixture,
- Drive head ground assembly fixture,
- MegaModule Hoist Quick-Release Tool,
- Laser alignment method.

Use of a forklift to install MegaModules was explored, but rejected as impractical.

At the end of Phase II, Amonix completed the design of a beta version of the service module to address a number to improve field assembly relative and reduce cost relative to the alpha design.

Phase III

During Phase III, Amonix completed a number of improvements to the Balance of System design and to system installation hardware and processes, as discussed below. These improvements were evaluated during system installations that occurred during Phase III.

Amonix fielded the beta version of the service module. Reduced part count and increased use of factory-assembled modules led to reduced manufacturing cost and field assembly time. The new pre-assembled service module, shown in Figures 10-4 and 10-5, was filled with hydraulic fluid in the factory, was transported from the truck via forklift, and integrated into the system in less than three hours at Amonix's City of Industry test site, compared to ten hours required to install the previous version of the service module. Additionally, the improved layout eliminated 85% of the fieldwork related to electrical conduit assembly and 80% of the cost of conduit materials.

Figure 10-4
Service module hydraulic side.

Figure 10-5
Service module electrical side.

Several installation tool concepts were evaluated during installation of the pedestal, drive, torque tube, and MegaModules at the City of Industry site, as shown in Figure10-6   Among the tools evaluated were pedestal stabilizers, outrigger spacers, and fixtures for hoisting the MegaModules.

Figure 10-6: MegaModule installation at City of Industry, CA.

While installation of the MegaModules from truck to torque tube can be performed very quickly, as shown in the figure a crane and two aerial platforms were required. Later in the phase, additional installation tools were developed to enable lifting the torque tube with the MegaModules already installed, as shown in Figure 10-7. This allows the MegaModules to be installed on the torque tube while it is still at ground level, which shortens installation time, improves safety, and reduces the disruption of MegaModule installation due to high wind speeds. This rapid deployment capability means that all seven MegaModules of the Amonix 7700 System can be up and tracking in approximately three hours – from truck bed to tracker in less than half a day. A video is available on-line at: http://amonix.com/sites/default/files/AmonixInstallation_5_no_music.swf.

Figure 10-7. Lifting seven MegaModule array to drive head.

Through ongoing installations of ten systems, some at sites not involving DOE funding, Amonix was able to finalize its installation and commissioning manuals as well as certify installation and operation and maintenance.

Amonix also designed and costed alternatives to the standard drilled pier pedestal, including vibratory pile (Figure 10-8), extended height (for distributed power applications in parking lots), and bolt on flange for use with a spread footing where piers or piles are not practical. The first of two systems were installed at UC Irvine with the first system being supported by the TPP and the second system to be installed under a separate Amonix/UCI project funded by the California Public Utility Commission.

Figure 10-8: Vibratory installation of pedestal.

Figure 10-9 shows the method Amonix has developed to clean the lenses on its systems. The use of a specially-designed brush mounted on an extended pole is more effective, and uses less than half the water and half the manpower than the off-the-shelf brush and spray system shown in Figure 10-10. Concentrating solar systems are more sensitive to soiling than non-concentrating systems because light that is redirected by soil cannot be concentrated. A cost-effective cleaning approach that requires minimal water is advantageous.

Figure 10- 9. Amonix-designed **e**xtended pole brush used to wash lenses.

Figure 10-10: Off-the shelf brush and spray system.

As shown in Figure 10-11, the effects of soiling were modeled in Task 1 using the multijunction cell parameter model. Initially, a flat 6% soiling derate factor was applied. This linear correction was revised to reflect 12% soiling after three months without cleaning at the UNLV site. This corresponds to an annual mean of a 6% soiling rate if the system is cleaned four times each year. The location at UNLV is subject to urban soiling levels exacerbated by its position in the flight path of the Las Vegas airport and consequent exposure to volatile organic compounds from jet fuel residue. Thus, the soiling rate observed at the UNLV site represents something of a worst-case scenario. This situation was made even worse in late August 2009 when forest fires in the Los Angeles area caused a drastic (and visible) decrease in Las Vegas air quality.

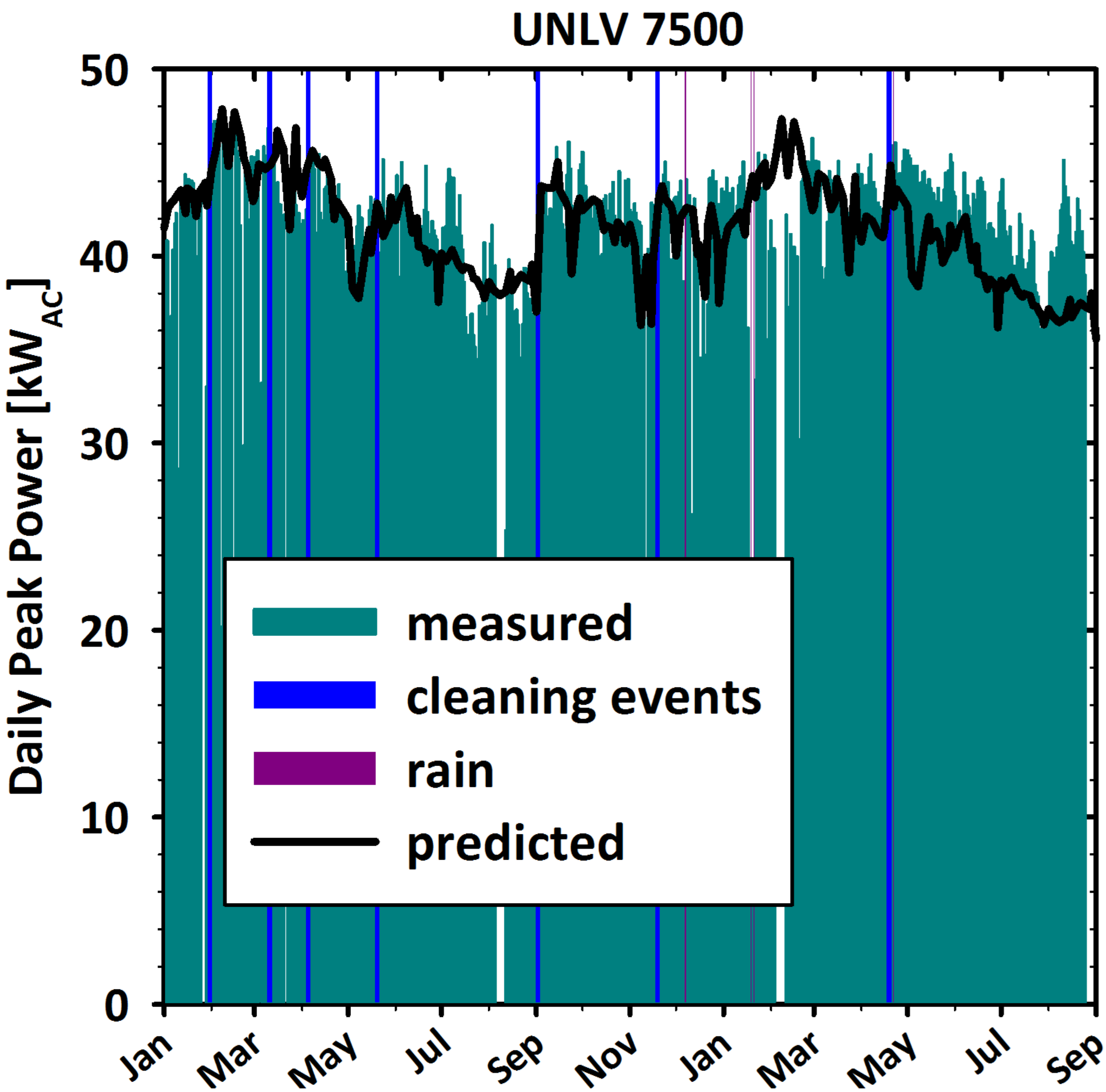


Figure 10-11. Predicted and modeled performance with cleaning events and rain. Performance predicted from TMY-3 data, not real-time measured data.

Task 11: Field Testing
TPP Task Participants: Amonix, UNLV Phases I, II & III

Task Objective: Verify and monitor performance and reliability of the 7700 system.

Highlights:
- Data monitoring systems were implemented and reliability data were collected, and energy production was measured and modeled for fielded systems.
- A SCADA system was developed and implemented to provide system remote monitoring and control.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	C	Test first prototype 16" focal length MegaModule.	Complete.
		Phase II	
✓	C	Acceptance test of first 7700 system.	Complete.
✓	C	Review of power, energy, tracking & reliability performance of first operating system.	Complete. Reported to DOE (quarterly reports).
		Phase III	
✓	SG	Compile reliability data on first 7 MegaModule system.	Amonix routinely compiles field reliability from SolarTAC. Reported to DOE (Quarterly Reports).

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments
This task performed acceptance tests and collected energy performance data, reliability data, and O&M labor time and material from fielded systems, including the 7500 and 7700 test systems installed at UNLV and the six Amonix 7500 systems at Southern Nevada Water Authority. Additional measurements made under this task included deflection under load and strain measurements. These data were provided to other tasks to inform research and development.

This task also supported development of Supervisory Control and Data Acquisition (SCADA) to support remote monitoring and control of system operation.

Phase I
Testing was performed on the 16" breadboard and multijunction prototype MegaModules installed at UNLV under task 6 (see Figure 6-1). Static loads and gravity sag were measured for the 16" focal length "breadboard" MegaModule, as shown in Figure 11-1. Initial efficiency tests were also performed for the prototype 16" multijunction MegaModule, as reported in Task 6, Table 6-1. Weather, solar resource, and performance data from a 21" focal length mini-module were collected as well.

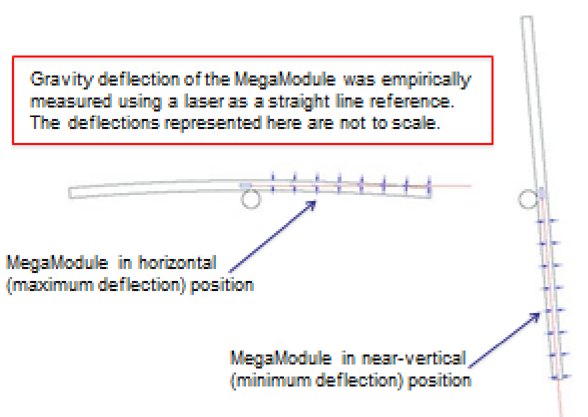


Figure 11-1: Deflection testing of 16 inch MegaModule.

Phase II

Amonix began testing of five multijunction MegaModules on an existing tracker at UNLV in November, 2008. In addition to automated performance monitoring, IV measurements on a single string were performed on a regular basis, as shown in Figure 11-2. These single string measurements are particularly opportune since variables such as lens cleanness, tracking, etc. can be controlled closely. Strain gauges were installed and correlations between wind and performance were monitored.

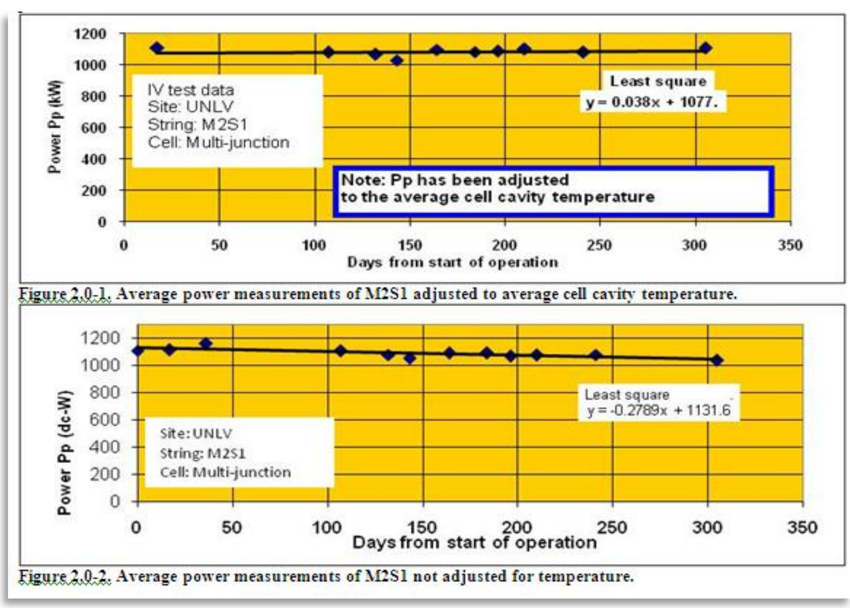


Figure 11-2. Peak power measurements on string MS21, with and without temperature corrections.

Installation of a 7 MegaModule system at UNLV and six non-DOE-funded 7500 systems at Southern Nevada Water Authority brought the number of MegaModules being tested to 42. Two different predictions (one with flat soiling and the other with a linear time-dependent soiling model) were used to compare predicted performance to measured performance. The impact of lens washing events cleaning on performance was also monitored. Figure 11-3 shows the Data Acquisition System that was used to monitor energy production during Phase II. Weekly reports were generated and provided to the relevant tasks. Accumulated energy generation at Southern Nevada Water Authority (SNWA) is shown in Figure 11-4.

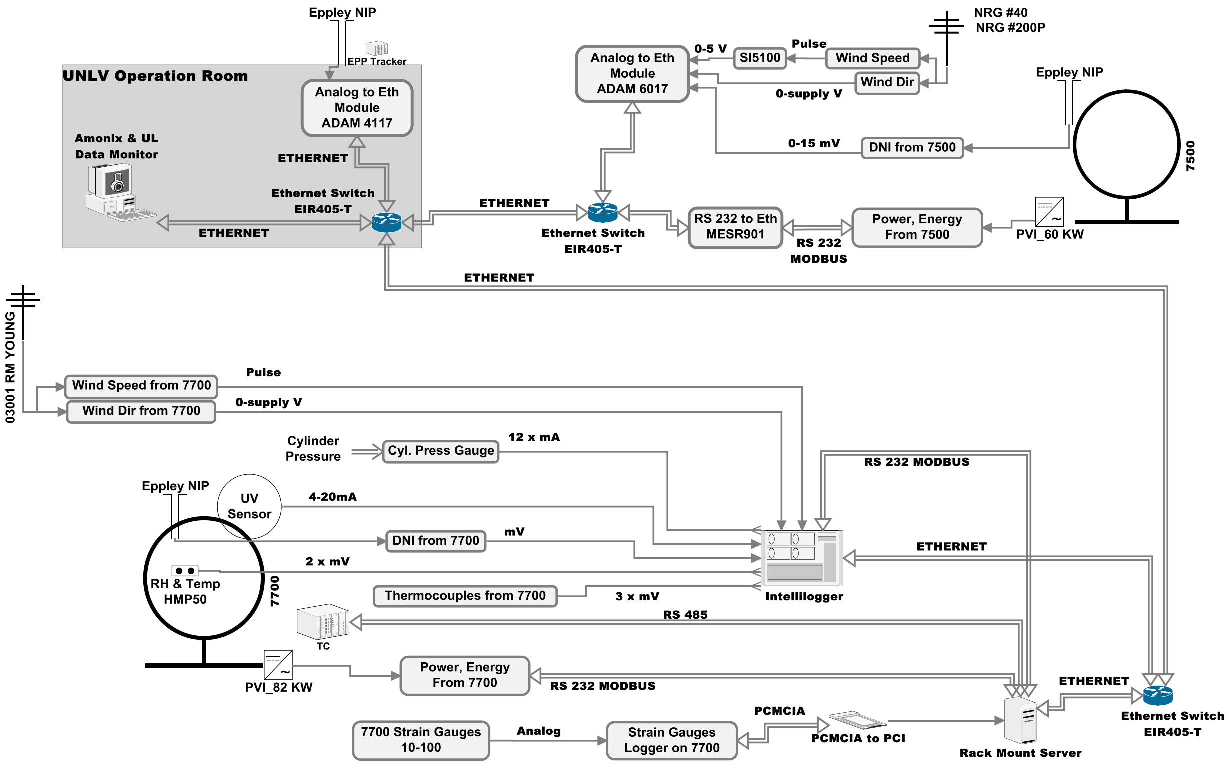


Figure 11-3. Data Acquisition System.

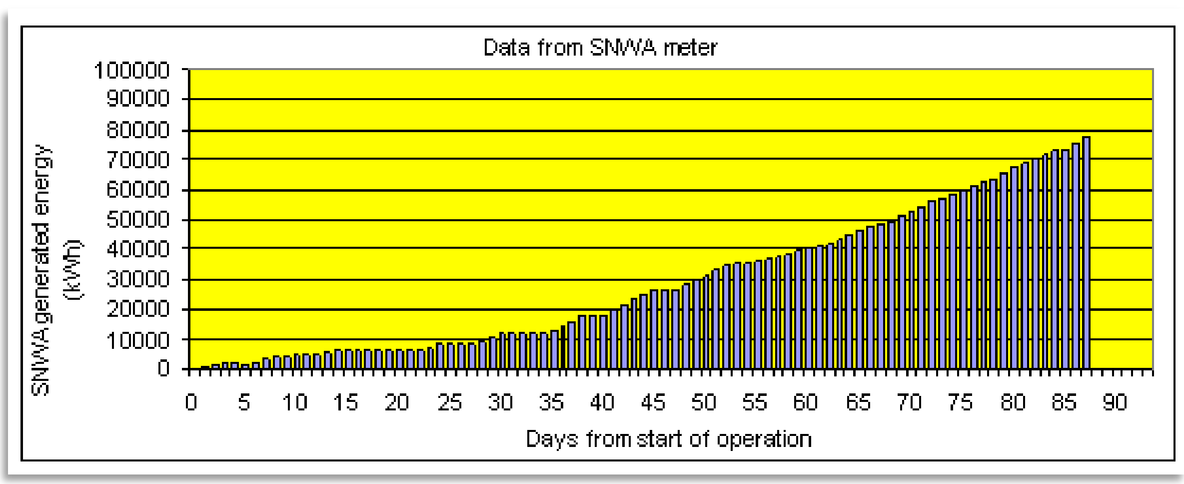


Figure 11-4. Accumulated net AC energy as measured by SNWA field meter.

Additional instrumentation was deployed as needed to monitor and diagnose system operation. For example, to monitor tracking system operation, tracking was monitored along with power output, hydraulic pressure, and corresponding strains, and correlated with ambient weather conditions.

Phase III

During Phase III, Amonix upgraded the data and weather systems to include the ability to provide real-time monitoring of inverter health and output power as measured with a revenue grade meter for the 7500 and 7700 systems at UNLV. The UNLV real time monitoring system also collected the following environmental data: wind speed, wind direction, ambient temperature, relative humidity, UV irradiance, MegaModule temperature, and direct normal irradiance, as well as both system power outputs. The monitoring software was improved to generate a weekly production report, track planned and unplanned outages, and compare production with expected generation, using a performance curve generated from year-long data on the 7500 system.

A SCADA roadmap was developed and implemented, including upgrade of the tracker controller software language to Modbus so that information from the controller information could be included in the dashboard and recorded by the server. Support of remote control and command via laptop computer was also implemented.

The field testing task also supported testing of installation hardware and O&M, as described in Tasks 9 and 10.

Task 12: Solar Advisor Modeling and Market Analysis
TPP Task Participants: Amonix Phases I, II & III

Task Objective: Under this task, analysis is performed to demonstrate progress towards DOE-established Key Performance Parameters (KPP) goals, including calculations of projected Levelized Cost of Energy (LCOE) and projected market volume.

Highlights:

- Measured performance and manufacturing cost data show that Amonix is on-track to meet DOE's Levelized Cost of Energy goals for 2015.

Milestone Summary

		Milestone	Status as of Phase Completion
		Phase I	
✓	SG	Demonstrate progress towards 2010 KPP goals of: LCOE of $0.14/kWh and manufacturing capacity of 25 MW/Year.	Data delivered to Navigant Consulting and Sandia National Labs for due diligence.
		Phase II	
✓	SG	Demonstrate progress towards 2010 KPP goals of: LCOE of $0.14/kWh and manufacturing capacity of 25 MW/Year.	Data delivered to Navigant Consulting and Sandia National Labs for due diligence.
		Phase III	
✓	SG	Achieve 2010 KPP goals of: LCOE of $0.14/kWh and manufacturing capacity of 25 MW/Year.	Data delivered to Navigant Consulting and Sandia National Labs for due diligence.

SG = DOE Stage Gate Milestone. C = Internal Amonix Control Milestone

Technical Accomplishments

At the application stage and at each stage gate, calculations were made of Levelized Cost of Energy for the current year and projected for future years using NREL's Solar Advisor Model (now called the *System* Advisor Model, which also models non-solar technologies). Amonix determined system performance parameters through regression analysis of measured performance and weather and solar resource data. Manufacturing cost data were developed as the manufacturing line was installed and placed into pilot production and volume production. Installation and O&M costs were developed and refined as systems were installed and operated, both through this project and commercially.

Cost data were submitted to DOE's due diligence consultant, Navigant Consulting, Inc., which performed an independent analysis of the data. The performance analysis and Levelized Cost of Energy calculations were submitted to Sandia National Laboratories for independent review.

Key inputs into the LCOE calculation are annual energy production, expected rate of degradation in annual output, system location (solar resource and weather), installed price, operating and maintenance costs, and assumed financial parameters. Because Amonix targeted the utility market, DOE required that the analysis be performed assuming Independent Power Producer financing. IPP financing requires the project developer to assume project risk in exchange for an expected return on investment. Under these assumptions, Levelized Cost of Energy is higher than it would be if commercial financing is assumed in which the user of the energy is the customer that purchases the system. The DOE-mandated financial parameters are shown in Table 12-1.

Table 12-1. DOE specified location and financial data.

	Required Values
Environment	
Climate	AZ Phoenix.tm2
Financials	
Type of Financing	IPP/Utility
General	
Inflation Rate (%)	2.5
Analysis Period (yrs)	30
Real Discount Rate (%)	7.5
Loan Term (yrs)	20
Loan Rate (%)	6
Loan (Debt) Fraction (%)	Optimized
Federal Tax (%)	35
State Tax (%)	8
Property Tax (%)	0
Insurance (%)	0
Sales Tax (%)	0
Federal Depreciation Type	MACRS-Mid-Q
State Depreciation Type	MACRS-Mid-Q
Constraining Assumptions	
PPA Escalation Rate	0
Target Internal Rate of Return	15
Target Minimim Debt	1.4
Positive Cash Flow	Yes
Incentives	
Federal ITC Percent (%)	10

Note that, for consistency, DOE assumes a Federal Investment Tax Credit of 10%, and not the currently available 30% credit. That is because the 30% credit did not exist when this project began and will expire, whereas the 10% credit is permanent, at least until the tax code is changed. All calculations are also required to be performed in 2005 dollars, consistent with DOE's LCOE goals. An inflation rate of 2.5% was used to deflate current year dollars to 2005.

The Levelized Cost of Energy targets established by DOE at the start of the project are shown in Table 12-2.

Table 12-2: DOE cost targets for grid-connected PV systems in key market sectors (2005 $'s).

Market Sector	Current U.S. Market Range (c/kWh)[1,2]	Solar Electricity Cost – Current and Projected (c/kWh)[1]		
		Benchmark	Target	
		2005	2010	2015
Residential[3]	5.8-16.7	23-32	13-18	8-10
Commercial[3]	5.4-15.0	16-22	9-12	6-8
Utility[4]	4.0-7.6	13-22	10-15	5-7

[1]Costs are based on constant 2005 dollars.
[2]Current costs are based on electric-generation with conventional sources.
[3]Cost to customer (customer side of meter)
[4]Cost of generation (utility side of meter)

Figure 12-1 and Table 12-3 summarize the Levelized Cost of Energy calculations performed by Amonix over the course of the project, based on the expected performance, installed cost, and O&M costs. The green shaded area shows DOE's LCOE targets for reference. Amonix's LCOE projections have been fairly consistent through the life of the project except at the first stage gate in 2008, when the early stage of transition from silicon to multijunction technology led to more conservative calculations. The data show that Amonix projects its cost of energy will meet DOE targets.

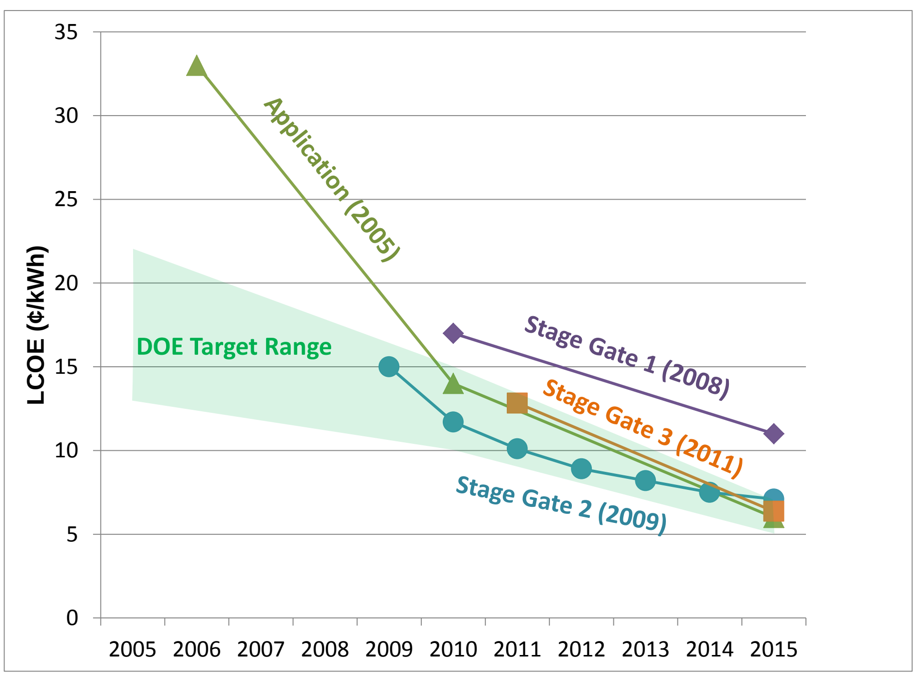


Figure 12-1. Projected Levelized Cost of Energy in ¢/kWh (2005 $'s) calculated using NREL's Solar Advisor Model and DOE-specified financial assumptions. Project-specific LCOE will vary depending on location and project financing.

Table 12-3. Projected LCOE (¢/kWh) in 2005 dollars *(year projection made).*

	DOE Target Range *(2005)*	AMONIX			
		App. *(2005)*	**SG 1** *(2008)*	**SG 2** *(2009)*	**SG 3** *(2011)*
2005	13-22				
2006		33			
2007					
2008					
2009				15.0	
2010	10-15	14	17	11.7	
2011				10.1	12.8
2012				8.9	
2013				8.2	
2014				7.5	
2015	5-7	6	11	7.1	6.4

Another Key Performance Parameter of interest to DOE is annual manufacturing capacity. At the time of the application and at each stage gate, Amonix projected manufacturing capacity for years 2010 and 2015. The first row of Table 12-4 shows the year in which the projections were made. *Actual capacity data*are given for years 2009 and 2011.

Table 12-4. Projected manufacturing capacity (MW's) vs. time of projection (stage gate-year) .

Target Year	**Proposed** (in 2005)	**SG 1** (2006)	**SG 2** (2009)	**SG 3** (2011)
2009			*0.2*	
2010	60	60	16	30
2011				*90*
2015	1000	1000	>500	>500

Deliverables

Task		Deliverable	Criteria	Status as of Phase Completion
		Phase I		
4	✓	Redesigned 16" Si module passes all relevant aging tests as listed in the draft IEC concentrator standard.	ASU test results of module components subjected to aging tests.	Si IEC test conducted. Multijunction module certified to IEC 62108 in Phase III.
6	✓	Redesigned 16" Si MegaModule maintains or improves baseline module performance.	Access to installed and fully operational Si MegaModule at UNLV for testing.	Field test by Sandia National Labs showed 19% improvement.
7	✓	Redesigned 16" MegaModule design yields combined materials, manufacturing and labor production cost reduction of 35% over baseline MegaModule structure.	Manufacturing cost study report including material and equipment quotes and data to enable Navigant cost analysis.	Data delivered to Navigant Consulting for due diligence.
8	✓	Plant and equipment design & plan for 7 MW production line is complete including selection of building, development of handling equipment, design of assembly fixtures and fabrication of shipping accessories.	Plant & equipment plan.	Building selected and NEPA form filed. Plan complete and execution underway.
12	✓	Demonstrate progress towards 2010 KPP goals of: LCOE of $0.14/kWh and Manufacturing Capacity of 25 MW/Year.	Stage gate report with updated analysis of key performance parameters.	Data delivered to Navigant Consulting and Sandia National Labs for due diligence.

Task		Deliverable	Criteria	Status as of Phase Completion
		Phase II		
3	✓	Selection of final production package design/process.	Report to DOE of package design selection.	Complete. Reported to DOE (Quarterly Reports).
6	✓	Demonstrate 24% DC MegaModule efficiency (PTC).	Access to MM site for DOE testing.	Field test by Sandia National Laboratories showed 28.7±1.5% efficiency at STC, 26.9±1.4% at PTC.
8	✓	Validation of MegaModule semi-automated work unit.	Report on production capability and updated manufacturing cost study including time/labor assessment and data to enable cost analysis.	Data delivered to Navigant Consulting for due diligence.
9	✓	Demonstrate successful operation of Gen 1 7700 tracker [Within 0.15 degrees tracking all day, 1.75 min stow, 9 to 90 degrees and + 180 degrees azimuth rotation].	Test data and analysis report	Field test by Sandia National Laboratories showed specification met except ±0.15° azimuth. Specification met in Phase III.
10	✓	Install and operate 7700 system.	Notice to DOE that first 7 MegaModule system installation is complete and operational.	Delayed 2 months after stage gate. Reported to DOE (quarterly report). Press release 10-27-2009.
12	✓	Demonstrate progress towards 2010 KPP goals of: LCOE of $0.14/kWh and manufacturing capacity of 25 MW/Year.	Stage gate report with updated analysis of key performance parameters.	Data delivered to Navigant Consulting and Sandia National Labs for due diligence.

Task		Deliverable	Criteria	Status as of Phase Completion
		Phase III		
1	✓	Demonstrate 2% increase in cell current. [Baseline: current from cell with vendor grid lines optimized for AM1.5 and 25 C].	NREL verification of current increase.	Complete. Cell design transferred to Spectrolab for production. Cell sent to NREL.
4	✓	MegaModule passes IEC 62108 and UL 8703 tests.	Test reports from Nationally Recognized Testing Laboratory.	MM passed IEC 62108 tests at TÜV-PTL in Tempe. Completed UL 8703 tests except for damp heat, which is in progress.
6	✓	Demonstrate 26% DC MegaModule efficiency (PTC).	Access to MM site for DOE testing.	Phase II field test by Sandia National Laboratories showed 28.7±1.5% efficiency at STC, 26.9±1.4% at PTC.
8	✓	Demonstrate production rate of 25 MW/year meeting 2010 cost target .	DOE access to manufacturing facility.	Production demonstrated at Amonix Seal Beach facility. Production transferred to Amonix/Flextronics North Las Vegas plant where 3 lines have a total production rate of 90 MW/yr.
11	✓	Compile reliability data on first 7 MegaModule systems.	Quarterly reports of quality and reliability data.	Amonix routinely compiles field reliability from SolarTAC. Reported to DOE (Quarterly Reports).
12	✓	Achieve 2010 KPP goals of: LCOE of $0.14/kWh and manufacturing capacity of 25 MW/year.	Final project presentation with updated analysis of key performance parameters.	Data delivered to Navigant Consulting and Sandia National Labs for due diligence.

Publications

Project Overview

- V. Garboushian, R. McConnell, K. Stone, R. Gordon, G. Kinsey, C. Crawford. "Reliable Deployment of High Concentration PV Systems,"*SPIE Optic and Photonics Conference Proceedings,*San Diego, California(August 2008)
- R. McConnell, "Concentrator PV: A Breakthrough for a Historic Solar Technology", *Proceedings of International Colloquium for Environmentally Preferred Advanced Power Generation*, Costa Mesa, CA (February 2011)
- R. McConnell, "Large Transmission Scale Concentrated PV Deployment", *Proceedings of International Colloquium for Environmentally Preferred Advanced Power Generation*, Costa Mesa, CA (February 2011)

Task 1 Multijunction Cell Optimization for Field Operation

- G. Kinsey and K. Edmondson, "Spectral Response and Energy Output of Concentrator Multijunction Solar Cells," *Prog. Photovoltaics* (December 2008)
- G. Kinsey, P. Pien, P. Hebert, and R. Sherif, "Operating Characteristics of Multijunction Solar Cells," *Solar Energy Materials and Solar Cells* (June 2009).

Task 4 Standards Compliance and Reliability Testing

- R. McConnell. "CPV Reliability—Reliability in an Expanding Technology," *Accelerated Aging Testing in PV Workshop Proceedings*, Lakewood, Colorado (April 2008)
- R. McConnell, M. Symko-Davies, and S. Kurtz, Conference Co-Chairs of *5th International Conference on Solar Concentrators, Palm Desert, CA,* Proceedings CD, ISBN: 978-0-61529119-2 (November 2008)
- N. Bosco, C. Sweet, and S. Kurtz , "Reliability Testing the Die-Attach of CPV Cell Assemblies," *34th IEEE PV Specialists Conference*, Philadelphia, Pennsylvania (June 2009)
- R. McConnell, V. Garboushian, J. Brown, C. Crawford, K. Darban, D. Dutra, S. Geer, V. Ghassemian, R. Gordon, G. Kinsey, K. Stone, and G. Turner, "Assuring Long-Term Reliability of Concentrator PV Systems," *SPIE Optic and Photonics Conference Proceedings*, San Diego, CA (August 2009)
- R. McConnell, "IEC CPV Standards", *Proceedings of Intersolar North America Conference*, San Francisco, CA(July 2011)

Task 11 Field Testing

- V. Garboushian; K. Stone; R. Gordon; A. Slade. "Performance of the Amonix High Concentration PV System in Southern Nevada." *Power-Gen Conference 2008 Proceedings*; Las Vegas, Nevada (February, 2008).
- G. S. Kinsey, R. Gordon, K. Stone, and V. Garboushian "III-V multijunctions in Amonix solar power plants" *Proceedings of the 6th International Conference on Concentrating Photovoltaic Systems* (April 2010)
- G. S. Kinsey, K. Stone, and V. Garboushian "Energy prediction of Amonix solar power plants" *Proceedings of the 35th IEEE Photovoltaic Specialists Conference*(June 2010)
- G.S. Kinsey, K. Stone, J. Brown, and V. Garboushian "Energy prediction of Amonix solar power plants" *Progress in Photovoltaics: Research and Applications, vol. 18, p. 1-4,* (August 2010)
- G. S. Kinsey, K. Stone, and V. Garboushian "Energy prediction of Amonix solar power plants" *Plenary presentation, EU-PVSEC, Valencia, Spain* (September 2010)

Patents:

- "High-stiffness, lightweight beam structure" U.S. Patent 7877937, issued February 1, 2011

Awards:

- Amonix was inducted into Environmental Hall of Fame, June, 2008
- Amonix received a 2010 R&D 100 Award, "Amonix 7700 Solar Power Generator," with the National Renewable Energy Laboratory

Installed Systems

Table S-1 lists all of the systems using Amonix technology installed to date by Amonix or by project developers. The systems in the upper portion of the table all use the multijunction MegaModules developed under the Technology Pathway Partnership. The systems listed in the lower portion of the table are earlier generation systems using silicon cells. Guasor Fotón manufactured and installed Amonix technology under a license agreement with Amonix

Table S-1. Amonix CPV systems installed to date.

Project	Location	Capacity AC PTC	Project Developer	Commissioned
Multijunction				
Alamosa, CO	US	30.7 MW	Cogentrix	Planned 2012
UC Irvine, Irvine, CA	US	0.11 MW		Planned 2012
Hatch, NM	US	5.0 MW	NextEra	2011
UASTP, Tucson, AZ	US	2.0 MW		2011
SolarTAC, Aurora, CO	US	0.75 MW		2011
Swan, Tucson, AZ	US	0.18 MW	Granite	2011
Indio, CA	US	0.32 MW	Granite	2011
Juwi Blue Wing, San Antonio, TX	US	0.05 MW	Juwi	2010
California Polytechnic University, Pomona	US	0.1 MW		2010
Mobile Pipe Wrappers, Adelanto, CA	US	0.2 MW		2010
CER UNLV, Las Vegas, NV	US	0.1 MW		2009
River Mountains, Henderson, NV	US	0.23 MW	SNWA	2009
Solar CPV Plant NV Energy Clark Station	US	0.1 MW[†]	NV Energy	2006
Silicon				
Guascor Fotón Murcia CPV Plant	Spain	2.0 MW	Guascor Fotón	2009
Guascor Fotón Navarra CPV Plant - Phase II & III	Spain	5.8 MW	Guascor Fotón	2008
Guascor Fotón Energias del Tietar	Spain	1.0 MW	Guascor Fotón	2008
Guascor Fotón Navarra CPV Plant - Phase I	Spain	2.0 MW	Guascor Fotón	2007
Guascor Fotón Tecnohuertas CPV Plant	Spain	1.5 MW	Guascor Fotón	2006
Solar CPV Plant APS STAR Center	US	0.3 MW		2002-2003
Prescott CPV Plant, AZ	US	0.2 MW		2003
Glendale CPV Plant	US	0.1 MW		2001

[†] Original plant capacity of 75 kW installed in 2006 was repowered to 130 kW in 2011 by replacing silicon receiver plates with multijunction plates.