Final Technical Report for Automated Manufacturing of Innovative CPV/PV Modules

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Executive Summary:

Cogenra's Dense Cell Interconnect system was designed to use traditional front-contact cells and string them together into high efficiency and high reliability "supercells". This novel stringer allows one to take advantage of the ~100 GW/year of existing cell production capacity and create a solar product for the customer that will produce more power and last longer than traditional PV products. The goal for this program was for Cogenra Solar to design and develop a first-of-kind automated solar manufacturing line that produces strings of overlapping cells or "supercells" based on Cogenra's Dense Cell Interconnect (DCI) technology for their Low Concentration Photovoltaic (LCPV) systems. This will enable the commercialization of DCI technology to improve the efficiency, reliability and economics for their Low Concentration Photovoltaic systems.

In this program, Cogenra Solar very successfully designed, developed, built, installed, and started up the ground-breaking manufacturing tools required to assemble supercells. Cogenra then successfully demonstrated operation of the integrated line at high yield and throughput far exceeding expectations. The development of a supercell production line represents a critical step toward a high volume and low cost Low Concentration Photovoltaic Module with Dense Cell Interconnect technology and has enabled the evaluation of the technology for reliability and yield. Unfortunately, performance and cost headwinds on Low Concentration Photovoltaics systems including lack of diffuse capture (10-15% hit) and more expensive tracker requirements resulted in a move away from LCPV technology. Fortunately, the versatility of Dense Cell Interconnect technology allows for application to flat plate module technology as well and Cogenra has worked with the DOE to utilize the learning from this grant to commercialize DCI technology for the solar market through the on-going grant: Catalyzing PV Manufacturing in the US With Cogenra Solar's Next-Generation Dense Cell Interconnect PV Module Manufacturing Technology. This program is now very successfully building off of this work and commercializing the technology to enable increased solar adoption.

Background:

Approximately 90% of solar being deployed today utilizes front-contact silicon solar cells. There are four major issues for using these front-contact cells for strings for LCPV, all of which were addressed using Dense Cell Interconnect technology.

- First, front-contact cells typically employ front-to-back connections with ribbons which necessitates a gap between each cell to allow space for the ribbons and the strain-relief of those ribbons to accommodate the relative motion between cells caused by the mismatch of the coefficients of thermal expansion among the materials involved.
- Second, cell-to-cell interconnect ribbons block part of the active area of front-contact cells. Elimination of this dead-space in LCPV (as well as the dead space between cells) has extra leverage because the total area of the mirrors is a multiple of the area of the receiver.
- Third, the higher peak temperature of operation and the more frequent temperature changes (from passing clouds) of LCPV receivers relative to flat-plate modules increase the stress on interconnect ribbons relative to flat-plate modules. And, note, failure of interconnect ribbons is historically one of the top two failure modes of conventional flat-plate modules.
- Fourth, the higher illumination intensity of LCPV increases the cell current density, resulting in high series resistance losses (which are proportional to the square of the current) if the size of cells and interconnect design of conventional modules were to be used.

The Dense Cell Interconnection technology addresses all four of these problems. The overlap of the cells eliminates the between-cell and ribbon-shaded dead space; elimination of the cell-to-cell interconnect ribbon eliminates the metal-fatigue failure mode and the reduction of stress on the cell from the low-temperature application of ECAs instead of high temperature soldering further decreases the impact of thermal cycling;

and the use of small cells and the eliminations of ribbons greatly reduces resistance losses.

The Dense Cell Interconnection technology also addresses similar problems in flat-plate (non-concentrating) modules. The elimination of the spacing required between cells and the ribbon shading increases module efficiency accordingly; the elimination of ribbon interconnect eliminates the ribbon-fatigue mode; and the use of small cells reduces the series resistance losses which are a significant part of the power loss between cells and conventional modules made from those cells. Because the extent of these issues is less than in LCPV, it is even more important for there to be a reproducible, low-cost method for manufacture of the supercells for Dense Cell Interconnect technology to improve costs and reliability in flat-plate modules.

Deployment of conventional front-contact silicon photovoltaics has continued to accelerate and technology improvements such PID resistant encapsulant and Passivated Emitter Rear Cell (PERC) cells have become more common in the industry to improve reliability and/or efficiency. Dense Cell Interconnection technology is similar in that it should be able to apply to any front-contact cell technology and we expect it to become more common in the industry, increasing module efficiency and reliability.

The concept of a shingled front contact photovoltaic technology has been in the patent literature for decades but was not commercialized in high volume due to a lack of high quality and low cost electrically conductive adhesives and equipment to enable low cost manufacturing. Recently, electrically conductive adhesives have become more common for automotive, medical, electronic, and aerospace industries, which spurred the development of a variety of low cost electrically conductive adhesives. Formulations and details of these developments are generally proprietary for the suppliers so cannot be discussed in detail, but as part of Cogenra's work on Dense Cell Interconnection technology, collaboration and development with numerous suppliers occurred. This has enabled Cogenra to stay apace any development in the field. The scope and focus for this grant is the development of equipment for Dense Cell Interconnection to enable the application of electrically conductive adhesives to front contact cells and the subsequent stringing of the cells to form super cells to give a high efficiency and high reliability solar cell string for LCPV application.

Project Objectives, Scope and Impact:

As explained in the Background section above, Dense Cell Interconnect technology enables front-contact cells, which comprise ~90% of the solar industry, to be used for LCPV by 1) eliminating the loss of efficiency associated with the gaps between cells and ribbon shading, 2) eliminating key reliability failure modes, and 3) increasing efficiency by reducing resistance losses. Dense Cell Interconnect technology has similar benefits in flat-plate modules. The result is a Dense Cell Interconnection module with increased efficiency and improved reliability leading to lowered installed system costs and levelized cost of energy, which improves the economic value proposition to consumers and businesses and will increase the adoption of solar.

DCI technology has an added benefit of improving flat-plate module aesthetics, which can be important in some applications such as residential, which can further increase the deployment of solar.

A key barrier to the adoption of DCI technology was that the equipment necessary for low-cost manufacture of high-reliability strings did not exist. Thus, the objective of the program was to develop, demonstrate, optimize, and validate a first-of-kind automated solar manufacturing line that produces supercells based on Cogenra's Dense Cell Interconnect (DCI) technology. The equipment would be compatible with a variety of front-contact cells to future-proof the value. The automated equipment to be developed in the project aims to dramatically multiply labor productivity and throughput, and significantly enhance yield, compared with the current pilot manufacturing line, which serves as the project baseline. The key proof-point is demonstration of the ability to consistently produce low-cost, high-reliability strings.

The major project goals were to:

- Develop, build, install, and start up the manufacturing tools to assemble supercells and successfully demonstrate operation of the integrated line.
- Verify performance of supercells produced in the manufacturing line.
- Evolve the process development test bed to achieve commercial scale production and demonstrate continuous operation meeting yield and throughput targets.
- Reduce the cost to fabricate supercells by 80% (excluding cell/materials costs) compared with the project baseline.
- Prepare the fabrication process for efficient further scale up to 250 and 1000 MW/yr in the US (beyond the project scope).

This program and scope will enable evaluation of the economics for Dense Cell Interconnection technology with the expectation that the ~1% absolute efficiency improvement and increased reliability for the modules will help reduce overall installed systems costs substantially.

The specific scope of the proposed project was to automate the manufacturing of "supercells" based on Cogenra's Dense Cell Interconnect (DCI) technology. DCI supercells are assemblies of cells that have been cleaved into strips. The strips are arranged so that each strip slightly overlaps the adjacent strip. The strips are joined with conductive adhesive. The interconnects between adjacent cells are concealed under the overlapped cells area. Current flows along the fingers (oriented parallel to the string), through the cell, and across the interconnect to the next strip in series. The strips are short to keep currents low and series resistance low. Dense Cell Interconnection eliminates busbars, ribbons, and the need to tab and string, shortens the fingers (which substantially reduces series resistance losses), decreases metal shading from interconnects, and eliminates the gaps between cells in a module. The final assembly of supercells into modules is outside the scope of the project.

A summary of the technical scope of the project is:

- Finalize design of the supercells, incorporating design-for-manufacturability changes.
- Design, fabricate, install, and qualify the overlap and curing process step tools.
- Finalize design and procurement specifications for, order, install, and qualify components for other required process tools.
- Startup the process line and perform process engineering to refine the process parameters.
- Refine manufacturing cost models and system performance cost models.
- Demonstrate automated production and achieve preliminary factory performance metrics as specified in the PMP
- Perform reliability testing to validate product reliability per IEC 62108.
- Demonstrate final key manufacturing performance objectives (throughput, yield, and labor productivity).
- Update performance and cost models, and demonstrate achievement of cost reduction objectives at the supercell, module, and system levels.

The major deliverables during the work on the grant were (detailed list of deliverables and status are in Table 1) broken into two phases. The completion of Phase one deliverables required a go/no-go decision and enabled us to continue work onto Phase two.

Phase one

1. Technology: Verified the performance of the supercells.
2. Manufacturing: Developed, built, installed, and ran tools to assemble supercells and successfully demonstrated operation of the integrated line.
3. Cost: Demonstrated a trajectory to a cost-effective commercial production

Phase two

1. Evolve the process development test bed to achieve commercial scale production and demonstrate continuous operation meeting yield and throughput targets
2. Reduce the cost to fabricate supercells by 80% (excluding cell/material costs) compared with the project baseline

Major Task/Milestone Schedule			
SOPO Task # M.S. #	Task Title and Milestone Description	Performer	Task Start Date
1	*Design and build production line*		
1.1.1.	*Specifications of all process tools completed*	Cogenra	10/1/2014
1.1.2	*Design of all process tools completed*	Cogenra	
1.1.3	*Major components ordered*	Cogenra	
1.2.1	*Supercell overlap tool assembled*	Cogenra	1/1/2015
1.2.2	*Supercell curing tool assembled*	Cogenra	
1.3.1	*Factory prepared for tool installation*	Cogenra	1/1/2015
2	*Startup production line*		
2.1.1	*All process tools qualified*	Cogenra	4/1/2015
2.1.2	*Manufacturing line started up*	Cogenra	7/1/2015
	Go/No-Go		
	Demonstrate readiness for pilot production	Cogenra	7/1/2015
2.1.3	*Reliability red-flag testing*	Cogenra	
3	*Optimize production line*		
3.1.1	*Second operational test passed*	Cogenra	10/1/2015
3.1.2	*Third operational test passed*	Cogenra	1/1/2016
3.1.3	*Cell spacing tolerances achived*	Cogenra	
3.1.4	*Fourth operational test passed*	Cogenra	4/1/2016
3.1.5	*Reliability red-flag testing*	Cogenra	
3.1.6	*Labor productivity verified*	Cogenra	7/1/2016
4	*Validate Project KPPs*		
4.1.1	*System performance model validated*	Cogenra	1/1/2015
4.1.2	*Manufacturing cost model developed*	Cogenra	4/1/2015
4.1.3	*Cost model refined*	Cogenra	

Table 1. Showing SOPO Tasks and Milestones and completion.

This scope of work was established to prove that the Dense Cell Interconnection technology was suitable for automation and thus high-volume manufacturing. This first-generation DCI stringer proved out the manufacturing cost metrics, efficiency gains, and quality and reliability necessary to be commercialized. The ~1% absolute efficiency improvement and reduced degradation demonstrated should impact installed system costs and value for customer on the order of multiple cents per watt.

Project Results and Discussion:

This program very successfully developed and built first of a kind automated Dense Cell Interconnect stringer tools and proved that they could economically produce supercells for integration into modules. Some of the results remain proprietary and cannot be included in this public report. All major deliverables were executed, and all deliverables which underpin payments were externally validated.

Task 1. The design, purchase, and installation of the tools.
Task 2. Qualify and startup the production line
Task 3. Optimize production line
Task 4. System performance model validated and manufacturing cost model developed

The results established a baseline for a high-volume manufacturing viability for Dense Cell Interconnection. In this section, we discuss the results for each task, though proprietary information is not included.

Task 1. Design and build production line

Objective: Finalize the design and specifications, order or fabricate, and install all process tools; complete design-for-manufacturing of the supercells and associated changes to process parameters.

Cogenra designed the Dense Cell Interconnection tools, completed the specifications, facilitized the factory, ordered components and tools and then built and installed all stringer components. The design and process flow for the tools is proprietary but is intended to

1. Maintain full wafer size as long as possible to enable utilization for industry standard components
2. Minimize handling of cells to minimize yield loss
3. Bottleneck at the most expensive sub-tool

A fundamental proprietary assumption about handling of wafers was critical for the success of the program and was proven by running the line as part of Task 2 and 3 and discussed in more detail in the continuation report. All tools were facilitized, installed and made operational.

Task 2 and 3. Startup and optimization of production line

Objectives: Startup and debug all process equipment and material handling systems; perform process integration; achieve first supercell out from the line; and commission the production line.

In Q3 of this program, all tools were qualified by the Director of Manufacturing Engineering per original schedule, and the line started to run the full process at the end of Q3 (June 2015), per milestone 2.1.2. completion report.

The line was run on a regular basis and made continuous improvement week-on-week. A set of KPI (Key Process Indicators) was established by the Director of Manufacturing Engineering and are measured/charted for every run. An excerpt of these are shown in the next pages.

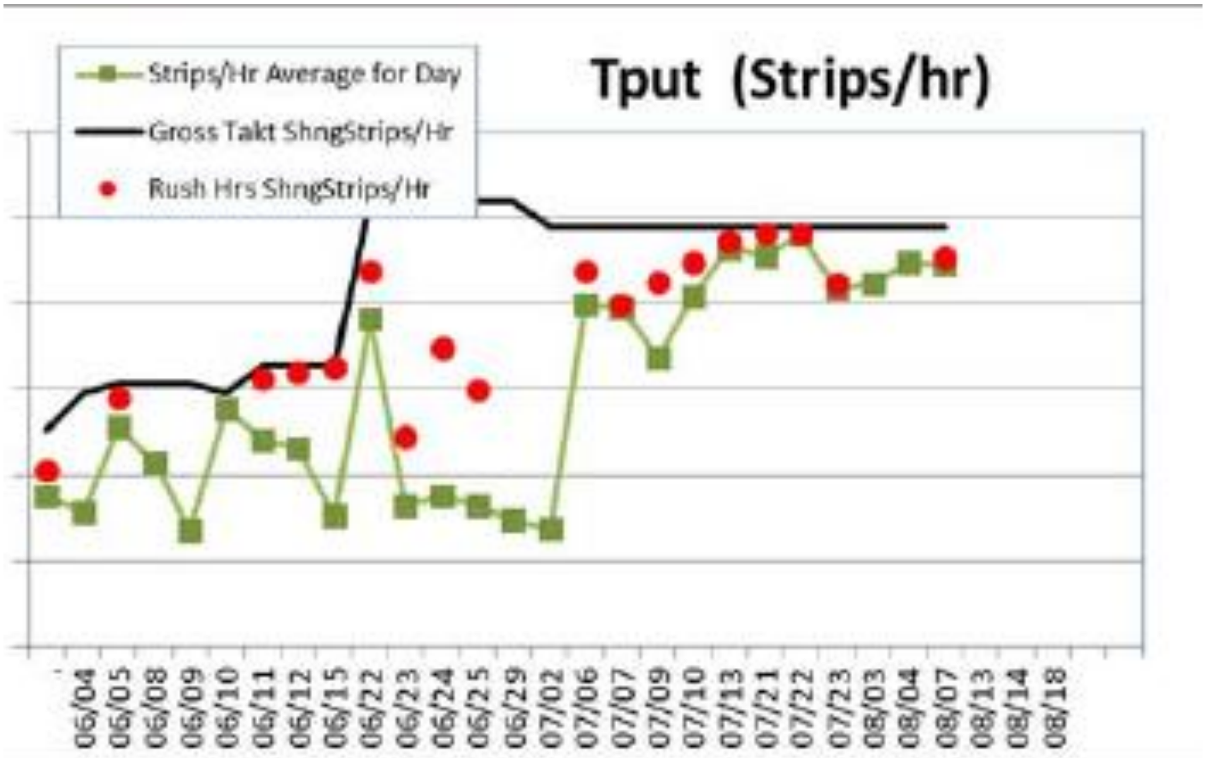

Figure 3. Average and peak throughput of supercell line. Y-axis is unlabeled to maintain proprietary information.

The target throughput for Go/No-Go decision was 10 supercells of 24 strips each over one hour, which translates to 240 strips/hr) as shown in Fig 3. The throughput of the line exceeded this target by more than an order of magnitude (proprietary information was redacted for this report but is included in other submitted documents).

Finally, average throughput over the total daily run-hours (varying from 1 to 6.5 hrs) was also encouraging (green square dots). The average of the last 14 runs (totaling 30 hours) is 84% productivity (actual output divided by maximum possible output in 24/7 operation) for the entire supercell line - a very high number for a new tool set.

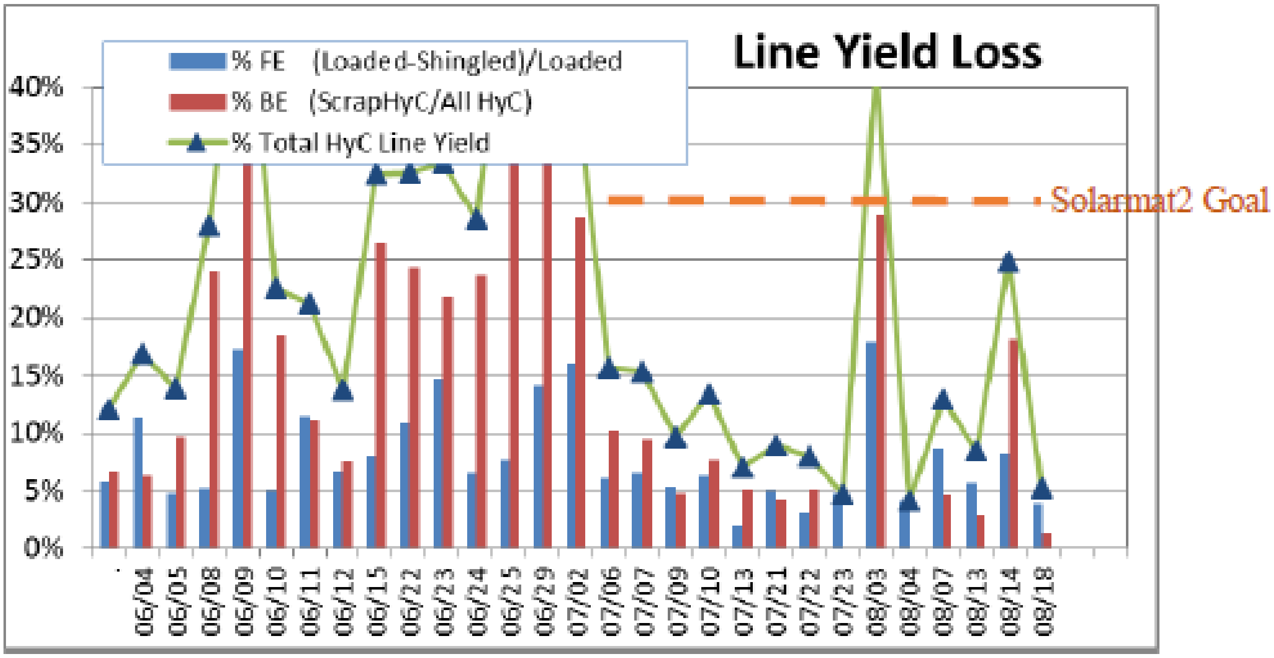

Figure 4. Line Daily Yield Loss, broken down to (FE) front-end (print, cleave, shingle) and (BE) back-end (shingle-error, cure)

Line yield is an early indicator of the cost potential of a new technology. Fig.4 above charts the evolution of line yield loss over 2.5 months. The yield losses varied wildly between 40% and 4%, and the Solarmat2 goal for year - 1 (70% yield, i.e. 30% loss) was achieved and exceeded. To understand the causes of yield loss, we also drilled-down to understand the loss by tool. Such proprietary details were discussed in previous reports. Production on 07/13, 07/23 and 08/18 met or exceeded Task 3.1.1 Second Operational Test (85% yield) and 3.1.2 Third Operational test (90% yield) optimization metrics. Cell spacing was run continuously at the cell spacing requirement for Task 3.1.3. Cell placement accuracy remains a challenge and vision system improvements were continuous - but risk is mostly on cosmetic defects associated with misalignments.

Materials and Process Development - Design for Manufacturability

Cogenra continues to invest in the fabrication and test of supercells to continuously improve on manufacturing cost and reliability of the supercells in finished products. One area of constant effort is the reduction of ECA (electrically conductive adhesive) and reduction of the overlap. While the path to making these changes is straight forward, they require significant effort, starting upstream with the re-design of contact geometry and managing tolerance stacks with cell suppliers, all internal tools, and finishing downstream with intelligent test coupons design and extensive reliability testing.

Task 4. System Performance and Cost Model

Critical to the success of the program is the evaluation of the supercell efficiency with Dense Cell Interconnection technology. Shown in Figure 5 and Figure 6 are the results for a low concentration photovoltaic system and for 1-sun modules respectively. Both show efficiency exceeding target and exceeding generally available solutions on the market at the time and are based on utilization of Heterojunction with Intrinsic Thin-Layer (HIT) cells that flash at 21.8% at 1-sun with three busbars.

At x10 sun the supercell efficiency was 21.66% which exceeded the 21.60% as set in the milestone. The following graph and table show the measurement result at 10 sun.

Param.	Module	Cell	Units
Pmp:	131.13	5.464	W
Eff:	21.66	21.66	%
Voc:	18.717	0.780	V
Vmp:	14.384	0.599	V
Isc:	9.641	9.641	A
Imp:	9.116	9.116	A
FF:		72.7%	
Jsc:	0.3745	0.3745	A/cm²
Jmp:	0.3542	0.3542	A/cm²
Rsh (at 0.45 V):		641	Ω-cm²
Rs* (at Jload):		0.30	Ω-cm²
Rmodulation		1.00	Ω-cm²
Rmod (actual)		0.15	Ω-cm²
T (Vload):		23.7	°C
Date:		28-Aug-15	
Time:		11:32:51	

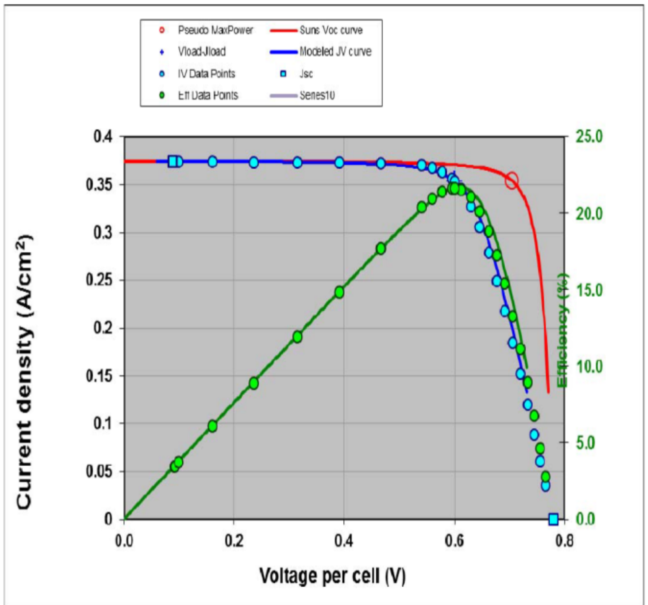

Figure 5. Flash test data showing supercell efficiency of >21.6% at 10x suns for low concentration photovoltaic systems.

At x1 sun, the supercell efficiency was 22.18%, which exceeded the 20.5% as set in the milestone. The following graph and table show the measurement result at 1 sun.

Param.	Module	Cell	Units
Pmp:	13.70	0.571	W
Eff:	22.18	22.18	%
Voc:	17.493	0.729	V
Vmp:	14.602	0.608	V
Isc:	0.992	0.992	A
Imp:	0.938	0.938	A
FF:		79.0%	
Jsc:	0.0385	0.0385	A/cm²
Jmp:	0.0365	0.0365	A/cm²
Rsh (at 0.45 V):		3390	Ω-cm²
Rs* (at Jload):		0.09	Ω-cm²
Rmodulation		1.00	Ω-cm²
Rmod (actual)		-0.19	Ω-cm²
T (Vload):		23.7	°C
Date:		28-Aug-15	
Time:		10:16:11	

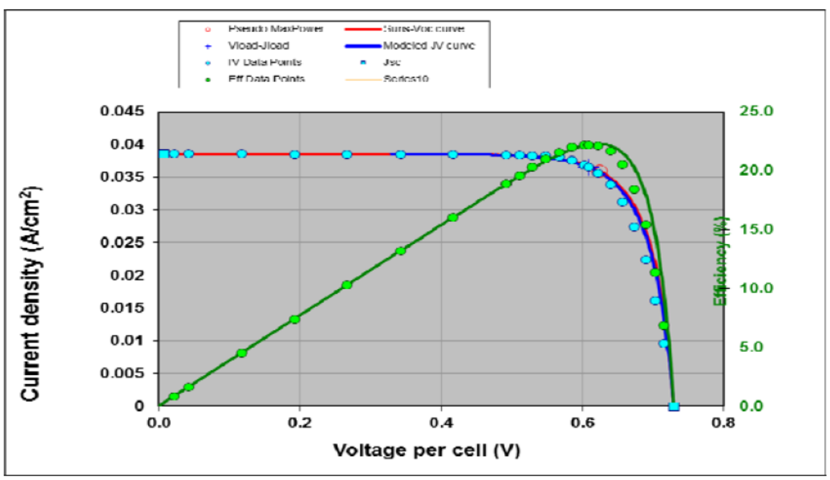

Figure 6. Flash test data showing supercell efficiency of >22% for 1-sun modules.

Cost Model:

The cost model for the concentrator was developed and updated based on the findings discussed in the previous pages and showed a relatively-competitive predicted cost for a low concentration photovoltaic module equivalent in $/Wp (Table 2).

Wp/Receiver	994	
Receiver Cost	$ 0.120	/Wp
Mirror Bed	$ 0.105	
iBos Kit	$ 0.014	
Cooling Kit	$ 0.055	
Module $/W	$ 0.298	

Table 2. Predicted module equivalent cost for Low Concentration Photovoltaic Module including receiver, mirror, iBOS, and cooling. Proprietary details for the cost model have been submitted in previous reports.

Summary Status

Table 3 provides a summary of status of the technical scope at end of award. At the end of the award substantial progress toward our goal was realized but due to a change in direction for the program, final manufacturing performance objectives, certification of an LCPV system and a final performance and cost models were not completed. Interim key manufacturing performance objectives in the table were met but not validated -- these objectives have not and will not be invoiced.

It should be noted that the change of direction from the use of DCI strings in LCPV to flat-plate did not reduce the benefit of the program. The development of the equipment as part of this program provided the foundation for subsequent work that will have a positive impact through the development and deployment of low-cost, high-reliability modules.

Technical Scope	Status
Finalize design of the supercells, incorporating design-for-manufacturability changes	Completed
Design, fabricate, install, and qualify the overlap and curing process step tools.	Completed
Finalize design and procurement specifications for, order, install, and qualify components for other required process tools.	Completed
Startup the process line and perform process engineering to refine the process parameters.	Completed
Refine manufacturing cost models and system performance cost models.	Completed
Demonstrate automated production and achieve preliminary factory performance metrics as specified in the PMP	Completed
Perform reliability testing to validate product reliability per IEC 62108.	Not Completed
Demonstrate final key manufacturing performance objectives (throughput, yield, and labor productivity).	Completed 3.1.1 and 3.1.2*
Update performance and cost models, and demonstrate achievement of cost reduction objectives at the supercell, module, and system levels.	Not Completed

Table 3. Summary of status of the technical scope at end of award. *Interim key manufacturing performance objectives were met but not validated. These objectives have not and will not be invoiced.

	Technical Scope	Status
Go / No-Go	Technology: Supercell built on process line has efficiency ≥ 21.6% at 10-suns STC (or 22.2% at 14-suns STC or 20.5% at 1-sun STC).	Completed
	Manufacturing: Throughput ≥ 10 supercells per hour over one hour of operation. Yield ≥ 70%	Completed
	Commercial: Cost model updated with data from manufacturing run specified above.	Completed
Final Deliverable	Technology: Receivers submitted to third party for IEC 62108 certification	Not Completed
	Commercial: Receiver fabrication cost calculated ≤ $40 (excludes BOM); {8} Module-equivalent cost calculated ≤$0.32/Wp {9}	Completed
	Manufacturing: Yield ≥ 96%, Throughput ≥24 supercells per hour over forty hours of operation using ≤ 0.25 operator-hrs/supercell.	Not Completed

Table 4. Summary of status of the interim and final deliverable status. Due to lack of competitiveness of Low Concentration Photovoltaics submission for certification and final manufacturing of supercells for LCPV receivers was not completed. All other deliverables were completed.

Significant Accomplishments and Conclusions:

Products developed under the award and technology transfer activities:

During the program, Cogenra was able to push the world record in PV module power for each type of cell commercially available using Dense Cell Interconnection Technology. This pushes traditional PV module efficiency ever higher helping to fit more PV in space constrained environments and leverage down mechanical balance of systems costs.

- March 4th 2015, 400W 72-cell format, n-type mono-crystalline cells
- March 4th 2015, 352W 72-cell format, multi-crystalline cells
- October 16th 2014, 334W 60-cell format, n-type mono-crystalline cells
- October 16th 2014, 301W 60-cell format, p-type mono-crystalline cells
- October 16th 2014, 288W 60-cell format, multi-crystalline cells

Challenges Encountered Under this Award:

Unfortunately, the relatively-low cost in $/Wp for the concentrator module equivalent, though initially attractive, does not compete well when taking into account higher system level cost and lower energy harvest due to higher operating temperature and lack of capture of diffuse light (10-15% performance hit). The result is a 10-15% higher Levelized Cost of Energy (LCOE) that makes the Low Concentration Photovoltaic product non-competitive compared to traditional flat plate modules. With a higher risk profile and without a path to a competitive solution, the Low Concentration Photovoltaic program was discontinued and invoicing stopped. Focus changed toward a flat plate product and DOE EE-0007190 for commercialization of Dense Cell Interconnect technology for flat plate modules. As a result, some technical scope items and final objectives were not completed as shown in Table 3 and Table 4.

Path Forward/Commercialization Plan:

As discussed in the section on the challenges, commercialization of a Low Concentration Photovoltaic system was not cost competitive resulting in movement away from this system. Cogenra instead switched focus toward the 1-sun application of Dense Cell Interconnection technology in collaboration with the DOE as part of Grant EE-0007190: A New Slate: Catalyzing PV Manufacturing in the US with Next-Generation Dense Cell Interconnect (DCI) PV Module Manufacturing Technology. Product produced using tools developed under EE-0007190 has proven to be successful, deploying at large volume in large part thanks to the efforts and support from this grant. Detailed discussions have been submitted as part of the EE-0007190. The DCI module technology has proven to be cost competitive and continues to gain market share in the US commercial sector.