CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Low-cost, High Concentration System for Industrial Solar Cogeneration

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Low-cost, High Concentration System for Industrial Solar Cogeneration is the final report for the Low-cost, High Concentration System for Industrial Solar Cogeneration project (PIR-20-005) conducted by Skyven Technologies, Inc. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project, funded under the California Energy Commission's Gas Research and Development Program, aimed to develop and demonstrate a low-cost, high-concentration photovoltaic and thermal (HCPVT) system for industrial cogeneration. The system integrates solar thermal and photovoltaic technologies into a single receiver, enabling simultaneous generation of electricity and thermal energy within a compact footprint.

Skyven Technologies led the design, testing, and pilot deployment of the system. The project followed a phased approach, beginning with component-level testing of triple-junction solar cells, optical homogenizers, and a custom heat sink manifold. Integrated system testing demonstrated a combined efficiency of up to 56 percent, with peak electrical and thermal efficiencies of 13 and 43 percent, respectively. Reliability and durability testing confirmed the system's resilience to environmental stressors, including pressure, water ingress, mechanical load, and thermal cycling.

A pilot installation at Fresno State University was installed to validate real-world performance, with the system averaging 138,000 British thermal units and 7.54 kilowatt-hour (kWh) of average weekly output over six months. The pilot system demonstrated a weekly average combined efficiency of 51.3 percent with peak electrical and thermal efficiencies of 12 and 39.3 percent, respectively. Economic analysis showed a levelized cost of electricity of $0.28/kWh and a levelized cost of heat of $0.084/kWh.

The project supports California's clean energy and climate goals by enabling distributed, on-site renewable energy generation. Benefits to utility ratepayers include reduced grid and pipeline congestion and improved energy resilience.

Keywords: California Energy Commission, final report, Gas R&D Program, HCPVT

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Background

California's clean energy and climate goals demand innovative technologies that reduce greenhouse gas emissions and support the transition to renewable energy. This project addresses that need by advancing a novel solar hybrid system that simultaneously generates electricity and thermal energy within a single, compact footprint. Unlike earlier high-concentration photovoltaic (HCPV) systems that failed to commercialize due to mechanical complexity and high costs, this system builds on Skyven's Intelligent Mirror Array solar thermal platform, which is designed for simplicity, durability, and compatibility with standard photovoltaic (PV) installation practices.

The project is especially timely given California's push to decarbonize its industrial sector, which remains one of the largest sources of emissions. Recent policy developments, such as SB 100 and the state's Scoping Plan (CEC 2025, CARB 2022), have increased pressure on industries to adopt clean technologies. The food production sector, currently valued at $29.5 billion and comprising over 5,500 facilities, is a key early market for this innovation. By enabling facilities to generate both heat and power on-site, the technology reduces reliance on fossil fuels, lowers energy costs, and supports grid resilience.

Project Purpose and Approach

Skyven's goal was to demonstrate that its high-concentration photovoltaic and thermal (HCPVT) system could reliably deliver combined heat and power for industrial applications, with a focus on sectors like agriculture that benefit from both thermal and electrical energy. The intended market includes facilities aiming to reduce energy costs and carbon emissions through high-efficiency solar solutions.

Skyven's additional objectives included achieving strong thermal and electrical performance (targeting ≥20 percent electrical efficiency and a combined efficiency of 50 percent), maintaining durability under environmental stress, and validating long-term reliability.

The project approach included component-level validation, integrated system trials, and rigorous durability assessments such as thermal cycling, pressure, water ingress, mechanical load, and impact resistance testing.

The project followed a phased approach that included first testing individual components like solar cells, homogenizers, and heat sinks, then evaluating full system performance outdoors, and finally validating reliability and durability through extended on-sun exposure and lab simulations.

Key Results and Conclusions

This project demonstrated the technical feasibility of an HCPVT system for industrial cogeneration. Component-level testing validated each subsystem, with triple-junction cells showing strong electrical output under standard conditions but reduced efficiency at high temperatures. Homogenizers achieved 82.6 percent optical transmittance and showed no material degradation and a redesigned copper heat sink significantly improved thermal performance. The receiver enclosure passed all durability tests, including vacuum, pressure, and environmental stress.

Integrated system testing achieved a peak combined efficiency of 56 percent (13 percent electrical, 43 percent thermal) following iterative improvements in the receiver design. A pilot deployment at Fresno State confirmed real-world performance, averaging 138,000 British thermal units (Btu) of thermal energy and 7.54 kilowatt-hour (kWh) of electricity per week, with a combined efficiency of 51.3 percent. The system's levelized cost of electricity was $0.28/kWh and levelized cost of heat was $0.084/kWh.

While the system showed strong thermal performance and cost-effectiveness, electrical efficiency limitations and supply chain constraints—particularly the reliance on a single PV cell supplier—led Skyven to conclude that commercial deployment is not viable at this time. However, the project highlights the potential of HCPVT systems in industrial applications and identifies clear pathways for future research and development.

Knowledge Transfer and Next Steps

Skyven has prepared a case study outlining the research and development efforts, lessons learned, and the technological progress for the HCPVT system. This case study has been permanently posted to the Skyven website at https://skyven.co/resources/case-study-legacy-insights/. And a blog post has been prepared at https://skyven.co/news/insights-legacy-solar-thermal/.

Benefits to California Ratepayers

This HCPVT technology reduces the amount of electrical power that must be sourced from the grid and reduces thermal energy that must be sourced from the natural gas pipeline network. This distributed generation can prevent future congestion and capacity constraints on both the grid and pipeline. It also provides a means for California to avoid expanding its natural gas pipeline network as thermal energy demand grows. Additionally, thermal energy production from the proposed innovation supports the use of thermal energy storage, which is widely documented as being more cost effective than electrical energy storage (batteries) for thermal end-uses.

CHAPTER 1: Introduction

California's clean-energy and climate goals call for innovative solutions that reduce greenhouse gas emissions, improve energy efficiency, and accelerate the adoption of renewable technologies. This project directly supports those goals by advancing new solar technology that combines electricity generation and thermal energy production in a single, streamlined system designed specifically for industrial applications. The goals of this project are to demonstrate the technical feasibility of an integrated solar thermal and photovoltaic (PV) system, with a goal of meeting at least a 50 percent combined electrical and thermal efficiency (with 20 percent electrical efficiency) and to validate its cost-effectiveness through real-world deployment. The primary audience for this technology includes industrial facilities in the food and beverage industries.

High-concentration photovoltaic (HCPV) systems attracted significant investment between 2005 and 2015 but failed to achieve widespread commercialization. These systems relied on complex optics and mechanical tracking, which proved difficult to scale and cost-reduce compared to simpler PV technologies. In contrast, Skyven's Intelligent Mirror Array (IMA) solar thermal collector uses embedded control systems to eliminate mechanical complexity and pairs with an innovative receiver design that provides both thermal and electric power. This new HCPVT system integrates solar thermal and photovoltaic capabilities while maintaining the ability to utilize standard PV racking and installation procedures making it easier and more cost-effective to deploy.

Recent developments in California's energy landscape have created a strong demand for such solutions. The state's industrial sector, particularly food and beverage production, faces increasing pressure to decarbonize under policies like SB 100 and the Scoping Plan from the California Air Resources Board (CEC 2025, CARB 2022). At the same time, rising energy costs and grid reliability concerns have made on-site renewable energy generation more attractive. Skyven's high concentration photovoltaic and thermal (HCPVT) system addresses these needs by delivering both heat and power in the same footprint, reducing reliance on fossil fuels and improving operational resilience.

Compared to existing technologies including Fresnel lens-based HCPVT systems[1] and parabolic troughs,[2] the proposed solution offers similar electrical efficiency, lower installation and maintenance costs, greater durability and reliability, and flexibility for installations on rooftops and carports.

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[1] A Fresnel lens-based High-Concentration Photovoltaic/Thermal system uses large, lightweight Fresnel lenses to concentrate sunlight by a factor of 500 to 2000× onto tiny, high-efficiency multi-junction solar cells, while an integrated liquid cooling circuit actively removes the waste heat and converts it into useful thermal energy.

[2] A parabolic trough system employs long, curved parabolic mirrors that focus sunlight along a linear focal line (typically 40 to 100× concentration) onto an absorber tube containing a heat-transfer fluid (oil, molten salt, or steam, etc.), which is then used either directly or via a heat exchanger, with electrical efficiencies of 13 to 20 percent but high thermal storage capability.

CHAPTER 2: Project Approach

Skyven has developed an HCPVT system designed to deliver combined heat and power (CHP) for industrial applications. This system has two major devices, the receiver and the collector. The receiver utilizes homogenizers and triple-junction solar cells which are bonded to a copper manifold to generate both thermal and electric power. This is then paired with Skyven's IMA collector, which concentrates sunlight onto the receiver.

The project's approach was structured around three core steps: component-level testing, integrated system performance evaluation, and reliability and durability validation.

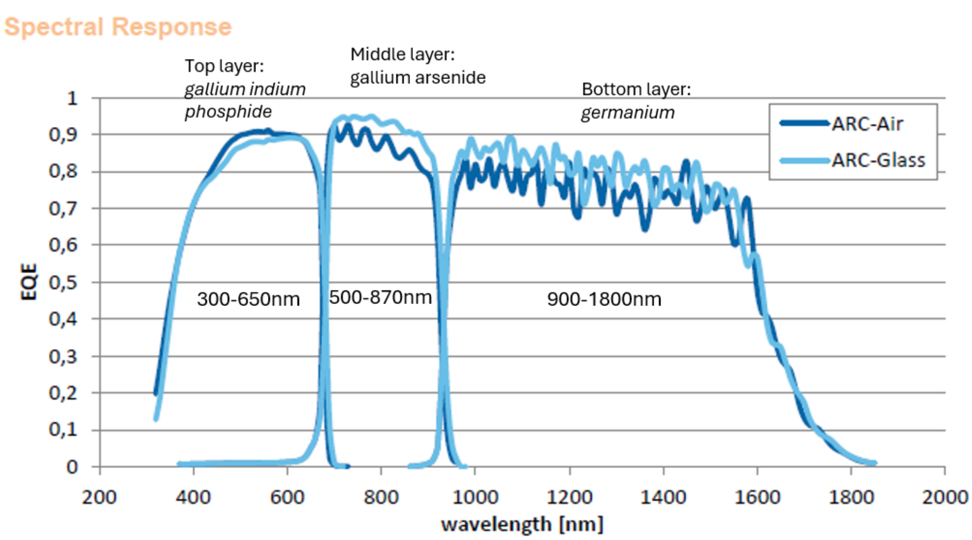
Component-Level Testing

Skyven began the project with a component-first testing strategy, focusing on the four primary subsystems of the HCPVT receiver: the triple-junction solar cells, optical homogenizers, heat sink manifold, and the receiver enclosure. Each component was tested independently under both laboratory and outdoor conditions to evaluate its performance, durability, and compatibility with the overall system.

Triple Junction Solar Cells

Triple junction solar cells are built with three distinct layers, each made from a different substrate material. Each material focuses on stripping electrons from different wavelengths of sunlight to create electrical energy. Figure 1 shows the different wavelengths that each layer of material is capable of capturing. Triple junction cells are therefore able to achieve higher efficiencies compared to conventional monocrystalline PV cells, which are limited to a single wavelength band.

Figure 1: Spectral Response of Triple Junction Cells

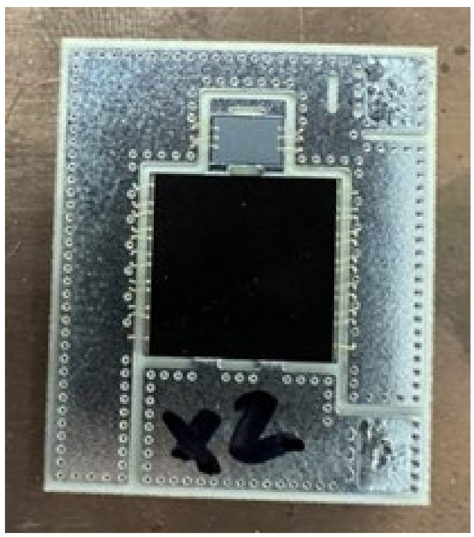


Source: Azurspace, 2015

Figure 2 shows the triple junction cells themselves - the black region represents the active PV layers where light is absorbed and electrons are generated and the surrounding silver contact grid collects and transports the generated electrons. Electrical connections are made by soldering to the designated positive and negative terminals (in Figure 2, the negative terminal is at the top of the cell). This configuration enables efficient extraction of electrical current from the cell for external use.

The triple-junction solar cells, manufactured by Azurspace, were subjected to rigorous testing to assess their response to concentrated sunlight. These tests included spectral irradiance analysis, thermal behavior monitoring, and electrical output characterization. Testing was conducted using both simulated solar conditions and natural sunlight to replicate real-world operating environments. Long-term exposure testing was initiated to monitor degradation trends, while thermal cycling protocols were used to evaluate the cells' resilience to temperature fluctuations.

Figure 2: Azurspace Triple Junction PV Cells



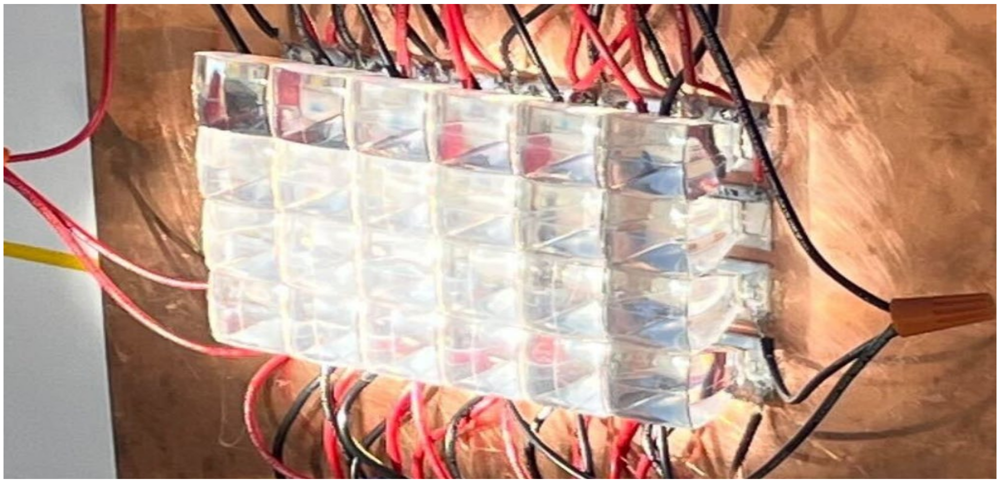
Source: Skyven Technologies, 2023

Homogenizers

The optical homogenizers play a critical role in distributing concentrated sunlight evenly across the solar cell surface. Skyven explored multiple designs for the optics including Fresnel lens, secondary reflectors housed around the cells, and many variations of light pipes/homogenizers. Ultimately, it was determined that homogenizers would be the best solution for collecting and distributing the light across the PV cell in the most uniform fashion.

The optical homogenizers are fabricated from an ultra-clear, two-part optical silicone. Each homogenizer increases the effective target area from the cell's native 10×10 millimeters to 28×28 millimeters, allowing more concentrated sunlight to be captured while minimizing the formation of hot spots. As light travels through the homogenizer, it is diffused and evenly spread across the cell surface, improving overall performance. Figure 3 shows an early prototype test using a 6×4 array of homogenizers, designed to evaluate how a group of homogenizers would perform. Skyven conducted performance characterization testing by directing a controlled amount of light onto the top surface of the homogenizers and measuring the light intensity received at the PV cells beneath to confirm the homogenizers' effectiveness in delivering consistent and uniform light distribution.

Figure 3: Full Size Set of Homogenizers on PV Cells

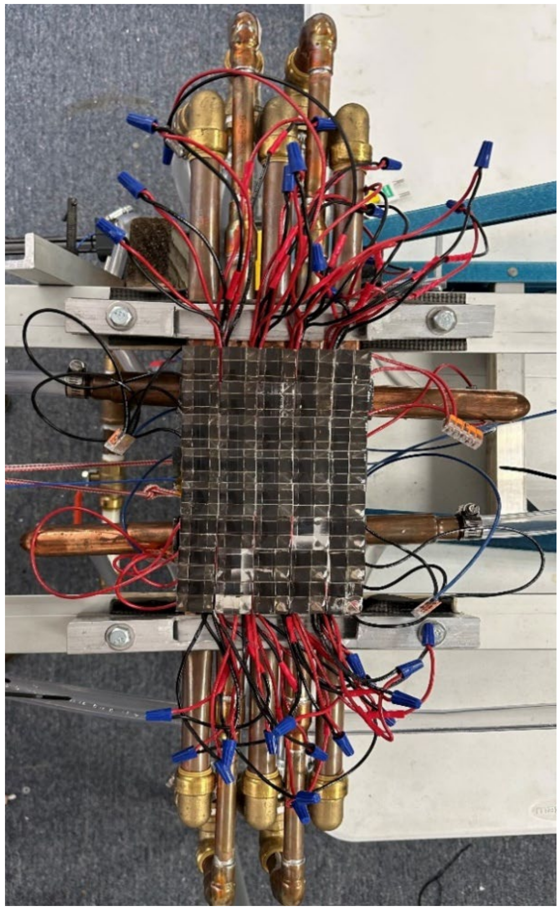


Source: Skyven Technologies, 2023

Heat Sink Manifold

Effective thermal management on the heat sink manifold is essential to maintaining solar cell efficiency and preventing performance losses due to overheating. The initial heat sink manifold design, shown in Figure 4, consists of a series of parallel pipes, each designed to support a single row of triple junction solar cells. To ensure effective thermal contact, thermal paste and solder paste were applied between the bottom of each cell and the corresponding pipe. Water was circulated through each pipe to actively draw heat away from the cells, helping to maintain optimal operating temperatures and prevent thermal degradation. The heat sink manifold was tested for its ability to extract and distribute heat uniformly across the receiver which involved flow testing and assembly validation.

Figure 4: PV Cells Bonded to Initial Heat Sink Manifold

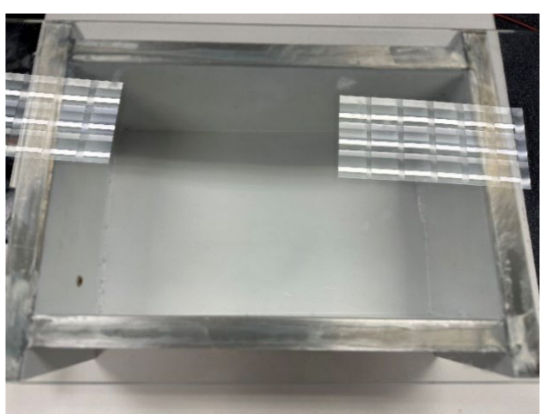


Source: Skyven Technologies, 2023

Receiver Enclosure

The receiver enclosure, shown in Figure 5, was evaluated for its ability to protect internal components from environmental exposure while maintaining structural and thermal stability. Initial testing included a vacuum seal test. Further testing of the receiver enclosure was conducted in the reliability and durability tests.

Figure 5: Initial Receiver Enclosure



Source: Skyven Technologies, 2023

Integrated System Testing

Following component-level validation, Skyven progressed to integrated system testing using both single-collector and two-collector configurations. These tests were conducted outdoors under varying solar irradiance conditions to evaluate the system's thermal and electrical efficiency in real-world environments.

Single-Collector Testing

Single-collector testing was performed to establish a baseline efficiency for the system using just one collector. This single collector approach makes it easier to direct all incoming light into the receiver allowing for a clearer understanding of the systems efficiency. Figure 6 shows the receiver setup using the initial pipe-based heat sink design. Figure 7 provides a view of the full test configuration, with the collector positioned on the far right and the receiver on the far left. The outcome of this testing can be found in Chapter 3: Results.

Figure 6: Single Collector Test Set Up – Receiver

Source: Skyven Technologies, 2023

Figure 7: Single Collector Test Set Up

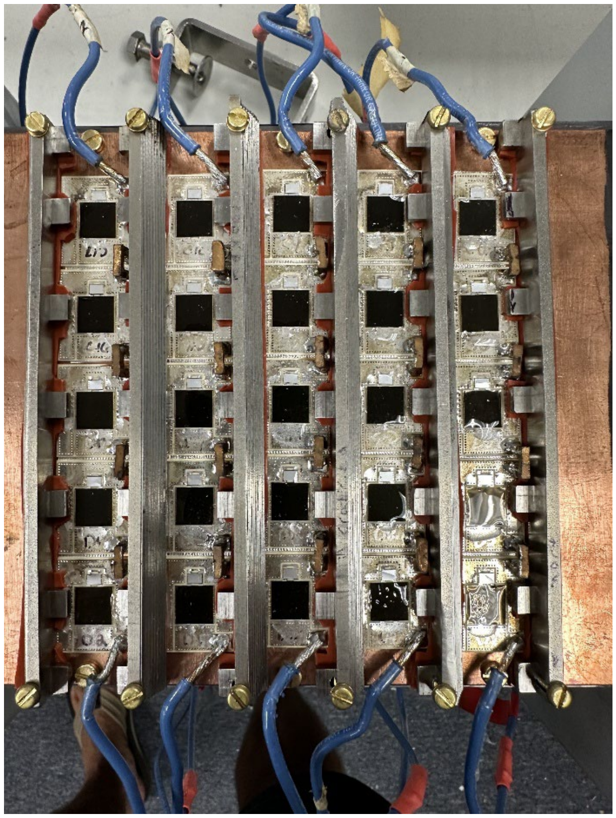
Source: Skyven Technologies, 2023

Skyven implemented a series of targeted improvements across optical, electrical, and thermal domains as the initial testing with the single collector test set up showed that electrical efficiency was falling short of the 20 percent goal. These improvements include:

- **Optical Enhancements:** Precision-molded pushrods replaced inconsistent 3D-printed components to ensure accurate focal alignment on the solar collectors. A machine-applied mirror film process was introduced to eliminate surface bubbles that previously scattered light and reduced reflectivity.
- **System Positioning:** The modular test setup used in early phases limited optimal alignment. Permanent racking and component placement, guided by computational modeling, were installed in the long-term test area to reduce geometric losses and improve consistency between tests.
- **Electrical Optimization:** Series resistance within and between cell strings was reduced by replacing long, flexible wires with rigid, low-resistance conductors. Cells were grouped into balanced strings, and permanent soldered or crimped connections replaced temporary modular wiring. Power optimizers were also added to mitigate mismatch losses and improve overall electrical output.
- **Thermal Management:** The heat sink was redesigned with a simplified bonding method of an indium heat spring that was compressed to ensure consistent thermal contact. The pipe arrangement was also swapped out for a copper plate with machine channels that allows the water to pass through which allows for more surface area contact with the copper and increased thermal management. Figure 8 shows the PV cells connected to the copper plate and Figure 9 shows the channels on the backside of the copper plate where the water runs through. This change improved heat transfer

efficiency and reduced the risk of PV cell overheating, which had previously impacted both thermal and electrical performance.

Figure 8: PV Cells Connected to Revised Heat Sink Copper Plate



Source: Skyven Technologies, 2023

Figure 9: Water Channels Machined on Back Side of New Heat Sink Copper Plate

Source: Skyven Technologies, 2023

Two-Collector Testing

The two-collector configuration was introduced to validate system scalability and assess the impact of design improvements such as the revised heat sink manifold. This setup aimed to increase the concentration of sunlight on each photovoltaic cell, with the goal of boosting electrical output. In theory, higher concentration on the receivers would reduce the number of receivers required, thereby lowering overall system costs, as the PV cells are the most expensive component. Figure 10 shows the two-collector test configuration, with the collectors positioned on the right and the receiver on the left. The outcome of this testing can be found in Chapter 3: Results.

Figure 10: Two Collector Test Set Up

Source: Skyven Technologies, 2023

Reliability and Durability Testing

To ensure the long-term viability of the HCPVT system, Skyven implemented a comprehensive Reliability and Durability Test Plan focused on the receiver enclosure and internal components. The IMA collector was excluded from this phase, having been validated in a prior program (the IMA collector was developed under National Science Foundation Small Business Innovation Research Phase 1 and 2 grants and underwent certification with Solar Rating & Certification Corporation testing). The testing plan included both long-term outdoor exposure and controlled laboratory simulations of environmental and mechanical stresses. The items below outline the testing that was completed on the receiver enclosure and internal components. The outcomes of these tests can be found in Chapter 3: Results.

Long-Term On-Sun Testing: The receiver was exposed to outdoor conditions for three months under ISO 9806:2013 Class B (Sunny) conditions. The units were mounted at a 45° tilt and operated under wet conditions to simulate real-world use.

Pressure Testing: Pressure testing was conducted using Skyven's TM 1-003 pressure testing protocol which sees pressurized air pumped into the receiver for a duration of 15 minutes.

Water Jet Testing: Water jet testing was performed to IP65 standards. The receiver was placed horizontally on a flat-rigid stand and sprayed from all angles at 15 pounds per square inch for 15 minutes. The unit was then dried and inspected for any water inside the unit.

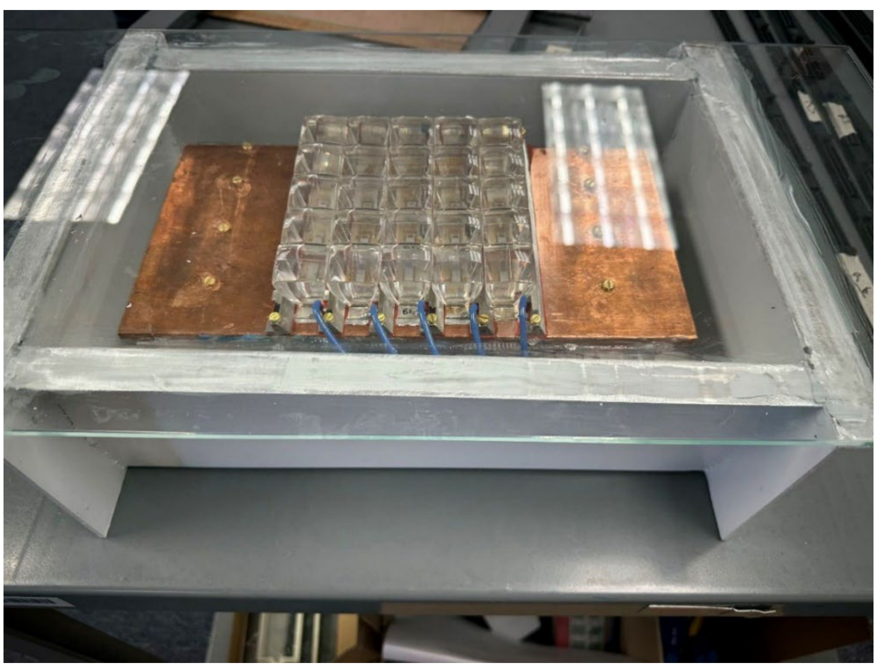
Mechanical Load Testing: A mechanical load test was performed to simulate snow or debris loads on the receiver. A 2,400 pascal load was applied via water weight for a total of 30 minutes.

Impact Resistance Testing: Impact resistance testing was performed to simulate hail impacts on the receiver. A 130 gram steel ball was dropped on the receiver glass from 78 inches at two different angles five times in a row.

Thermal Cycling: The receiver was subjected to 60 thermal cycles between 68 degrees Fahrenheit (°F) (20 degrees Celsius [°C]) and 176°F (80°C) over 10 days in a custom heat/humidity chamber. This test introduced thermal stress to validate seal integrity and component interaction.

Final Inspection: After the above tests were performed, the receiver was disassembled for a detailed visual and functional inspection. Figure 11 shows the final receiver enclosure prior to disassembly for final inspection.

Figure 11: Final Receiver Enclosure



Source: Skyven Technologies, 2024

Pilot Testing of the Receiver and Collector

Skyven partnered with Fresno State University to install a four collector and receiver setup at their agricultural facility to validate and test the system in a real world environment. Figure 12 shows the four collectors and receivers installed at Fresno State. Figure 13 shows a close up of one of the receivers that were installed at Fresno State.

Figure 12: Collector and Receiver Setup at Fresno State

Source: Skyven Technologies, 2025

Figure 13: Receiver at Fresno State

Source: Skyven Technologies, 2025

The thermal energy produced by the HPCVT system is used to pre-heat boiler feedwater for the agricultural facility and the electricity produced by the HPCVT system is used to power an electric tractor utilized at the facility.

The system was installed and commissioned at Fresno State on February 10, 2025.

CHAPTER 3: Results

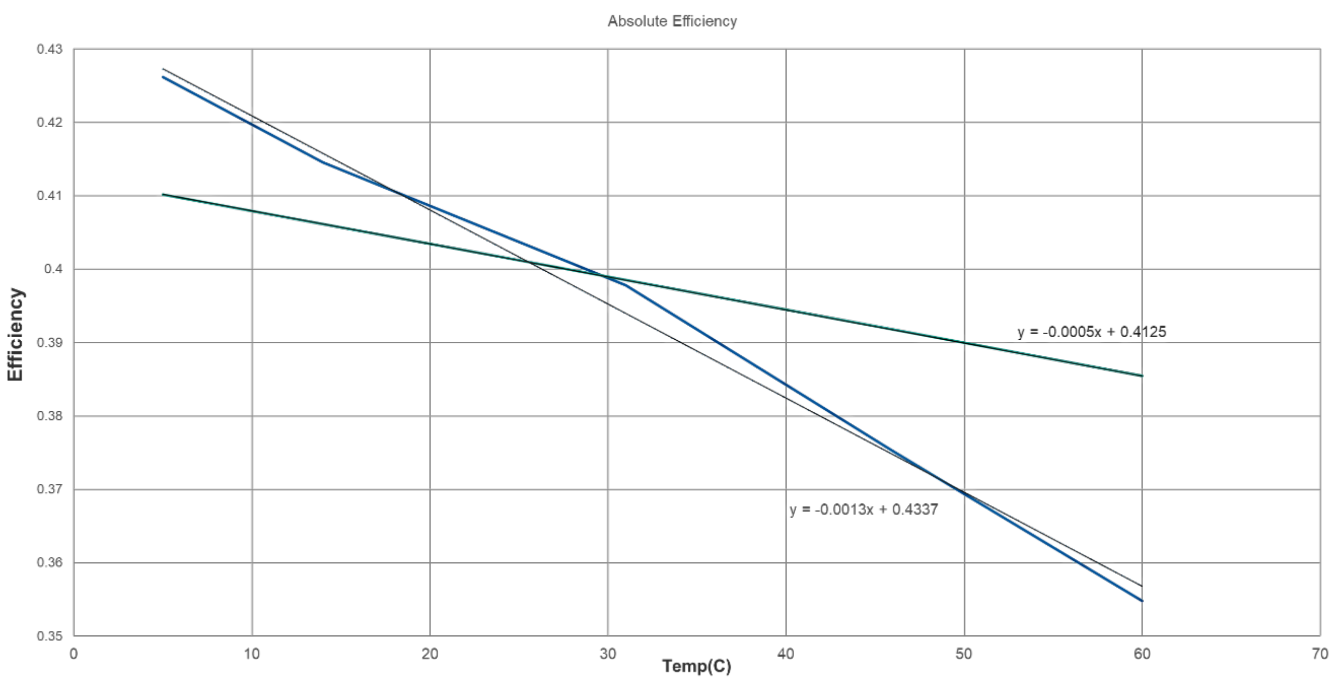
Component-Level Testing

The following paragraphs outline the results of the component level testing.

Triple Junction Cells

The solar spectral irradiance tests showed passing result as did the electrical output characterization testing. The thermal behavioral testing, however, showed that the cells underperformed at temperatures above 140°F (60°C). Figure 14 shows the comparison between the temperature coefficient provided in Azurspace's datasheet (green line) and the coefficient measured during testing (blue lines). At an operating temperature of 140°F (60°C), the tested cells exhibited an efficiency drop of nearly 10 percent, highlighting a significant deviation from expected performance and underscoring the challenges of maintaining efficiency at elevated temperatures. These results emphasize the importance of operating the system at lower temperatures, as the current cells underperform relative to their datasheet specifications under thermal stress. However, with improved cell technology or cells that consistently meet datasheet performance without limitations, higher operating temperatures may be achievable.

Figure 14: Temperature Coefficient (Azurspace Datasheet Versus Measured)



Source: Skyven Technologies, 2025

Homogenizers

The homogenizers were tested for dimensional stability and were not affected by stress testing in a temperature and humidity cycling chamber or under ultraviolet lamps. The homogenizers also underwent performance characterization testing where they showed an average of 82.6 percent efficiency for transmittance. Finally, the homogenizers were subjected to material degradation testing where it was determined that there was no degradation or discoloration of the silicone MS-1002 material used for the homogenizers.

Heat Sink Manifold

The flow testing on the heat sink manifold confirmed that the flow rate was balanced which is crucial for ensuring heat can be evenly pulled off the cells; if any cell becomes hotter than any other, the performance of all cells will decrease to the lowest performing cell. The assembly validation confirmed that the solder joints on the piping were acceptable which is critical as a leaking in the thermal fluid could cause shorting through the whole system. After single collector testing, the heat sink was redesigned with a simplified bonding method of an indium heat spring that was compressed to ensure consistent thermal contact. The pipe arrangement was also swapped out for a copper plate with machine channels that allows the water to pass through which allows for more surface area contact with the copper and increased thermal management.

Receiver Enclosure

Initial vacuum seal testing showed that the receiver enclosure could properly hold vacuum for over two weeks.

Integrated System Testing

Single Collector Testing

Initial testing with a single collector demonstrated a peak thermal efficiency of 53 percent. However, electrical efficiency peaked at only 10.2 percent, falling short of the electric efficiency goal of 20 percent. Analysis revealed that a significant portion of the incident solar energy was being dissipated as heat due to underperforming electrical conversion. This highlighted the need for improvements in electrical interconnects, power optimization, and thermal management. These improvements are described in Chapter 2: Project Approach.

Two Collector Testing

In this setup, thermal efficiency peaked at 41 percent, slightly lower than the single-collector test due to improved electrical efficiency of 14 percent which was an expected tradeoff. During this testing, it was determined that it was too challenging with two collectors to be as precise with the solar focus on the receiver as was desired. Therefore, it was determined that a single collector would be utilized for the pilot system at Fresno State.

Single Collector Testing – Final Test

After it was decided a single collector would be used for the pilot, final single collector testing was completed with the updated electrical optimization, new heat sink, and revised receiver gasket. In this set up, combined efficiency peaked at 56 percent with peak electrical efficiency hitting 13 percent and peak thermal efficiency hitting 43 percent.

Reliability and Durability Testing

Long-Term On-Sun Testing: While the enclosure and seals remained intact, thermal expansion of the homogenizers caused partial separation at the PV cell interface, slightly reducing performance. This issue was addressed in an updated design by adding an additional machined aluminum block heat sink to reduce thermal expansion.

Pressure Testing: This test confirmed that the receiver maintained internal pressurization with no measurable pressure loss or pinhole leaks before and after exposure.

Water Jet Testing: No water ingress was observed therefore confirming the integrity of the sealing system.

Mechanical Load Testing: After the test, the receiver showed no deformation or visible damage.

Impact Resistance Testing: The receiver glass withstood all impacts without cracking, chipping, or breaking the surface of the glass.

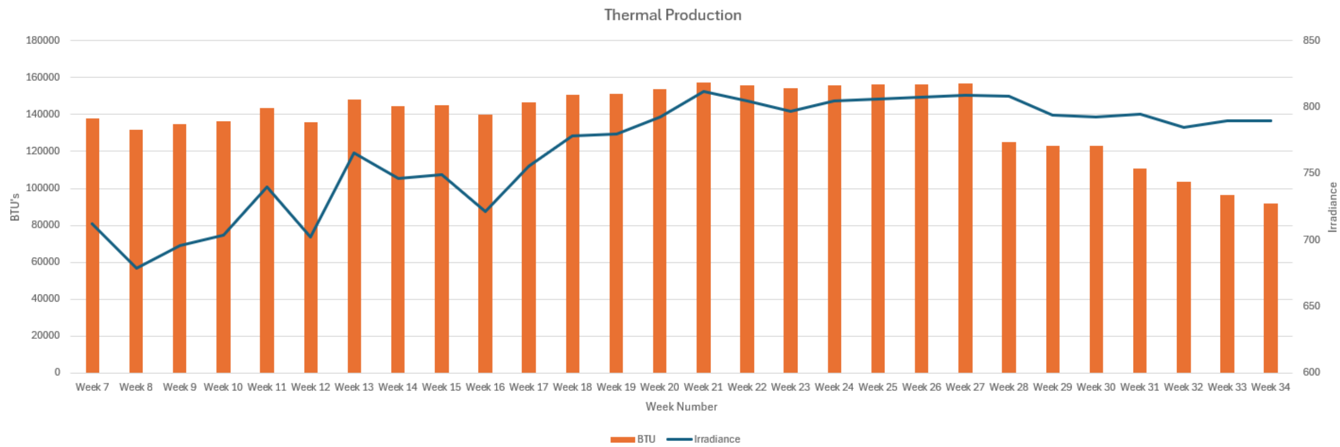
Thermal Cycling: The receiver passed all post-test inspections and performance checks.

Final Inspection: All components passed inspection however minor corrosion was observed around the gasket area causing the team to replace the gasket material for the final design.

Pilot Testing of the Receiver and Collector

Skyven began collecting data on the four collectors and receivers at Fresno State on February 10, 2025. Figure 15 below shows the weekly thermal production of the system in Btu's starting in "Week 7" of 2025 (specifically, the week of February 10 when the pilot was commissioned).

Figure 15: Weekly Btu Production of Pilot System

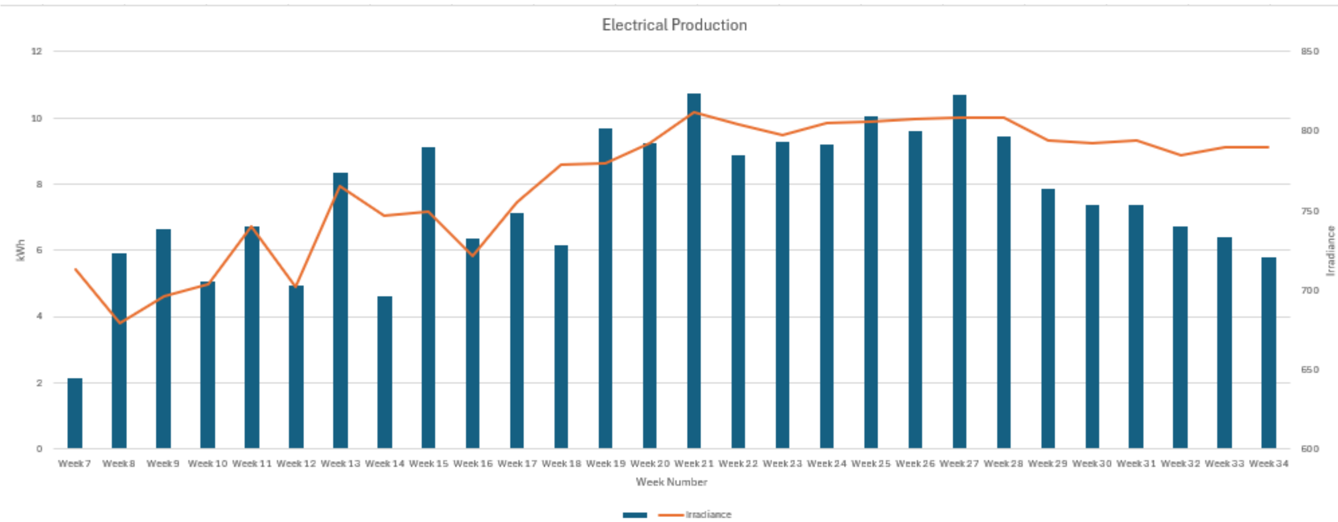


Source: Skyven Technologies, 2025

Weekly Btu production averaged 138,000 Btu/week over the six-month testing period, totaling 3.8 million Btu. There was a small decline in output during the final month due to one of the panels losing focus, which could not be troubleshooted on-site, leading to its shutdown for safety purposes.

Figure 16 below shows the weekly electrical production of the system in kWh starting in "Week 7" of 2025 (specifically, the week of February 10 when the pilot was commissioned).

Figure 16: Weekly kWh Production of Pilot System



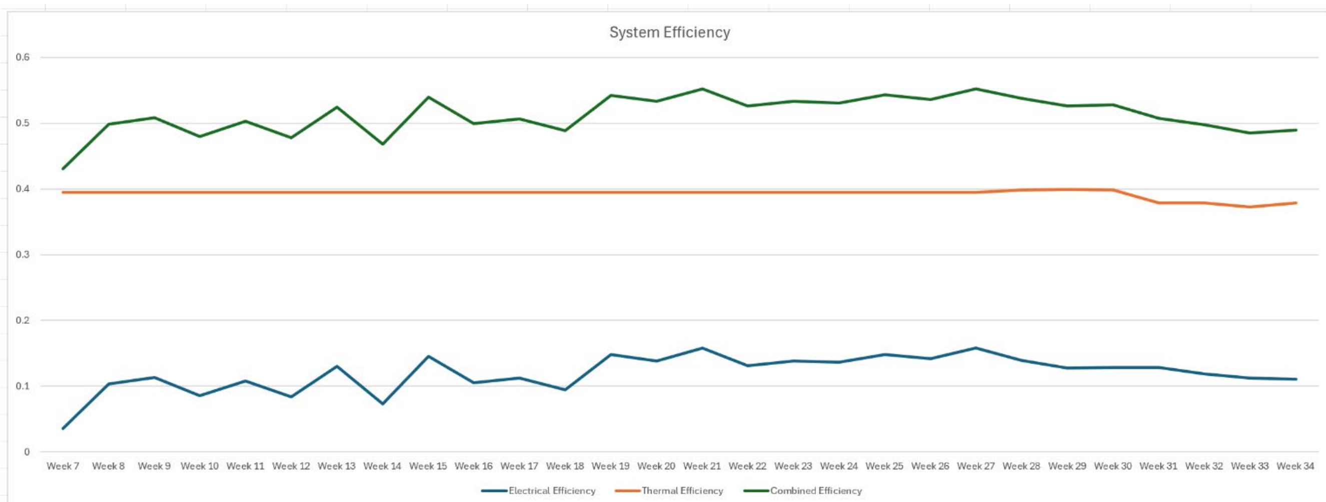
Source: Skyven Technologies, 2025

Weekly kWh production averaged 7.54 kWh over the six-month testing period, totaling 211 kWh. There was a decline in output during the final month due to a panel losing focus, which could not be troubleshooted on-site, leading to its shutdown for safety purposes.

At scale, the system demonstrates promising economics based on its current performance metrics. With an installed cost of $1,500 per unit, and assuming a 20-year lifetime, a 3 percent discount rate, and the calculated capital recovery factor of 0.0672 (specifically, the specified discount rate to reflect the cost of capital over time) yields a levelized cost of electricity (LCOE) of approximately **$0.28/kWh**, based on an annual electrical output of 360 kWh. Similarly, the levelized cost of heat (LCOH) comes to **$0.084/kWh**, given an annual thermal output of 1200 kWh. These figures reflect the system's baseline cost-effectiveness, and further reductions in LCOE are anticipated as improvements in cell temperature coefficients and enhanced precision in system targeting are realized. These advancements are expected to boost electrical efficiency and optimize energy capture.

Figure 17 below shows the weekly thermal and electrical efficiencies (along with the combined efficiency) of the pilot system over the last six months.

Figure 17: Weekly Efficiencies of Pilot System



Source: Skyven Technologies, 2025

Weekly combined system efficiency averaged 51.3 percent over the testing period, with a weekly electrical efficiency of 12 percent and weekly thermal efficiency of 39.3 percent.

CHAPTER 4: Knowledge Transfer

Skyven prepared a case study outlining the research and development efforts, lessons learned, and the technological progress for the CPVT system. Additionally, Skyven created a blog post to accompany the case study. The blog post can be found posted to the Skyven website at https://skyven.co/news/insights-legacy-solar-thermal/. The landing page where the case study can be downloaded can be found on the Skyven website at https://skyven.co/resources/case-study-legacy-insights/.

Additional information can be found on this project at the California Energy Commission's "Energize Innovation" website. The "Low-cost, High Concentration System for Industrial Solar Cogeneration" landing page can be found at https://www.energizeinnovation.fund/projects/low-cost-high-concentration-system-industrial-solar-cogeneration.

CHAPTER 5: Conclusion

This project demonstrated the technical feasibility of an HCPVT system for industrial cogeneration. Component-level testing validated the performance of each subsystem of the receiver. The triple-junction cells showed strong electrical output under standard conditions, but performance declined at elevated temperatures. The homogenizers demonstrated high optical transmittance (82.6 percent) and long-term material stability. The redesigned heat sink of a copper plate with machined channels significantly improved heat dissipation. The receiver enclosure passed vacuum, pressure, and environmental stress tests, confirming its durability.

Integrated system testing revealed that the HCPVT system could achieve a combined efficiency of up to 56 percent, with peak electrical efficiency at 13 percent and thermal efficiency at 43 percent. These results were achieved after iterative improvements in optical alignment, electrical interconnects, and thermal bonding. Further reliability and durability testing was done to confirm the system's resilience to real-world conditions, including mechanical load, water ingress, and thermal cycling.

The four collector and receiver system deployed at Fresno State University provided real-world validation of the HCPVT system. Over a six-month period, the system produced an average of 138,000 Btu of thermal energy and 7.54 kWh of electricity per week with weekly average combined efficiency of 51.3 percent (12 percent electrical and 39.3 percent thermal). The LCOE was calculated at $0.28/kWh, and LCOH at $0.084/kWh. It is expected that these values could be improved with further optimization, particularly in PV cell performance and system targeting precision.

Future research in this area includes the thermal tolerance of solar cells and refining optical alignment which could allow for higher efficiencies and reduce system costs. Future iterations could focus on higher-tolerance components and alternative PV cells to meet efficiency targets.

By enabling on-site generation of both electricity and heat, the HCPVT system reduces demand on the electric grid and natural gas infrastructure, benefiting California ratepayers. This distributed generation model can help alleviate grid congestion, defer infrastructure upgrades, and enhance energy resilience which is particularly important as the state transitions away from fossil fuels. The system also supports thermal energy storage, which is more cost-effective than battery storage for many industrial applications.

In summary, Skyven's HCPVT pilot at Fresno State demonstrated the potential for solar CHP in industrial applications, achieving a competitive LCOH and robust thermal performance. However, electrical efficiency challenges and supply chain constraints of Azurspace being the only reliable PV cell provider, limited commercial viability and therefore Skyven will not be pursuing commercial deployment of the technology at this time.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Btu	British thermal units- the amount of heat needed to raise one pound of water at maximum density through one degree Fahrenheit
°C	degree Celsius
CEC	California Energy Commission — The state of California's primary energy policy and planning agency
CHP	combined heat and power
°F	degree Fahrenheit
HCPV	high-concentration photovoltaic
HCPVT	high-concentration photovoltaic and thermal
IMA	Intelligent Mirror Array – Skyven Technologies' proprietary solar collector technology
kWh	kilowatt-hour
LCOE	Levelized Cost of Energy - the average cost per unit of electricity ($/kWh) generated by a system, accounting for all the costs incurred over its operational life
LCOH	Levelized Cost of Heat - the average cost of producing usable thermal energy ($/kWh)) over the lifetime of a heating system
PV	photovoltaic
Skyven	Skyven Technologies

References

California Energy Commission (CEC). 2025. *SB 100 – Achieving 100 Percent Clean Electricity.* California Energy Commission. https://www.energy.ca.gov/sb100.

California Air Resources Board (CARB). 2022. *2022 Scoping Plan for Achieving Carbon Neutrality.* California Air Resources Board. https://ww2.arb.ca.gov/resources/documents/2022-scoping-plan-documents.

Project Deliverables

The following is a list of all the products produced under this agreement:

- Receiver Design Documentation
- Component Test Plan
- Component Prototyping and Test Report
- Single Collector and Receiver Test Plan and Report
- Reliability and Durability Test Plan
- Reliability and Durability Test Report
- Two-Up Collector Test Plan and Report
- Pilot Test Plan
- Pilot Test Report
- Critical Project Review (CPR) Reports
- Quarterly Progress Reports (QPR)

The above project deliverables, including the CPR and QPR interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.