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FINAL PROJECT REPORT

PREDICTABLE AND LOW-COST CONCENTRATING PHOTOVOLTAICS FOR CALIFORNIA COMMUNITIES

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Predictable and Low-Cost Concentrating Photovoltaics for California Communities is the final report for the project of the same name (contract number PIR-12-016) conducted by Cool Earth Solar. The information from this project contributes to Energy Research and Development Division's Renewable Energy Technologies Program.

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ABSTRACT

This project developed a suite of new solar technologies to help close the price gap between centralized and distributed generation, while providing stable, predictable power at an affordable cost. Solar photovoltaics technologies have traditionally been based on flat panel crystalline silicon modules, because they tend to have lower costs, expanded availability, and lower risk when compared to other technologies. The researchers at Cool Earth Solar decided to pursue a unique inflated concentrated photovoltaic module and two-axis tracking system with the potential to dramatically reduce installed costs The project team collected data on system performance to evaluate uptime, tracking accuracy, and overall system efficiencies, which illustrated a competitive advantage compared to other existing solar products, particularly for medium and large ground-mounted applications. The data illustrated this system is appropriate for community-scale solar installations in municipal energy parks or behind-the-meter commercial and industrial applications. The project team also examined a new method of cloud sensing to address solar energy forecasting requirements. Results show the approach is potentially useful for large-scale solar deployments and multi-site data fusion.

Keywords: solar, inflatable, low cost, distributed, ground mount, cloud sensing, forecasting, concentrating, photovoltaic, performance ratio, uptime, availability, power, CPV

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EXECUTIVE SUMMARY

Introduction

The US solar industry has seen enormous growth in the last few years as flat panel crystalline silicon modules have dropped significantly in price. In particular, the residential rooftop market segment has exploded, in part due to the availability of financing to defray the up front capital investment costs of typical homeowners. This market momentum is moving into commercial and industrial (C&I) applications as more business owners are recognizing the potential for a low-risk investment that, in some cases, can be cash positive from day one. The exception to this flood of new solar installation has been the utility-scale market. Large-scale projects are still more challenging because of the scale of investment required and the complex deals necessary to execute on a major solar power plant.

While large-scale centralized power plants (above 10 megawatts) are still a consideration in the future, current market conditions suggest that distributed installations – homeowner roof tops and "behind the meter" C&I opportunities – may be the better choice. A third option of community-scale generation has recently emerged and offers some potential benefits when compared to either large-scale or standalone distributed generation. Community-scale generation is larger scale than individual building-level projects to leverage economies of scale, while being located close to pockets of energy demand to minimize energy losses that come with transmitting electricityover great distances.

Project Purpose

Cool Earth Solar has been developing a low-cost concentrated photovoltaic (CPV) system using inflated thin film plastic optics to produce solar energy, concentrating sunlight by a factor of twenty and decreasing costs by reducing the number of expensive solar cells required to generate the same amount of power. Each unit of the collection system includes a two-axis tracker on which three inflated CPV modules are mounted. Based on the technology configuration and findings, this technology is best-suited for ground-mounted distributed generation projects from small commercial and industrial installations, to community-scale installations, up to the largest utility scale projects.

Cool Earth Solar's system can economically produce solar power across a wide scale of installation sizes, making it an attractive alternative for community-scale projects that could benefit from a renewable energy source. Under varying weather conditions, this study examined the ability of Cool Earth Solar's system to provide typical community power demands, measure and predict solar resource availability, qualify system performance and determine the impact of solar intermittency. The project team reduced costs by creating their CPV system in a way that requires no specialized manufacturing facilities. The project also included examination of a new technique for using multiple low-cost solar sensors to enable solar resource forecasting to predict performance issues and outages due to cloudiness at a lower cost than other existing methods.

Project Process and Results

The research team deployed 20 kilowatts of Cool Earth Solar technology to study system performance and projected costs at scale. Performance metrics for tracking accuracy, precision, and energy production were monitored for consistency with system design specifications and market requirements. A month-long trial was performed on a single 810 Watt test module to measure system energy production. The system produced more than 190 kilowatt hours, equivalent to nearly nine hours each day at full power. These results illustrated a positive comparison with most flat panel solar installations with less efficient fixed-mount trackers.

The team used an industry standard metric called the performance ratio to evaluate system performance. Performance ratio is a measure of the energy collected compared to the total solar resource available. Cool Earth Solar's technology had a performance ratio of almost 84 percent. . This compares favorably to typical fixed flat panel systems that usually perform in the mid-seventies. This field deployment allowed Cool Earth Solar to significantly improve and validate their CPV system technology, cost, and performance. Successful installation and operation of the engineering units have been largely influential in generating customer agreements for commercial use of this new solar technology.

The team also developed, deployed, and studied new sky imaging sensors to predict and mitigate solar intermittency due to cloud cover. Since CPV systems rely on solar imaging, they must keep optical elements aligned with the sun to ensure maximum energy harvest. The project team focused on the Compound Eye approach for this forecasting task, a technique that uses multiple imagers from different sites to produce a wider area perspective on the data. The primary focus was whether the solar hardware could be adapted to provide useful sensing capabilities to existing systems at no additional cost. The team also considered if whether the results from multiple simultaneous sensors have the potential to be combined to provide a deeper understanding of the available solar resource.

The study concluded the Compound Eye concept can combine two independent data streams to provide useful information about solar resources using unmodified hardware from the collection system. This technique could be implemented within a single large field of many individual solar collectors or across multiple different solar installations to combine data from a broader geographical area, such as the entire state of California.

The final task within the grant agreement was the application of solar energy forcasting to manage onsite buildings' electrical load to match available power. The building chosen for a potential demo site proved to be unsuitable for the task. Therefore, the scope of this task was not completed and the allocated EPIC funding for this activity remains unspent.

After successful feasibility studies, Cool Earth Solar examined the commercial viability of the technologies. The team noted three main requirements to reach this goal - market demand, the ability to produce the technology at relevant volumes and cost, and sufficient funding to continue operations. Cool Earth Solar has successfully achieved each of these market-driven requirements in the form of contractual agreements for investment funding, vendor capability, and market employments. With these in hand, the project team will continue to pursue further

commercialization efforts to transfer this innovative solar technology out of the laboratory and into the marketplace.

Project Benefits

Cool Earth Solar is a California-based company; and California ratepayers will benefit through secondary economic activity from growth of successful implementation of the subject technology. Cool Earth Solar's technology is applicable for centralized utility-scale, community-scale, and large ground-mounted C&I installations in the state, and it is expected to produce energy in the California market at or below the future projected cost of solar competitors or natural gas. As a result of the Compound Eye forecasting approach and research concepts, ratepayers may also benefit from lower energy costs and a more reliable grid.

The results from this grant have also allowed Cool Earth Solar to complete key business milestones. Market demand has been demonstrated by a signed deployment agreement for over 100 megawatts of solar capacity. This includes use of the new inflated modules and two-axis tracker. Key supply chain agreements have also been secured, enabling rapid volume scale-up for Cool Earth Solar's system.

Finally, the next round of investment expansion for Cool Earth Solar has been secured, providing multi-year scaling activities and allowing this technology to obtain more bank financing for projects. During the next four years, Cool Earth Solar anticipates shipping as much as 100 megawatts of solar capacity to support these activities. Achieving bankability allows full participation and competitiveness in the solar industry marketplace. Projected system costs are expected to be at or below $1 per watt and 6 cents per kilowatt-hour levelized cost of energy by 2020.

The interested stakeholder community has also grown through relationships with local and international governmental organizations, domestic and international solar project development companies, other solar industry participants, and many suppliers and vendors. Relationships were built through the Livermore Valley Open Campus (LVOC), an industry partnership outreach program run jointly by Sandia and Lawrence Livermore National Laboratories. The Cool Earth Solar project was the first to leverage this partnership and make use of the shared demonstration space and resources that came with it.

Cool Earth Solar has been able to develop a novel solar collection technology to the point where commercial viability is present. Market demand (in the form of a deployment contract) provides "pull" for commercialization of the system. In parallel, critical supply chain infrastructure has been set in place through contracts with strategic vendors. As a result, new investor funding for deployment of Cool Earth's systems has validated progress enabled by the grant. Taken together, these accomplishments will enable further commercialization of this important new tool for harvesting solar energy.

CHAPTER 1: Introduction

1.1 Solar Industry Market Segmentation and Landscape

1.1.1 Residential, Commercial & Industrial, Utility

The US solar industry has seen enormous growth in the last few years as flat panel crystalline silicon modules have dropped significantly in price. In particular, the residential rooftop market segment has exploded, in part due to the availability of financing to defray the up front capital investment costs of typical homeowners. This market momentum is moving into commercial and industrial (C&I) applications as more business owners are recognizing the potential for a low-risk investment that, in some cases, can be cash positive from day one. The exception to this flood of new solar installation has been the utility-scale market. Large-scale projects have seen a more difficult path to implementation due to the scale of investment required and the complex deals that need to be assembled in order to execute on a major solar power plant.

While large-scale power plants (above 10 MW) are still a consideration in the future, the current market conditions suggest that distributed installations – homeowner roof tops and "behind the meter" C&I opportunities – may be an easier path to implementation.

The push to distributed applications remains almost exclusively focused on flat panel crystalline silicon modules, which is consistent with market factors including cost, availability, and risk. Current distributed installations, however, come at a premium relative to purely large scale, utility style power plants where size and scale allow lower cost infrastructure. The question becomes whether there are new solar technologies that have an opportunity to close the pricing gap between centralized and distributed generation.

When considering applications of solar energy from a community perspective, the predominant impact today is via individual residential installations. The current strong growth in the C&I market can have direct positive impact on local businesses, including off-grid agricultural applications. This is still on a one-by-one basis for each project. Perhaps the biggest impact on community-scale solar energy prospects is the emergence of community-based utilities that, depending on the locale served, range from tens to hundreds of kilowatts. Such community-based solar farms act as third-party providers to enrolled ratepayers.

1.1.2 Flat Panel vs. CPV

To answer how a new technology can reduce the cost of distributed solar energy, it's useful to recall that the single largest line item cost in a flat panel solar module is the cost of the silicon cells used to build it. Since the cells in flat panels collect sunshine directly, for each square meter of sunshine collected, a square meter of solar cell is required.

One potential for reducing the high cost of solar cells is to introduce an optical element to focus the sunshine from a larger collection area onto a smaller area of solar cells. Each relatively costly cell, therefore, receives a multiple of the solar irradiance and subsequently produces a multiple of the power it would normally produce under non-concentrating conditions. Since more power

is produced from the same solar cell, the cost per watt becomes more favorable. The associated design challenge, however, is to keep the cost of the optical train and other system components required to perform the focusing below the savings realized from eliminating cells in order to provide net economic benefit.

The benefit realized through concentration would seem initially to continue to increase as the concentration factor increases. Just as a 2x focus would require ½ the solar cells of a 1-sun module, a 1000x concentration system would require $^{1}/_{1000}$ the cell area. This seemingly obvious point has been the basis for many CPV solar companies designing their systems around so-called high concentration factors of 500x to 1000x, or what is known as high-concentration photovoltaics (HCPV). Unfortunately, the industry has learned hard lessons regarding the offsetting system costs required to effectively collect electricity from 1000 suns of irradiance. The benefit of eliminating 99.9% of solar cell area is quickly overcome by higher costs in complex optics, heat management hardware, and tracking costs. Most CPV systems need to follow the sun to maintain focus onto the PV collection cells.

Cool Earth Solar has extensively studied the trade-offs involved in selecting a higher or lower concentration factor. While some concentration does provide economic benefit in the form of solar cell cost reduction, factors above ~50x cause prohibitive added costs from tracker stiffness, heat sink capacity, and manufacturing complexity. Cool Earth Solar's current optic falls in the range of low CPV at around 20x concentration. Magnification factors up to approximately 50x are generally referred to as low concentration.

In addition to gaining economic advantage over flat panel solar via concentration, Cool Earth Solar's system is designed to eliminate the need for major capital investment in production capacity. Construction costs for a typical solar cell factory are in the range of $1-2 per watt of capacity. Adding in the additional infrastructure needed to produce the ultra-pure polysilicon and manufacture silicon wafers and the factory costs add up to $5-6/Watt capacity. Therefore, 100MW capacity could require as much as $500 million capital investment. The need for investment capital remains a significant barrier for further industry expansion, particularly growth associated with the introduction of any new technology. New technology often carries higher risk and demands higher cost-of-capital to offset that risk.

Cool Earth Solar's approach has been to design the system in such a way that no specialized manufacturing facilities are required. Parts and subassemblies can be procured from existing manufacturing capacity within the US. The need for capital investment is largely eliminated to the extent that system components fit within the variable capacity available within existing industries. Since many of the technologies of interest come from other very high volume industries (by design), no new factories need to be built. Among the Cool Earth Solar subsystems that can make use of existing industrial capacity are the tubes, frames, motors, control boards, tubing, wiring, heat sinks, and more.

Figure 1: Cool Earth Solar's California-Grown CPV System

Photo Credit: Cool Earth Solar

1.2 Cool Earth Solar's CPV System

Cool Earth Solar's unique solar collection technology is the result of extensive development activity into methods and designs to maximize the amount of solar energy collected per unit cost. The result is a synergistic collection of system features that can provide competitive advantage in the solar energy market.

Initial design considerations quickly coalesced around a carousel-style altazimuthal mounting system for tracking. Key advantages to this design are the superior stability provided by a low aspect ratio, three-point ground contact, and the ability to eliminate most site preparation. Previous concerns about this architecture's need for high-cost foundations are eliminated by the roll-on-the-ground capability enabled using a low-cost on-board pointing system developed by Cool Earth Solar. Cool Earth Solar has had this method of tracking in use in the field continuously for more than five years without incident.

Figure 2: Cool Earth Solar Prototype with Altazimuth Design, Circa 2009

Photo Credit: Cool Earth Solar

Cool Earth Solar was founded around the concept of using inflated thin film plastic optics to minimize system cost. This technology is leveraged through the use of a cylindrical shape to implement the design principle of tensegrity – the separation of compressive and tensile elements within a mechanical system. By using compressive air to inflate a tensile thin film plastic tube, optimal optical alignment can be achieved as a natural result of the design. Happily, the cylindrical shape is also low wind drag (~1/3 that of flat panel), substantially reducing frame stiffness requirements (and therefore tracker mass and cost).

Figure 3: Geometrically Stable Optics

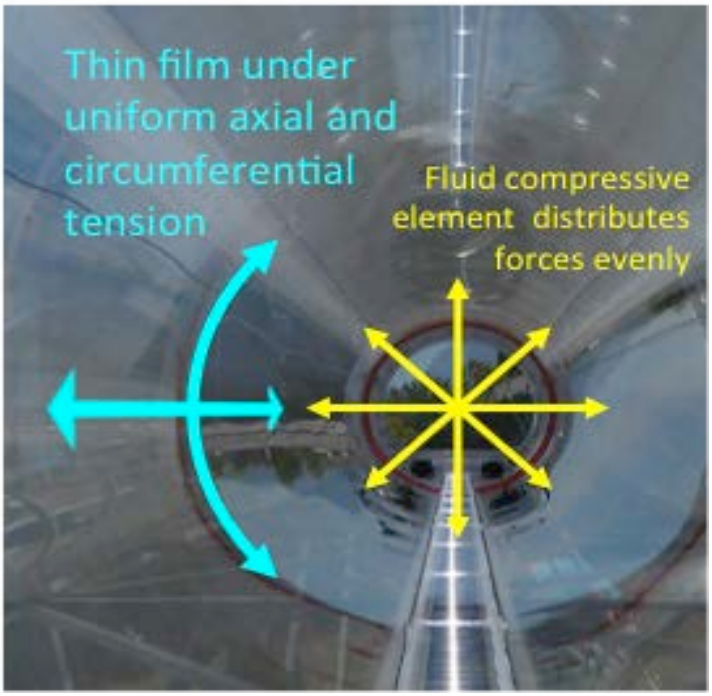

Photo Credit: Cool Earth Solar

Accompanying the use of cylindrical geometry is the choice of refractive optics. Inflated thin film optics are very low mass structures. Using a lens instead of a mirror provides a beneficially low mass distribution when considering the orientation of the optical element relative to the source and focal point. Refractive optics allow the heavier portions of the optical train (the receiver containing the solar cells) to be placed closer to the ground which minimizes frame stiffness requirements even further.

Figure 4: Early Transparent Tubes Demonstrating Low Center of Mass Refractive Optics

Photo Credit: Cool Earth Solar

Finally, a key design element that's difficult to isolate for identification is the overriding drive to globally optimize the number of watts collected for every dollar spent. The approach has balanced the drive to minimize balance of system (BOS) cost impact by increasing system size against the cubic increases in mass required to stiffen larger structures. Similarly, gains in amortizing expensive solar cells by continuing to increase the concentration factor are offset by increasingly costly design challenges to remove waste heat. A third example of a design tradeoff of this nature is the possible use of very high efficiency triple junction solar cells. In practice, the increases in cost driven by the design complexity offset any gains realized from cell efficiency. One example of this is the possible use of wire bonding to connect to the high efficiency cell which can cost as much as $0.10/W. Such a process would consume nearly the whole budget for the cost of the entire cell assembly in a system designed for $1/W all-in costs.

Figure 5: Cool Earth Solar's Long and Deep Experience Studying Design Trade-Offs

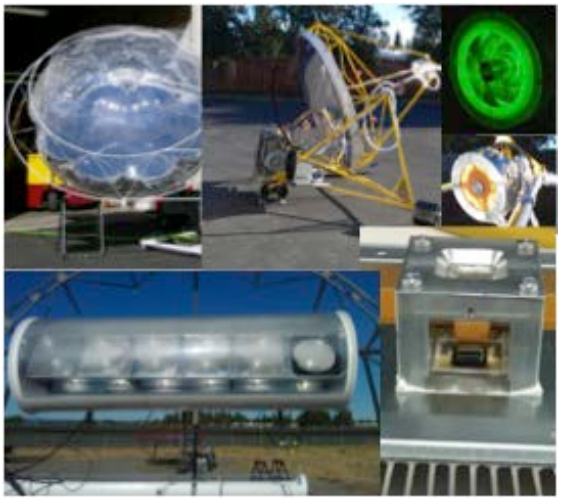

Photo Credit: Cool Earth Solar

Cool Earth Solar has developed novel solar energy collection technology that is unique in the industry. Each of the technological pivots implemented in the system architecture allows for cost reductions by eliminating materials and labor through beneficial design features. Cool Earth Solar's system represents an optimal balance of high performance energy collection and low cost manufacturing, installation, and operation.

CHAPTER 2:
CPV Program and Results

2.1 Operational Capability

Work performed under task 2 of the grant focused on the maturation of Cool Earth Solar's system through field deployments to test execution and performance.

As part of task 2.2, Cool Earth Solar needed to make the necessary arrangements and obtain the appropriate permits/approvals to allow the use of grid-tied solar units in the field. Cool Earth Solar successfully transformed a brown-field site at the LVOC into an operational facility that could host the necessary solar development activities in a representative operational environment.

Figure 6: Cool Earth Solar's Operational Field Site

Photo Credit: Cool Earth Solar

2.2 CPV System Deployments

The other four sub-tasks, 2.1, 2.3, 2.4, and 2.5 entailed the ordering, manufacturing, installation, and operation of solar collectors. Over twenty inflated concentrator modules were deployed to the site at LVOC, representing approximately twenty kW of capacity over the term of the grant. Much of the production and assemble of the system was done in-house. As such, no entire subsystems were obtained from significant vendors. Instead, materials were obtained on a piece-part basis commensurate with the hand-built nature of the systems deployed. Cool Earth Solar's next phase of scale-up focuses on development of a pilot manufacturing process that will allow a more detailed assessment of the manufacturing process itself.

A wide variety of improvements in design, manufacturing, and operation were made as a result of the learnings gained through these deployments.

One early design change made as a result of field deployment experience was the addition of bumpers on either side of each tube. The baseline design only held the inflated structures on the back along the edges of the narrow receiver tray. It did not provide sufficient vertical position stability. Changes in position of the tubes as the tracking followed the sun caused changes in the gravitational loads on the tubes. As a result of these variations, the tube positions would move depending on orientation of the rig. Changing the tube positions in this manner shifted the focal line relative to the receiving cells. Installation of bumpers immediately solved the problem. A second revision was made to the bumper design to eliminate frictional wear that shortened tube lifetime.

Materials used to make the inflated tubes were upgraded several times to address the ability to seal the films airtight. Many of the changes were in response to one-time conditions and don't represent breakthroughs in design or performance. An example of this was the tape seal joint around the optic that was qualified with excellent performance early in the program. Later shipments of the "same" tape from the vendor were noticeably different in color and gave off a distinct odor that was not previously noted. Seals made with the new shipments of tape failed early and often, requiring significant field repairs. Several changes were made to the in-house manufacturing process to account for the new material differences, including film dimensions and overlap, time/pressure/heat conditions, and the overall operational pressure within the tubes. Additional adjustments to the manufacturing processes are anticipated with every transfer between materials, tools, vendors, etc. Such process customization is common within manufacturing environments to "tune" the performance of the resultant system.

Design changes were made several times to the gear assemblies that held the upper frame. The exact distribution of weight was well modeled for fully populated rigs (3 tubes per tracker), but underpopulated systems were not originally considered in the gear designs. Upward forces on the gears driven by wind and underpopulated weight distributions caused failures of the gears on two occasions. A more robust design to capture the upper rack and hold it on the gears was introduced in response to the first failure and modified to address the second. A third redesign was made when excessive friction was seen in some orientations.

A significant amount of work was spent on calibrating the performance of the tracking system responsible for pointing the system at the sun. Part of the information used to orient the system comes from a magnetometer that senses the earth's magnetic field. Early difficulties with the magnetic readings were traced to the locations of ferromagnetic components around the sensing unit. Since most of the frame is made from steel, resolving these issues was a challenge. Placing the sensors on an aluminum strut as far from steel frame members as possible has stabilized the readings. Other work on the tracking system was focused on noise reduction in the sensor signals. Sources of noise included vibrational feedback to the system accelerometer when movements were commanded, flaky signals from water penetration of temporary electronic enclosures, and the inherent positioning errors due to step-wise commanded movements. A variety of signal averaging, error rejection, and data smoothing techniques were employed to achieve excellent overall positioning performance.

Many minor issues were noted with bracket design, hole placement, thread design, and lots more small mechanical issues. These were updated in real time with field modifications, replacement hardware, and design changes to the mechanical drawings.

2.3 CPV System Performance

At the same time that hardware issues were being discovered and resolved, critical performance capabilities of Cool Earth Solar's CPV system were validated via field-testing as described below.

Tracking the sun is one critical task the system must perform reliably to keep the focused sunlight on the solar cells embedded within each of the inflated concentrating modules. Cool Earth Solar implemented a system of tracking sensors and control software that keeps the modules pointed at the sun. This system was tested to determine both the characteristic pointing capability and the optical tolerance to misalignment. A reference scan was performed by passively allowing the sun to drift across a stationary collector. Given the horizontal linear concentration, azimuthal changes to the energy collected during the experiment were negligible. Figure 7 depicts the results from this experiment. The elevation window was determined by the angular width of the region in which the system produced stable output energy. This tolerance window was then compared with a month of on-sun elevation tracking data collected to assess the precision and accuracy of system tracking of the solar disk. The experiment showed ample pointing margin, inclusive of wind-driven inaccuracies, demonstrating the robust nature of Cool Earth Solar's tracking capability.

Figure 7: Tracking Capability Demonstrated

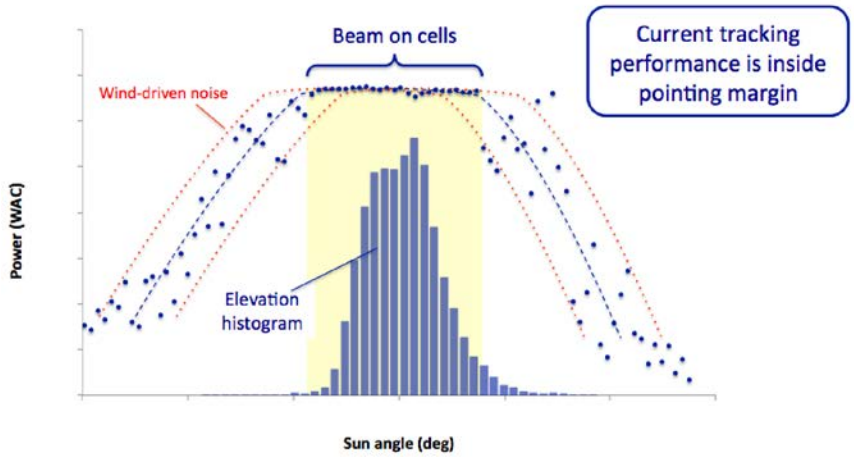

Photo Credit: Cool Earth Solar

A key capability to demonstrate in a solar energy system is the ability to handle waste heat. Common solar cells like those used in Cool Earth Solar's system absorb around 80% of sunlight they receive as heat. Elimination of the heat is instrumental to efficient operation since most solar cells become less and less efficient the hotter they get. Cool Earth Solar has designed the overall thermal path from the solar cell through a back-side heat sink to ambient to be highly efficient in heat removal while maintaining low manufacturing costs. Results obtained validated both the analytical thermal model, as well as the performance of the as-built thermal management system. (Note proprietary values have been redacted from the Figure 8 below.)

Figure 8: Thermal Management Design Verified

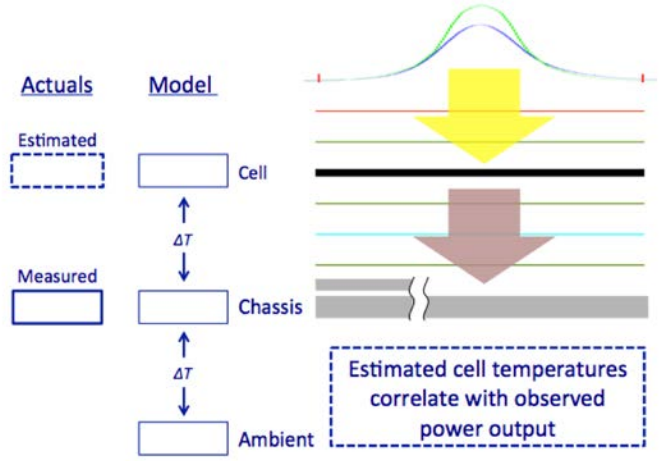

Photo Credit: Cool Earth Solar

Finally, internal design specifications can help guide development activities, but the most pertinent results are those directly related to the purpose of the system: collecting solar radiation and turning it into electricity. Cool Earth Solar has monitored performance on many of its deployed modules, but in particular ran a performance marathon on a single module during the month of June, 2014. Power produced by the unit was compared to the available solar resource to generate the performance ratio for the system.

The module was rated as "nameplate" 810W_{DC} under standard test conditions (STC) using industry standard definitions and methods. The electrical energy produced by the one-module system was monitored each day for a month. The week ending June 11th was chosen for a benchmark study. Comparisons between the actual power produced vs the nameplate model allowed calculation of a performance ratio of 83.8%. This is an excellent result for an early test system considering that most flat-plate silicon solar modules have performance ratios in the range of 70 to 80. During the selected week, over 7 $kWhr_{DC}$ energy was collected on average each day. This corresponds to nearly nine hours of full nameplate power generation, demonstrating the significant energy generation advantages of a 2-axis tracking system relative to a fixed flat panel system.

Figure 9: Energy Collection Performance

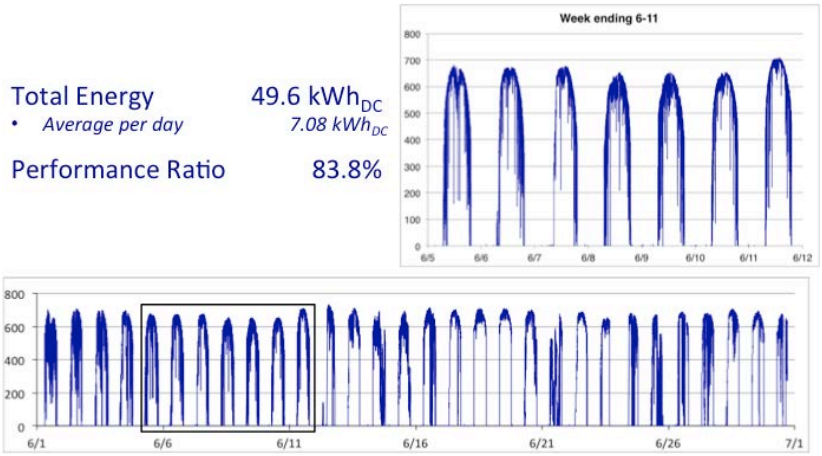

Photo Credit: Cool Earth Solar

Collectively, the work enabled under task 2 of this grant has allowed Cool Earth Solar to significantly mature and validate the CPV system technology, cost, and performance. The context for this progress is provided below in Chapter 9 on Production Readiness. A final validation of the total progress made was recently received in the form of outside investment funding for next phase commercialization and scale-up activities of Cool Earth's CPV system.

Figure 10: Cool Earth Solar Systems on Sun, Producing Energy

Photo Credit: Cool Earth Solar

CHAPTER 3:
Solar Resource Sensing

3.1 Background

As originally envisioned, Task 3 and Task 4 were tightly coupled activities built around multiple deployments of sky imaging meteorological stations, followed by a data analysis phase that would build a forecasting model to allow prediction of solar resource. Task 3 was overtaken by events when the baseline technology design for Cool Earth Solar's sky imager was denied patent coverage. Part of the reason for the denial was the commercial availability of systems with comparable features, performance, etc. Also early in the project timeline, several papers were published using data from these commercially available sky imagers. The techniques used and results obtained in published papers covered many of the capabilities described in Cool Earth Solar's statement of work for task 4. As described in greater detail in Chapter 5 of this report, the specifics of these tasks were revisioned to embrace work that had a greater chance of producing novel results.

3.2 Introduction

The driving force for developing systems and techniques to sense and forecast atmospheric conditions relevant to solar energy is the issue of intermittency. This is especially important for utility-scale solar power plants where a local change in weather can knock megawatts of energy production off-line within a very short period of time. From this view, a minute-by-minute forecast of cloud conditions near the plant can help operators predict energy output.

From the perspective of grid operations, however, the rise of distributed solar generation implies that weather driven intermittency happens on a more granular scale – more events of smaller size. This has the effect of smoothing the intermittency of energy production as smaller, more widely distributed systems jump in and out in a similar fashion to existing intermittent electrical loads on the grid. In this view, energy forecasting is limited by the timescales and capacities of the fossil fuel powered peaker plants used to balance the grid. A more reasonable goal is to predict grid-wide power production trends on the order of 30 minutes to three hours: the response time for the peaker plants.

Distributed systems are also more tolerant to shadowing. This means that variable and partial cloudiness can lead to significantly more energy production compared to utility scale because each system or individual panel can optimize power output to the variable solar resource it sees. This implies a need to understand more than just a cloudy/clear binary prediction when considering the solar resource available to distributed systems.

Figure 11: Distributed Systems Are More Tolerant to Variable Conditions

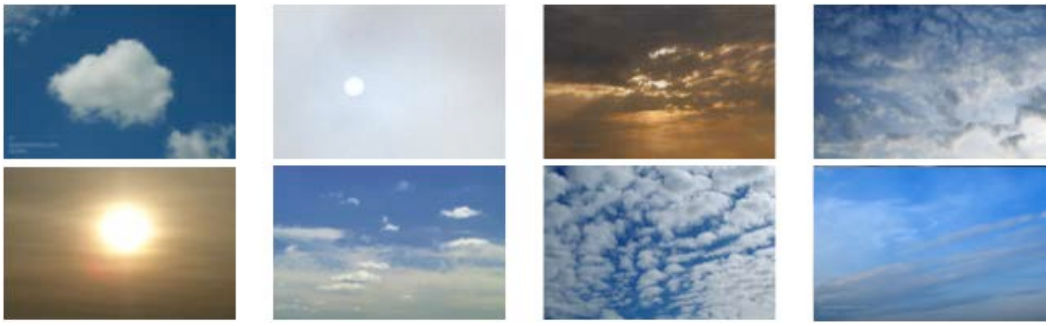

Photo Credit: Cool Earth Solar

3.2 The Compound Eye Approach

The concept of low-cost sky imaging called for the opportunity to utilize multiple imagers from different sites to synthesize a wider area perspective on the data. This data fusion activity made use of high-density local data provided by each of the imagers, but relied on relatively few imagers sparsely located regionally. As initial work proceeded on meteorology sensor development, questions were raised about the optimum tradeoff between data density at any one location versus the number of independent sites used. Consideration of the extreme case of a single photosensor replicated in a large number of locations led to the realization that solar energy collection devices, despite having a main purpose of collecting solar energy and converting it to electricity, fit the description of such a photosensor.

The pixel in this case would correspond to the smallest "grain size" of reported energy from solar installations. Thus, utility scale power plants using central inverters may only report an average across hundreds of panels, while microinverter technology would report results on each panel deployed. These individually addressable readings could form the ommatidia of an immense, irregularly arranged compound eye. A chief benefit of such a consideration would be that the sensing function comes along free – at no additional cost over already-paid-for deployment of the energy collectors themselves.

In the case of Cool Earth Solar's solar collection technology, an optical sensing unit was included in the tracking hardware implementation to provide fine-track control. The unit was designed as a non-imaging array of five photocells arranged beneath a circular aperture. Each of the five cells could be individually addressed by system software, providing data from five closely spaced overlapping views of a small portion of the sky.

Additional capability for sensing was present in the Cool Earth Solar system due to the nature of the system. A CPV system inherently needs to be able to move to keep the optical elements aligned with the sun as the Earth's rotation moves the sun's image across the sky. Modifications to the software used to direct the system could provide the capability to point the system and its associated fine-track optical sensors anywhere in the sky to collect information about the presence and characteristics of any clouds. This additional ability of 2-axis tracking systems enabled the possibility of actively probing a section of sky with multiple rigs to gain detailed

information on the localized distribution of light around clouds. Synthetic aperture data analysis techniques could then be used to provide scattering densities for the clouds in three dimensions.

The Compound Eye concept could then be conceived at two scales of operation. The collection and fusion of data across widely distributed data from multiple deployment sites and types of solar equipment could lead to very useful regional data on the real time variation of solar resource. Alternatively (but not exclusively), the pointing capability of CPV systems like Cool Earth Solar's could be employed using multiple systems across a locality to provide detailed volumetric data on the cloudiness responsible for loss of solar resource.

A significant economic barrier to the overall Compound Eye vision was the potential cost of modifying solar energy systems originally deployed for the purpose of energy collection. For example, in many large solar installations thousands of potentially independent solar panels have been strung together using central inverters. Access to each individual panel would require additional hardware costs over and above those required for the primary mission of energy collection. This demonstrated that any dual use intended to collect information about cloudiness needed to avoid increased deployment costs for the solar energy collection system.

The primary question studied by this work was therefore whether production-focused solar hardware could be adapted to provide useful sensing capability at no additional system cost. One non-obvious complication of using unmodified solar cells to image the sky is that they are inherently monochromatic – they "see" in grayscale. A casual perusal of monotone pictures of the sky highlights the challenge that "clouds" are sometimes lighter and sometimes darker that open sky. The obvious fixes of adding color filters or using color-sensitive cells have been ruled out under the philosophy that the Compound Eye concept would only achieve wide acceptance if solar collection units could be used without adding costs through modification. The key understanding that enables the Compound Eye technical approach was that the main characteristic of interest in the data collected is the change from one data point to another. It was therefore unnecessary to this task that a sensor be able to use a single-pixel, isolated light intensity value to determine information about the scene. Variations in the data over time and space allow identification of when and where the solar resource available to the collectors changes. The Compound Eye depends only on reading the variations and being able to extract useful information in the form of predictions.

A secondary question was whether results from multiple simultaneous sensors could be combined to provide a deeper understanding of the available solar resource. This question arose at two levels in regard to the Cool Earth Solar's implementation. The proposed use of the five photocells in the fine-track sensor head raises the question of how to use the data from each of the five cells. One possible use would be to combine the data from five different but overlapping fields of view to provide a single value representing a smaller region of sky. Combining readings from each of the associated fields of view to enhance the spatial resolution of the combined sensor suite was one possible approach. Alternatively, combinations of data streams could be directly compared to provide horizontal and vertical edge detection. Another opportunity for using combinations of signals arises from the spatial variation provided by

comparing signals from multiple tracker systems – either grouped into a single locale or distributed across several installation sites. In principle, the techniques for combining data from multiple sites are independent of the distance between readings. With proper handling, data from arbitrarily spaced sensors can be analyzed together.

Figure 12: Field Of View of a Single Fine-Track Photocell

Photo Credit: Cool Earth Solar

3.3 Work Performed

While Cool Earth Solar's CPV energy collection system was designed including an optical fine-track system, the deployments performed in Task 2 were implemented using magnetometer and accelerometer sensors as part of the system's so-called coarse-tracking module. Initial results from solar collection performance obtained in "coarse" mode (as shown in Chapter 2) were easily good enough to achieve the goals of the project. The additional capability of fine-track control can provide increases in energy production of a few percent, but this would only be relevant at later stages of commercialization. While the tracking sensor circuit board already included the five photocells, the necessary software to access the cells was not implemented as part of Task 2. Similarly, the access port in the electronics enclosure intended to allow apertured light to fall on the sensors was designed, but not implemented. A first task was therefore to implement the software and hardware modifications necessary to operate the optically based fine-track sensors. The necessary changes were completed and installed on two systems in the field. The silver colored sensor aperture tube can be seen just left of center in Figure 13. The larger clear plastic tube on the right enclosed a high-resolution camera mounted parallel to the fine-track sensor tube for test purposes to provide comparative control information.

Figure 13: Fine Track Optical Sensors are Part of Each Cool Earth Solar Tracker

Photo Credit: Cool Earth Solar

3.4 Results

Upon completion of the hardware and software development to make the fine-track modules operational, a first task was to verify that each of the five photocells was receiving light levels that matched the field of view presented to them. All five were verified functional and responsive to their environment as expected. The sensor head was then pointed to a section of sky off-sun that had variations in light intensity due to clouds. The system was then scanned manually in elevation while recording each of the five sensor values and a control image from the reference camera. The data from the camera image were post-processed to extract regions of the image corresponding to the five sensor fields of view. The average light intensity in each of those fields of view was calculated and compared to the sensor readings as depicted in Figure 14. The single-sensor readings were well matched to the simulated results calculated from the reference camera images.

This confirmed the use of monochromatic sensors and verified that each sensor was viewing a spacially distinct portion of the sky.

Figure 14: Measured and Derived Data Matched for Each Sensor

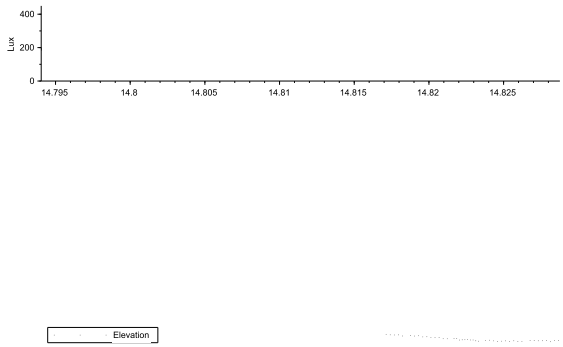

Photo Credit: Cool Earth Solar

As noted above, the values of interest are the relative light intensities as distributed across time and pointing direction. Tracking changes in intensity over time or across a field of view on the photocells depends on a good understanding of what sources of variation contribute to the overall signal observed. This concept prompted an examination of fine-track photocell readings from an "empty" sky. In this case, a uniformly blue sky without observable clouds was scanned to determine the variation of background signal. Again, the sensors were positioned oriented toward an off-sun position in the sky. The elevation was then scanned from below the location of the sun (closer to the horizon) to above it while staying at a constant azimuthal heading that was approximately 20 degrees to the west of the solar location. The total time for the scan was short enough that movement of the solar disk could be discounted. Figure 15 shows detection of the solar disk at ~ 45° in elevation as represented by the peak light intensity. This is a reasonable result considering that scattering from an empty sky is expected to drop off with angular distance from the sun. Since the scan in elevation followed a straight vertical path, the angular distance was smallest when the elevation equaled that of the solar disk. The fact that the monochromatic photocells of the fine-track sensor module were able to measure background illumination confirmed the capability of the system to determine systematic bias in scans of objects of interest. An important secondary use of this information is to allow the CPV system to detect the location of the sun independently of the coarse-track magnetometers and accelerometers, even when the sun itself is outside the field of view.

Figure 15: Sensor Signal Crossing the Sun in Elevation While Off-Sun in Azimuth

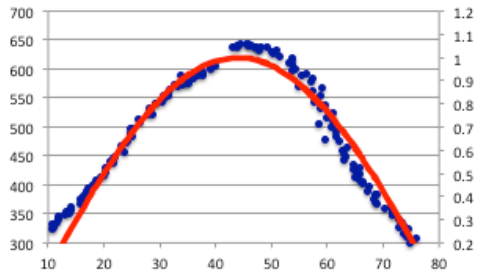

Photo Credit: Cool Earth Solar

The sensor head was then scanned across a skyscape filled with variable amounts of cloudiness. Figure 16 shows composite images from the reference camera of a high-to-low down scan followed by a low-to-high up scan. Superimposed on the images are two signal tracks extracted from sensor data from the unmodified fine-track head during each of the scans. The down scan is color-coded blue and the up scan red. The signal represents the difference between the summed signal intensity of the upper and lower pairs of sensors, using the center sensor to normalize the other four. Since the apertured field of view for the off-center sensors is reversed from the offset positions of the photocells, positive values of the difference suggest darker light intensity above and brighter below. Therefore movements of the blue and red traces toward the right correspond to detection of a dark-above/bright-below edge in the image. As one might expect, leftward peaks correspond to an edge that has dark below and bright above. The amplitude is displayed on an arbitrary scale. The amplitudes of the peaks do provide relative information about the spatial rate of change of the light intensity. The larger the excursion is horizontally, the faster the vertical transition is when scanning from light to dark or *vice versa*.

The field of view for each sensor is approximately 8° wide, as depicted in Figure 12. Any signal calculated from the data collected retains similar spatial averaging in the resultant traces both vertically and horizontally. Therefore, the traces only vary in response to larger features in the sky, while small variations seen in the high-resolution reference images are blended smooth.

Callout mark A in Figure 16 points to two consecutive peaks in the blue down scan. The bottom peak to the right reflects the presence of a dark over light edge as seen in the corresponding image. The next higher peak corresponds to a light-over-dark edge. As the sensor suite was scanned downward over the region, the signal amplitude first rose in response to the leading (lower) edge falling dark and dropped back toward center when both upper and lower collected light from similar fields of view straddling the dark band of open sky. As the scan continued, the lower sensors experienced a brightening ahead of the uppers, leading to a peak in the signal trace to the right. When both upper and lower sensors crossed the boundary, the signal again returned to the center. Note that the peaks correspond to the difference signal between the upper and lower photocells and therefore do not line up exactly with what a casual observer might identify as the edges of the dark band of open sky. Rather, they locate the point of highest rate of change in light intensity with respect to vertical location. As can be seen in

earlier portions of the blue trace, three additional transitions were identified within this portion of the scan.

Callout mark B points to two consecutive peaks in the red up scan that bridge the same dark band of open sky as mark A. Interestingly, the lower peak has shifted upward and the upper has broadened considerably relative to their predecessors in the blue down scan. The differences in the underlying images were a result from a short pause between the two scans, during which time the cloudscape moved right to left on the wind. This can be observed by noting the difference in position of the small puff of cloud in the middle of the dark band. The differences in peak shape and location can also be seen as differences in the images. The dark band itself has narrowed as a shelf of additional cloud mass drifted into view. This caused the upward shift of the bottom peak of the pair. The transition between peaks is much sharper in the red up scan because of this narrowing and a sharpening of the bottom edge of the dark band. The upper peak broadened in the upward direction because a darker pocket in the section of cloud above the dark band moved into view.

The very wide, low amplitude peak near callout mark C reflects the low rate of change of brightness as the scan covered that portion of sky.

Figure 16: Detection of Variable Cloudiness Using Unmodified Solar Collection Hardware

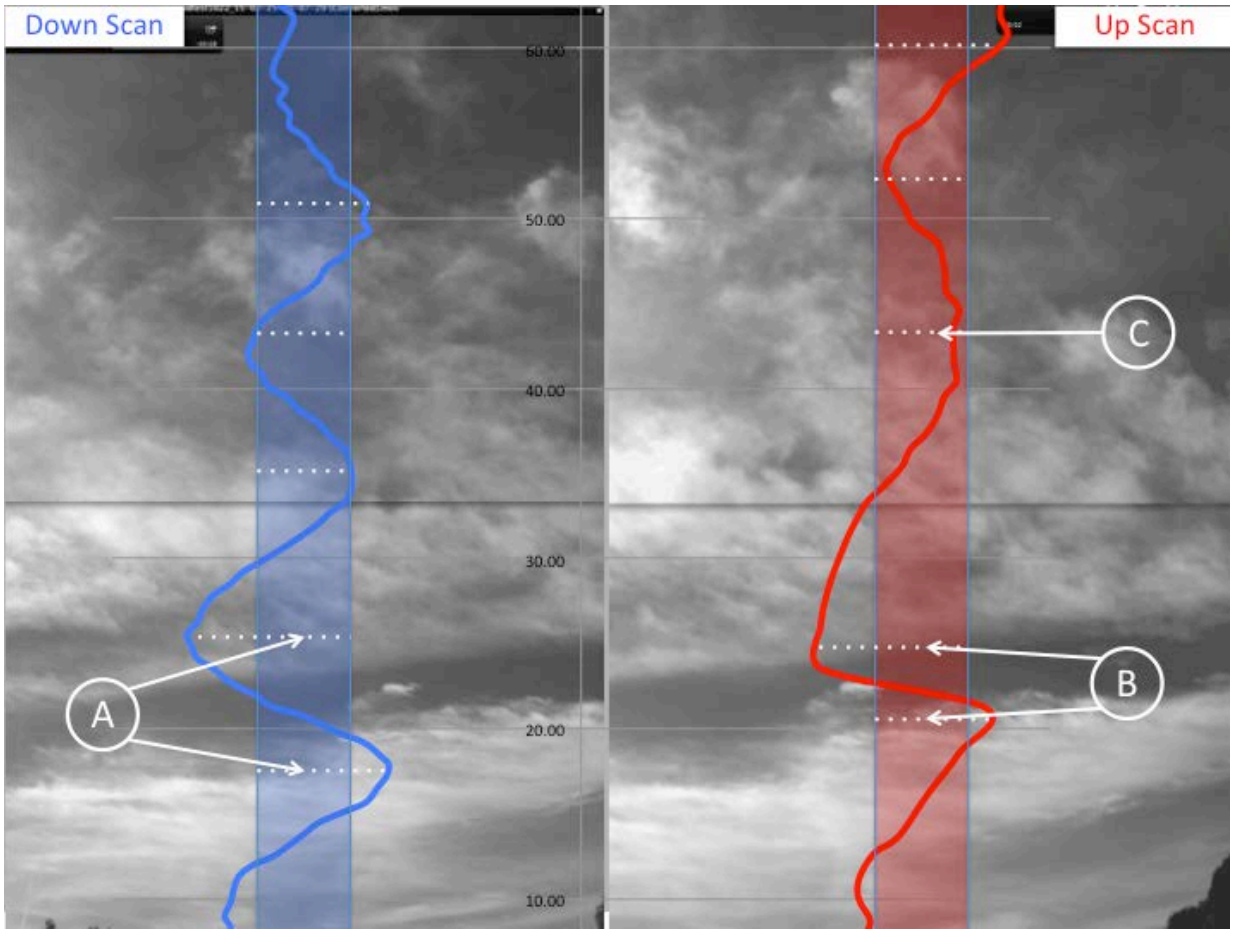

Photo Credit: Cool Earth Solar

3.5 Conclusions

The Compound Eye concept depended on two important verifications of feasibility. The concept needed to work with widely deployed solar collection units without adding any hardware costs. The data collected from these spatially distributed sensing streams also needed to combine to provide unique capabilities for detecting features of interest.

The feasibility of using unaltered solar hardware has been proven two ways. A more direct demonstration was the use of Cool Earth Solar's fine-track hardware to successfully scan cloud images. The scans revealed details of cloud structure such as the spatial locations and sizes of cloud masses, the rates of change of intensity versus location, each of these characteristics over time, and prevailing winds, if any. Additional comparisons within a larger data set could reveal a more comprehensive sense of solar resource, but the basic concept of using unaltered sensors has been proven. A weaker, but more general, point can be made that the photocells used within Cool Earth Solar's fine-track sensor head are an excellent representation of the low-resolution, monochromatic data which could be gathered from typical widely installed flat

panel solar modules. With appropriate adaptations for orientation and the inability to point, the data collected in this work demonstrates the viability of the Compound Eye method for flat panel solar modules.

The second feasibility goal of the task was to demonstrate the capability of spatially separated signals to resolve information otherwise inaccessible to a single sensor. As originally envisioned, this entailed using two separate fine-track units mounted respectively on two separate Cool Earth Solar collection systems. Physical limitations relative to our field site suggested that the 60′ baseline available between systems would be marginally adequate, under favorable conditions. Hardware failures caused a period of unavailability of one of the 60′-spaced systems during the portion of the schedule during which the Compound Eye data collection was to take place. The remaining two systems were only spaced 30′ apart and provided inadequate angular separation to obtain useful information from comparisons between the units.

This issue was resolved by reassigning the experimental plan for angular separation to the independent sensors within the fine-track module sensing head of a single system. The angular difference between the fields of view for the fine-track sensors are equivalent to those estimated in the original 60′ baseline geometry of two separate systems. The principles of data fusion between sensor data streams are agnostic to the orientation as long as they are independent – a condition satisfied by sufficient angular separation in either case. The ability to combine independent data streams to provide useful information was demonstrated by the calculation of a signal that responded to the edges of features in an image.

While minimal in breadth, the results obtained in the feasibility study of the Compound Eye concept have successfully shown the ability to combine two independent data streams to provide useful information about solar resource using unmodified hardware from a solar collection system.

3.6 Next Steps

The results obtained from this work have confirmed the basic feasibility of the Compound Eye concept. Realizing the benefits of this technology will still require a great deal of development work. Two main approaches forward suggest themselves for the Compound Eye sensing concept.

Cool Earth Solar's CPV solar collection system has been shown to have capability to provide useful sensing information using unmodified hardware. The incorporation of 2-axis tracking allows the system to point toward arbitrary locations in the sky. If multiple systems were scanned across regions of interest, the combined information would allow analysis of cloud structure in unique ways relative to single-location sensing technology.

Cool Earth Solar will continue to commercialize its technology with this inherent capability. Future Compound Eye related work could explore typical development-phase topics like sensitivity, universality, and reliability of using arrays of systems to extract useful information from a field of orientable sensors. Cool Earth Solar has taken a wait-and-see approach,

collecting information about the Compound Eye potential while continuing development of the system capabilities commensurate with its primary mission to collect solar energy.

Even without the ability to point to different locations in the sky, fixed solar collectors can still provide useful information about the solar resource. In this picture, the scale would expand from a single (potentially large) field of movable sensors to the entire geographical region of interest. A requirement for successful image processing using many fixed sensors would be that the sensors must provide sufficient coverage in the form of data density for the area considered. This type of implementation would likely entail a public domain, shared effort across many different entities including system owners and manufacturers to collect and process the available data.

It is possible to provide smaller-scale field tests of the fixed-sensor implementation. One method could be to deploy a large number of low cost apertured photocells that would collect light intensities from small, fixed portions of the sky overhead. By aperturing to a small field of view for each sensor, the deployment distances for the test could be managed on an experimentally accessible scale while still simulating relevant issues like irregular sensor spacing and overlap. Another possible experiment could explore the threshold density of sensors required over a regional area by engaging a single partner with access to larger numbers of systems already in commercial deployment. Cool Earth Solar has been in early discussions about studying the Compound Eye concept with a manufacturer of module-based power electronics who could provide information on power readings across multiple installation sites with a region.

Finally, regardless of how the data are collected, the significance and meaning of the features imaged would still need to be elucidated. The ability to link what is “seen” by an implementation of the Compound Eye to useful predictions of solar resource remains largely unaddressed. Until more data are available that provide imaging results from this novel approach, little can be gleaned about its potential relative to conventional sky imaging technologies.

CHAPTER 4:
Smart Building Task

As originally envisioned, task 5 of the scope of work included the application of solar resource forecasting to a real-world application of power management at an existing building. The concept of demonstrating end-to-end usefulness of collecting, sensing, forecasting, and responding to available solar energy remains a desirable goal. The ability to tailor local grid load in response to the availability of energy would directly address the variability of solar energy and thereby reduce the need for expensive peaker plant power. While such uses of forecasting data are widely recognized and modeled, examples of implementation remain scarce.

The current work contemplated the use of forecasting information generated via task 4 to implement load management of a building heating, ventilation, and cooling (HVAC) system. A seemingly obvious candidate for the work was an existing "smart building" at Sandia Livermore Laboratories equipped with the appropriate control infrastructure to respond to inputs derived from energy forecasting. The building was located close to Cool Earth Solar's deployment field at LVOC and the feedback from the relevant groups within Sandia was supportive and positive of the effort.

During the course of the agreement, a large roadblock was uncovered relative to the conflicting requirements of the envisioned building feedback control and site security for the national laboratory. Since the smart building was "inside the fence", the relevant building control systems were all implemented on an internal secure network. As such, direct digital communications were prohibited from the outside. This included, of course, information sent from the solar field located a short distance away in the LVOC. Of special concern was the idea that unsecured signals from the outside could directly control infrastructure systems at the lab as envisioned for task 5. An alternative approach suggested by Sandia's facilities team was to convert the digital communications stream to an analog 0-10V signal. This signal would then be passed via a twisted pair wire across the secure boundary. Additional hardware within the secure site would then measure the incoming signal and interpret the need for digital commands to the building HVAC. The *coup d'grace* for the effort was a requirement that the designs for the digital-to-analog-to-digital hardware just described would need to be submitted to Sandia's facilities and security groups for review and approval – a procedure that would have likely consumed a significant fraction of the time remaining to complete the task.

No viable alternatives were identified to host the building management portion of the grant. Task 5 was therefore not completed and all funds allocated to it remain unspent. The study of the systematic benefits of load management remains a topic of interest to Cool Earth Solar, but many other companies and research groups are pursuing the topic at this time. Since this portion of the work was not pursued, no momentum on this topic was generated by the project. Cool Earth Solar has no plans to perform future studies of load management

CHAPTER 5: Outreach

In the course of performing the tasks embodied within the statement of work, Cool Earth Solar has formed and deepened both new and existing relationships within the broader community of stakeholders.

First and foremost, Cool Earth Solar's role within the LVOC effort at Lawrence & Sandia National Laboratories innovated a new method of interaction between the national laboratories and a private enterprise. The agreement under which the solar field was operated allowed low overhead management of a safe and secure environment. This was enabled in part by the low infrastructure requirements of Cool Earth Solar's CPV system itself. The technology had a minimal environmental footprint requiring little disruption of the site. Modest facilities for equipment and communications were available as needed at the site for operation and development activities. Convenient site access was provided for the Cool Earth Solar engineering team enabled by the proximity between the LVOC and Cool Earth Solar's facility. Rules for occupational and site safety were sensible and workable. Overall, the LVOC has provided a wonderful outdoor laboratory at a critical phase of Cool Earth Solar's technology commercialization. The interaction overall could serve as a model for private-government interaction.

One of the resources provided by Sandia National Laboratory was the collection and distribution of local weather conditions at the LVOC site. These measurements were made remotely by Sandia's Albuquerque-based solar energy team and provided to Cool Earth Solar as a reference critical for calibrating energy output. These relationships led to others within the federal solar infrastructure. Notably, individuals at the National Renewable Energy Laboratory (NREL) have also provided their counsel and advice in their role as advocates for the entire solar industry. Cool Earth Solar's interaction with federally sponsored solar activities and programs has provided a firm connection point to the entire solar industry.

Cool Earth Solar's extended network of relationships obtained through federal referrals included contact with the Bay Area Photovoltaic Consortium, a grantee of federal solar funding. Pre-competitive discussions with the project manager and other stakeholders in that effort have allowed Cool Earth Solar to explore the near-future availability of advanced solar cell technologies. The communication of Cool Earth Solar's CPV experiences has stimulated discussion toward cell technologies that would optimize power production under concentration.

Efforts under this grant have enabled Cool Earth Solar to submit several proposals for funding to the US Department of Energy (DOE) solar programs. Applications using results from this grant were prepared and submitted for several DOE offerings, including Incubator 9, SolarMat 2, and SolarMat 3. After disappointments on the first two applications, Cool Earth Solar was "encouraged" on the concept paper for SolarMat 3. A full application has been submitted. Notification of grant awards will be made in late summer.

In order to broaden the impact of the project, Cool Earth Solar has featured results in a presentation (Appendix B) and a poster paper (Appendix C) at CPV-10, a solar industry conference dedicated to CPV. Each of these efforts led to face-to-face meetings with other conference attendees and several follow-on conversation streams. The poster paper, in particular, presented reliability results on thin film plastics that may prove useful to other solar industry participants.

The LVOC has also proven to be an excellent location for visits from various strategically interested parties to visit Cool Earth Solar's technology at a grid-connected, operational site. While individual identities cannot be shared due to various non-disclosure agreements, the list of visitors includes at least five potential or current investors in Cool Earth Solar, more than seven potential domestic and international development partners, teams from two different Fortune 500 companies, and dozens of potential vendors and suppliers. In short, it has proven to be a very effective communication tool for educating visitors about the potential of Cool Earth Solar's CPV technology.

CHAPTER 6:
Technology Transfer

In addition to demonstrating performance targets, new technologies must be buttressed by three key conditions to achieve commercial viability.

Market demand must be present to provide customers and revenue for the new product. In the case of Cool Earth Solar's CPV system, market demand has been demonstrated through commercial agreements for deployments at the D'Arcinoff Group's biofuel facility in Sierra Blanca, TX. Anticipated installed capacity of Cool Earth Solar CPV over the first two years of the project could approach a megawatt of nameplate power. Market opportunities exist within Phase II of the D'Arcinoff project to deploy up to 100MW of Cool Earth Solar collectors by 2020. Additional deployment opportunities outside of the D'Arcinoff deal are in development as of this writing.

The ability to produce the technology at volumes and costs relevant to the market must also be present. Cool Earth Solar's technology has so far been demonstrated with full-size prototypes and significant design-related testing to optimize the system architecture. The most recent DOE grant submission for SolarMat3 includes plans to create pilot line capabilities through appropriate manufacturing process development with new, more highly automated suppliers. These scaling-driven process transfers are typical of a growing manufacturing environment as larger and less expensive vendors are brought online. Cool Earth Solar has the specific advantage during this process of having designed each and every part and subsystem for ease of scaling. Defined price/performance paths to high volume manufacturing already exist for many system components.

Finally, funding sufficient to drive growth is needed to meet market penetration requirements. Implementing high volume manufacturing processes for any new product requires significant financial commitment. Even in favorable circumstances like those provided by Cool Earth Solar's system architecture, the cost of deployment for large fields is prohibitive until costs near break-even. This period of "crossing the chasm" involves up front funding of development activities and deployments and usually requires investment of millions of dollars. Cool Earth Solar has signed investment agreements to financially support development of the technology to the point of low cost availability that can compete for further commercial deployments.

Cool Earth Solar has successfully achieved each of these three market-driven requirements in the form of signed contractual agreements for investment funding, vendor capability, and market deployments. With these contracts in hand, Cool Earth Solar will pursue further commercialization efforts to transfer this novel solar technology out of the lab and into the marketplace.

A strongly viable new entry into the solar marketplace like Cool Earth Solar's CPV system could provide immense secondary benefit to regional and national suppliers for system subcomponents. In particular, Cool Earth Solar's improvements to solar films properties and experience operating solar cells under concentration could lead to diffuse benefit to the entire

solar industry in the form of availability of high performing subcomponents. More directly, if Cool Earth Solar can execute on its business plan, the cost of solar-generated electricity could be significantly reduced relative to future flat panel, unconcentrated solar power plants through the installation of gigawatts worth of low cost, high reliability power.

CHAPTER 7:
Production Readiness

Through the execution of this grant, Cool Earth Solar has achieved production readiness by accumulating all the key elements necessary for a business to move forward with volume shipments. Market demand has been secured through a commercial contract to deliver CPV units within a large solar deployment. Continuous funding is present from internal and external sources in support of planned expenditures. Using these resources, Cool Earth Solar has formed a comprehensive plan of execution to scale its technology to commercial viability.

Figure 18: Cool Earth Solar Has a Comprehensive Business Plan (Redacted)

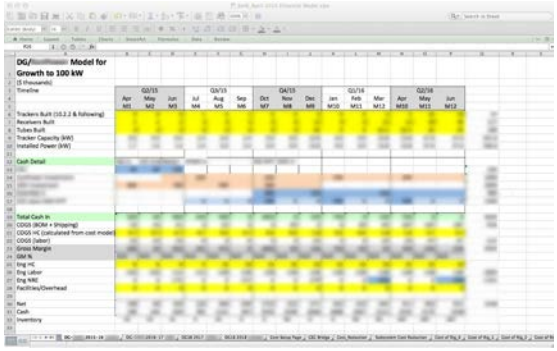

Photo Credit: Cool Earth Solar

Figure 18 is a redacted image of the first page of Cool Earth Solar's business plan. Included in the plan is a bottoms-up roll up of projected development costs over time that covers all the manufacturing process transfers necessary to scale to high volume. These costs have been incorporated into a model shipment schedule covering the next 4-5 years that reflects the estimated total financial requirement for the plan, including both direct and indirect sources of spending. This comprehensive picture of costs through time is matched to a detailed budget for funding available to Cool Earth Solar. The cash flow portion of the financial model projects a healthy balance of income and expenses throughout the plan.

Typical costs for early technology prototypes are often multiples of the final high volume cost floor. Cool Earth Solar's CPV system is no different. The size of deployments through time must therefore be managed to conserve total cash while achieving sufficient manufacturing maturity that the costs are reduced prior to the next ratcheting up in shipment volume. This balance is maintained throughout Cool Earth Solar's scale-up plan. The cross-dependencies of shipment volume and cost reduction are all based on real-world vendor information and bottoms-up detailed cost reduction programs.

Large size future deployments are required for more than just cost reduction. A parallel task is to prove sufficient risk reduction that Cool Earth Solar's CPV system can achieve reliability and economics commensurate with industry requirements. This key step of proving risk reduction will allow the use of third party financing for future deployments. This condition of so-called

“bankability” is the key milestone that enables widespread market penetration without the need for matching investment spending sourced from the company. Cool Earth Solar’s deployment plan for the next 4-5 years includes sufficient volume and time to verify system maturity and achieve bankable status.

CHAPTER 8:
Results and Conclusions

8.1 Conclusions

Cool Earth Solar's CPV technology entered the project as a highly mature and capable laboratory prototype. A key task was the field deployment of the systems to provide real-world feedback to the product commercialization process.

The initial subtask of securing a representative deployment site was successfully completed through the permitting and operation of a solar field at the LVOC. Subsequent activities resulted in the installation of three 2-axis tracking systems and 20 ~1 kW concentrating solar modules. The subsequent cycles of learning for materials and manufacturing processes allowed the identification and elimination of multiple system issues as is normal for technical commercializations like this one.

The system deployments allowed for key performance measurements demonstrating a wide performance margin and excellent collection efficiency. The necessary pointing accuracy for optimum energy collection was measured for the system. The coarse-track module was then demonstrated capable of keeping the system on-sun within the pointing window over an entire month. The total energy collected through the benchmark month demonstrated competitive advantage for the system relative to 1-sun alternatives.

The system results obtained have been instrumental in allowing closure of several commercial agreements for Cool Earth Solar's next deployments at a customer site. The path to bankability has been enabled through the results obtained in this work.

The Compound Eye concept depended on two important verifications of feasibility. The concept needed to work with widely deployed solar collection units without adding any hardware costs. The data collected from these spatially distributed sensing streams also needed to combine to provide unique capabilities for detecting features of interest.

The feasibility of using unaltered solar hardware has been proven two ways. A more direct demonstration was the use of Cool Earth Solar's fine-track hardware to successfully scan cloud images and provide information on the spatial locations and sizes of cloud masses, the rates of change of intensity versus location, each of these characteristics over time, and prevailing winds, if any. The low-resolution, monochromatic data collected in this work demonstrates the viability of the Compound Eye method for flat panel solar modules.

The second feasibility goal of the task was to demonstrate the capability of spatially separated signals to resolve information otherwise inaccessible to a single sensor. The ability to combine independent angularly orthogonal data streams to provide useful information was successfully demonstrated by the calculation of a signal that responded to the edges of cloud features in an image.

The results obtained in the feasibility study of the Compound Eye concept have successfully shown the ability to combine two independent data streams to provide useful information about solar resource using unmodified hardware from a solar collection system.

8.2 Benefits to California Ratepayers

The results from this grant have allowed Cool Earth Solar to complete key business milestones. Market demand has been demonstrated by a signed deployment agreement for over 100MW of solar capacity, including use of the new inflated modules and 2-axis tracker. Key supply chain agreements have been secured, enabling rapid volume scale-up for Cool Earth Solar's system. Finally, investment in Cool Earth Solar's next round of expansion has been secured. The results of the work have therefore enabled multiyear scaling activities that will lead to the subject technology achieving "bankability" – the ability to obtain bank financing for projects. Over the next four years, Cool Earth Solar anticipates shipping as much as 100 MW of solar capacity in support of these activities. Achieving bankability will allow full participation and competitiveness in the solar industry marketplace at projected system costs at or below $1.00/W and $0.06 levelized cost of energy (LCOE) by the year 2020.

A large early benefit for Cool Earth Solar as a result of working on this grant was the acquisition of a commercial agreement for deployment of CPV solar collectors. The D'Arcinoff Group has contracted with Cool Earth Solar to deploy approximately 265MW of mixed flat panel and CPV solar collectors. In addition to Cool Earth Solar receiving enormous economic benefit from developing such a large solar plant, D'Arcinoff explicitly wished to install as much Cool Earth Solar CPV as possible – up to 1% of the field. (Most of the field will be commercially available flat panel systems.)

Figure 17: Approximate Location of Planned Commercial Deployment

Photo Credit: D'Arcinoff Group, used with permission

The specific benefits to California ratepayers include the fact that Cool Earth Solar and many of its suppliers are California-based companies. As such, growth derived from successful implementation of Cool Earth Solar's technology will benefit the workers of the participating companies and the communities they live in through secondary economic activity.

Cool Earth Solar's technology is also highly appropriate for utility-scale deployments within the state of California. The excellent solar resource available in the state means that Cool Earth Solar's CPV technology can provide energy to the California markets below the future projected cost of solar competitors as well as traditional fossil-fuel based energy like that derived from the leading California energy source, natural gas.

To the extent that the "Compound Eye" solar resource measurement system can be realized on a broad scale, California ratepayers stand to benefit lower energy costs and a more reliable grid as a result of the potential of the imaging technology to provide useful solar forecasting. Initial benefits of this work include the influence this feasibility study will have on other industry researchers, leading to additional improvements on the initial concept.

8.3 Lessons Learned

The original research proposal brought together three areas for development that had mutual synergy from an overall integrated viewpoint. Each of these areas, however, required at least some basic development prior to becoming useful from an integrated perspective. The task of moving three independent sub-projects through development to the point of integrated operation was considerably more challenging than expected since the synergies and efficiencies expected were only present at the integrated system level. At the development level where the bulk of the work lay for each of the sub projects, there was little cross-fertilization or opportunity for dual-use effort. This caused tasks outside the mainstream expertise and focus of Cool Earth Solar to suffer from the inability to successfully pursue and support the wide range of activities necessary to develop each of the sub-areas from scratch.

A second area where difficulties were encountered was in the ability of the planned sub-contractors to participate in the work due to institutional barriers that made adaptation to circumstances impossible. When a barrier to Task 5, smart building management, arose due to security issues, there was no effective means to address the issue short of finding and developing a new building partner. This raised the difficulty and effort of the task beyond the ability to execute.

A third lesson was learned in response to program issues discovered along the way. During the execution of the grant, barriers and issues were encountered in each of the three major subdivisions of the grant (CPV, sensing & forecasting, smart building). Effective communication with the grant sponsor (the Energy Commission) allowed a refocus of efforts through the Critical Program Review (CPR). This refocusing resulted in revised methodologies in each of the task areas. When no viable/reachable alternatives were apparent, task 5 and its funding were excised entirely from the scope of work. This grant oversight process provided a positive impact on the ability to execute valued outcomes successfully. Close communication between grantor and grantee allowed these changes to be made in such a way as to maximize the received benefit of the work performed.

8.4 Next Steps

Cool Earth Solar has been able to mature a novel solar collection technology to the point where commercial viability is present. Market demand (in the form of a deployment contract) provides "pull" for commercialization of the system. In parallel, critical supply chain infrastructure has been set in place through contracts with strategic vendors. Finally, progress enabled by the grant has been validated by new investor funding for deployment of Cool Earth Solar's systems. Taken together, these accomplishments will enable further commercialization of this important new tool for harvesting solar energy.

Cool Earth Solar has also demonstrated the viability of a new approach to sensing and forecasting solar resource availability— the "Compound Eye". Combining existing (and future) solar harvesting units via data fusion techniques appears to be a possible method of predicting solar resource without adding additional costs for dedicated sensing hardware. While a clear pathway to commercialization of this new idea is not yet apparent, Cool Earth Solar will continue to develop its own capability to collect and utilize solar resource data. Business strategies for enabling broader adoption of these concepts to enable joint value amongst potential participants will also be explored.

GLOSSARY

Term	Definition
Tensegrity	A structural design principle where a core of compressive elements are surrounded by tensile elements, eliminating bending moments throughout the structure. Characterized by very high strength to weight ratios.
Performance Ratio	The ratio of the actual power collected divided by the nameplate power, normalized to available solar resource.
STC	Standard Test Conditions
Nameplate Power	Model power production for a design when operated at STC
Altazimuth	A design for tracking there the mechanism for elevation rides atop the mechanism for azimuth.
Azimuth	Angular measure of direction (i.e. analogous to compass heading)
Elevation	Angular height above the horizon
Smart Building	A building with sensors and actuators to enable integrated, automated control of building functions, e.g. heating & air conditioning
NREL	National Renewable Energy Laboratory
LVOC	Livermore Valley Open Campus
Compound Eye	An approach to solar resource forecasting that makes use of distributed solar collectors as "pixels" in a synthetic aperture spanning large areas.
Ommatidium	A single element or "pixel" of a biological compound eye (*pl.* ommatidia)
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
CPV	Concentrated Photovoltaic

APPENDICES

A CPR Presentation

B CPV-10 Presentation

C PV-10 Poster

These appendices are available as a single, separate volume, publication number CEC-500-2016-052-AP.