



Energy Research and Development Division

FINAL PROJECT REPORT

Commercializing a Disruptively Low-Cost Solar Collector

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Commercializing a Disruptively Low-cost Solar Collector is the final report for project (Contract Number EPC 16-016) conducted by Southern California Gas Company. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the <u>CEC's research website</u> (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Hyperlight Energy is developing a novel concentrated solar power reflector and receiver system called Hylux[™]. The reflector system consists of a water-borne, extruded plastic tube structure upon which flat glass mirror slats are mounted. Arrays of these tubes are connected using simple four bar linkages, which control the alignment of the mirrors and track the sun through the day. Using low-cost, long-life plastic, and minimizing the use of steel and concrete, substantial cost savings are achieved. This project sought to move Hylux[™] through the final stages of development, in preparation for commercial operation.

Initial testing of a Hylux[™] pilot production line and a reflector array was conducted at Hyperlight's facility in Lakeside, California, followed by limited on-sun testing of an array at the company's Brawley, California test site. Subsequently, a half-acre array of reflectors was manufactured, installed and tested in Brawley, California. Thermal efficiency achieved in testing has so far been in the range of 60 percent to 85 percent of modeled efficiency. Important milestones achieved in this project include the mass manufacture and installation of the tube structural components required to achieve the full cost-savings possible with the Hylux[™] design. Issues in manufacturing and installation with unskilled labor were identified. Design improvements to make the manufacturing and installation processes simpler and more robust are identified and planned for the future. Importantly, the level of performance thus far achieved supports economical installation at customer sites under existing commercial grant programs.

Keywords: solar power, Hylux[™],

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EXECUTIVE SUMMARY

Introduction

The power sector in California is faced with an unprecedented challenge: transition to 100 percent clean energy by 2045 (Senate Bill 100 [DeLeon, Chapter 312, Statues 2018]). This ambitious goal will boost the state's energy self-reliance, benefit the environment, and generate jobs. Achieving these benefits with the highest benefit to ratepayers requires pursuit of emerging technologies that can not only cost-effectively capture, but more importantly cost-effectively store, renewable energy.

Hyperlight Energy is pursuing a technology to help meet this challenge with its novel, low-cost concentrated solar power technology called Hylux[™]. This innovative technology replaces the expensive concrete and steel typically used to mount and aim glass mirrors in other concentrated solar technologies with low-cost materials and production techniques. Concentrated solar technology converts sunlight into heat, which can be stored in low-cost materials or used to drive other industrial processes that can convert waste products into chemicals, which can also store energy. By contrast, solar photovoltaic technology, converts sunlight directly into electricity that must then be used immediately or stored, for example, in batteries.

Despite the high cost, steel and concrete construction are the dominant materials in concentrated solar power because of accuracy and long life. The challenge in using alternative construction materials to mount and aim glass mirrors is achieving accuracy and durability. For example, it is not possible to simply swap metal components with plastic to be cost effective because the plastic would not be strong enough for long enough. Hyperlight Energy has reinvented concentrated solar power from the ground up by replacing the typical concentrated solar power support structures with extruded tube components that are well suited for plastics. Importantly, Hyperlight Energy has proven the optical accuracy of its extruded plastic components, and their durability in past work. Nevertheless, two large gaps remain that this project, and a closely associated parallel project, address.

The first gap exists because previous work on this technology focused on optical accuracy of the reflector system with less effort dedicated to the receiver. However, because thermal efficiency in concentrated solar power depends in large measure on the receiver system; it was essential to develop an optimized receiver for the Hylux[™] platform.

The second gap is component manufacturing and installation cost for the plastic tubes themselves. This gap is perhaps the most important because it relates directly to Hyperlight's core claim of developing a low-cost reflector system. Before this project, small plastic contract manufacturers who service the order size possible for a small emerging technology company like Hyperlight typically serve markets like medical devices where margins are very high on plastic parts. Plastic extruders that charge lower margins require enormous order sizes, far beyond what is possible for an early stage technology provider. This dilemma has proven to be a formidable challenge for developing this technology. Despite the fact that the cost of the material is very low, it has been impossible to prove out the fundamental cost model of the technology because of the structure of the plastics extrusion supply chain. This project focused on the second gap: solving the manufacturing and installation cost question. The project relates closely to work under a previous agreement that focused more on optimization of the receiver. Having said that, the two projects are necessarily interrelated because a concentrated solar power receiver cannot function without a reflector and vice versa.

Furthermore, in prior prototype installations, the personnel trusted to install the hardware were a combination of engineers who designed the technology and technicians who had worked with the technology for months, or longer. Another key part of the Hyperlight claim is the ease of installation by unskilled labor, without having to use an onsite fabrication shop for metal components, which is generally required for conventional concentrated solar power.

To address these gaps, the California Energy Commission (CEC) plays a critical role. Concentrated solar power as a category is not well-suited to small scale developments. High capital costs are required to test and install new technologies in this category. When investing large amounts of capital in energy projects, market players prefer the lowest technology risk possible, and so new technologies are difficult to fund, and established concentrated solar power technologies based on steel and concrete are preferred. CEC support has thus been vital in advancing this technology through the stages of development necessary for widespread commercial operation.

Project Purpose

Before this project, Hyperlight Energy had used only expensive third-party contract manufacturing to make the system and relatively highly skilled technicians to install it. Hyperlight had not installed a system with commercially relevant thermal efficiency. This project intended to bridge both of these gaps. The project team hoped to manufacture its system on a dedicated production line, with low cost materials and labor, install it using unskilled labor, and to dramatically improve thermal efficiency.

This project intends to help pave the way to adoption of this technology throughout California, improving the prospects for development of low-cost concentrated solar power and unlocking the potential of low-cost thermal energy storage.

This research can be used by policy makers, utilities, market players, and the public.

The goals and objectives of this project were to:

- Scale up production capability of Hyperlight.
- Design, build, and install, a Hyperlight system at 750-kilowatt (kW) scale.
- Operate the system and report on performance.
- Meet thermal performance requirements to achieve:
 - Total system annual solar-to-thermal efficiency of greater than 50 percent, for a half-acre-module plant.
 - Total system cost (as-built system cost including equipment, logistics, and installation/commissioning) less than \$99 per square meter of reflector area.

The last two goals and objectives for this project (EPC-16-016) are synergistic with the EPC-14-047 project.

Project Approach

The team is composed of Hyperlight Energy, an emerging technology company, developing its novel concentrated solar power technology, Hylux[™] and subcontractor, National Renewable Energy Laboratory, a globally recognized leader in renewable energy research and development, which supported design and analysis.

The project team performed design and fabrication of a 20-foot by 50-foot concentrated solar power reflector testbed and a half-acre reflector array in Brawley, California. Testing of the single testbed system and subsystems was conducted in a laboratory, with full scale testing at San Diego State University's satellite campus in Brawley, California.

One of the main challenges in this project was the design, procurement, and construction of the heat transfer fluid handling subsystem. While not an area of technical innovation, it is nevertheless a required element to test the other aspects of the system. To address the challenges around the heat transfer fluid system, modifications to the schedule and scope of the project were necessary.

The manufacturing and installation cost issues were addressed in this project.

Project Results

Hyperlight Energy's core claim of low cost manufacturing and installation of a reflector field was proven. The team was able to produce tubes to the required specification without substantial additional expense over and above the raw material cost and low-cost labor, plus supervision. The project also identified specific training needed for unskilled labor to enable smooth and effective installation of Hylux[™].

For system operation, issues that affected the schedule meant that only a limited set of operating conditions was tested, but the experience gained and knowledge developed is valuable for further development.

The system will be operated in the future in more configurations; however, current operational data are promising. In particular, the results of this project were sufficient for a commercial customer to choose Hylux[™] as the concentrated solar power technology for installation at one of its facilities under the CEC's Food Processing Investment Program.

While Hyperlight Energy plans to fully address those technical fixes identified during this project on limited configurations of the Brawley system, and continue data collection at the site, there is no additional research required prior to commercial adoption of Hylux[™].

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Hyperlight Energy has been developing multiple customer leads throughout this project, including food processors in the San Joaquin Valley. One processor has submitted a grant application to install Hylux[™] at one of its facilities. The initial target market for Hylux[™] is the food processing industry through the CEC Food Processing Investment Program. Midterm targets include enhanced oil refining operations, and long-term targets include hybridization with geothermal power plants and stand-alone power plants.

Using concentrated solar power for food processing is a small- to medium-sized market in California. Use for enhanced oil recovery and power production are large potential markets. Hyperlight Energy has several customer prospects, mostly in the San Joaquin Valley. The project team is actively pursuing these opportunities through direct outreach. Hyperlight hopes to establish its first customer installation in this market effort, then follow a path of increasing scale and decreasing cost as commercialization continues.

By advancing low-cost concentrated solar power, this project should lead to greater awareness of energy storage options outside of electric batteries. Development of this technology should help in the policy discussion of how to get to 100 percent clean energy in California.

Benefits to California

Lowering the cost of concentrated solar power and increasing the options for storing renewable energy in something other than batteries will support the successful implementation of Senate Bill 100 and the goal of 100 percent renewable and zero-carbon electricity by 2045.

Hyperlight Energy is currently observing performance at its Brawley site in the range of 60 percent to 85 percent of the thermal model. The thermal model is for an ideal system that is perfectly aimed, clean, and tracking. The project team's goal was to eventually achieve consistent results at about 90 percent of the model. However, even if results do not exceed 60 percent, the Hylux[™] technology is still expected to achieve a cost of \$4.50 per million British thermal units (MMBTU) once 3,000 acres (approximately 4.7 square miles) of the system are installed. If 85 percent efficiency is achieved, the Hylux[™] technology is expected to deliver heat energy at \$3.50 per MMBTU.

Figure ES-1 shows the decrease in implied levelized cost of heat of Hylux[™] with increasing scale, which lowers cost in multiple ways. First, by increasing the project number and size, the nonrecurring overhead costs can be amortized to lower values. Second, increasing order volumes leads to greater economies of scale and cost reductions per-unit. Third, product improvements will increase performance and lower base cost, which are planned on the development roadmap. This assumes large commercial, industrial, and utility-scale projects, not residential.

The next step for this technology is commercialization in its target market.



Figure ES-1: Cost Projection of Hylux[™] Systems

Projection assumes 85 percent and 60 percent of modeled efficiency. MMBTU = one million British thermal units.

Source: Hyperlight Energy

CHAPTER 1: Introduction

Background

Hyperlight Energy is funded under the California Energy Commission's (CEC) auspices to develop a disruptively low-cost, concentrated solar power solution. To achieve this objective, Hyperlight Energy has been developing an advanced linear Fresnel reflector design based on repurposing very low cost, agribusiness materials (such as water and plastic) that have demonstrated longer than 25-year product lifetimes. More importantly, these materials have demonstrated life in environments that are comparable, if not identical to, the environments (such as intense solar, intense heat, low humidity, blowing abrasive dust, rodent and insect infestation) in which Hyperlight products will ultimately be used. A previous project, EPC 500-10-063 (the "10-063 project") was performed to show that the basic optical accuracy necessary to achieve cost targets is possible with this approach. Optical accuracy of the system was measured at the beginning and end of the three years of system operation. A representative graph of the results is presented in Figure 1. The graph shows the intensity of light hitting the receiver target, represented by the black lines in the graph. Importantly, the system achieved and maintained less than five percent spillage (light missing the target) at beginning and end of the three-year operation; proving that the plastic/water structural approach was viable for concentrated solar power applications.

To capitalize on the strengths of recent low cost photovoltaic installations, Hyperlight is focusing its plant design on a scale that can readily be packaged for rapid, and cost-effective installation, with minimal required resources. This philosophy also emulates what has already been done in agribusiness operations for large surface area installations.

This project was executed in close parallel to EPC-14-047 (the 14-047 project), which focused on improving the Hylux[™] receiver subsystem.

Hyperlight Energy previously demonstrated the concept of a low-cost, plastic linear Fresnel reflector technology (Figure 2). The prototype system was built as the 10-063 project. As shown in Figure 3, Hylux[™] replaces the steel and concrete used to mount mirrors in traditional concentrated solar power applications with plastic and water structural components. While this leads to a substantial cost reduction, it was necessary in the 10-603 system to show optical accuracy and durability of materials. The 10-603 project operated for three years (2014 to 2016) to prove this approach.



Figure 1: Optical Accuracy Results

Source: Hyperlight Energy

Figure 2: Hyperlight Prototype, Brawley, California 2014 to 2016

Source: Hyperlight Energy



Figure 3: Diagram of HyluxTM System

Source: Hyperlight Energy

Gaps in the State-of-the-Art

CEC agreement 500-10-063 was critical - demonstrating that extruded plastic pipe could achieve and maintain the optical accuracy required for concentrated solar power. As shown in the stylized diagram of linear Fresnel geometry (Figure 4), the majority of a linear Fresnel reflector solar field is its ability to aim the sun on a solar receiver. Consequently, this is the largest area of potential cost reduction, and where Hyperlight's team focused its effort. Although this focus was necessary, successfully showing the technical capability of an extruded plastic structural approach is far from establishing a commercially viable offering. Two critical issues remained: (1) thermal performance gap and (2) manufacturing and installation cost gap.



Figure 4: Line Drawing of Linear Fresnel Optics

Source: National Renewable Energy Laboratory

Thermal Performance Gap

The first gap exists because previous work on this technology focused on the ability of the reflector system to hit a receiver. Almost no budget or schedule was previously available for development of the receiver. Consequently, almost no effort was spent on the effectiveness of the receiver in absorbing and converting heat from sunlight into usable energy. However, as shown in Figure 4, all the rays from the sun end up on the receiver, so performance improvements on this component could have a big impact.

To illustrate the complexity in designing to minimize optical loss in the receiver system, the pie chart (Figure 5) shows all sources of optical loss. It should be appreciated that a substantial design effort was necessary to optimize the receiver subsystem of Hylux[™].

Furthermore, when considering a receiver design, the primary way to increase temperature is to reduce thermal loss. This strategy also improves energy capture, which improves economics. For this reason alone, it makes sense for Hyperlight Energy to upgrade its receiver. A parallel project, the 14-047 project, was executed to achieve this objective.

Manufacturing and Installation Cost Gap

In addition to receiver optimization, another gap remained for Hylux[™] – the component manufacturing and installation cost for the plastic reflector tubes themselves. This is perhaps the most important gap to address, because it relates directly to Hyperlight's core claim of a low-cost reflector system. The types of contract manufacturers that generally service small orders (required for an emerging technology company like Hyperlight), typically serve markets such as the medical device market, where margins are very high on plastic parts. Plastic extruders that have lower margins require enormous order sizes, far beyond what is possible for an early stage technology provider. Inherent in the price/volume discussion is an implication of quality vs. quantity. For the medical device and similar markets, the volumes are lower but tolerances will typically be tighter and parts more complicated than what is required for high volume extrusion, such as simple round plastic pipe. For this reason, it was very important to validate Hyperlight's cost assumptions with real-world production experience. The critical question was, "What if the high mark-ups were required to be able to meet Hyperlight's tolerance specifications?" If this was the case, then perhaps the entire thesis Hylux[™] was predicated on was unfounded.



Source: Hyperlight Energy

Despite the centrality of this question, this issue had remained a dilemma of sorts and had proven to be a formidable challenge for development of this technology. Despite the fact that the material cost was known to be very low, it had been impossible to prove out the fundamental cost model of the technology because of the structure of the plastics extrusion supply chain. This example illustrates how difficult it was even to talk to the larger, low-profit margin, extruders. During the early stages of the 10-063 project, the team was able to acquire a first prototype extrusion from a small, high-margin extruder, before the team was able to just obtain a nondisclosure agreement with a large volume, low-margin extruder. This project had to address this dilemma.

The other core part of the Hylux[™] low-cost thesis is that the technology can be installed by unskilled labor, without the requirement for an onsite fabrication shop (an onsite factory, really), typically required for other concentrated solar power technologies. As far as the team

was aware, this core assertion had never been tested before this project. Generally, the labor used to install previous prototypes and systems had been composed of design engineers and skilled technicians who were already expert in the technology after months or longer of working with it. This project had to test this part of the Hyperlight low-cost thesis as well.

CHAPTER 2: Project Approach

Building on the successful demonstration of the optical accuracy and robustness of HyLux[™] in the 10-063 project, this project (EPC-16-016) intended to advance Hylux[™] to the point of readiness for commercial adoption. A key consideration, as noted previously, was that there remained a manufacturing and installation cost gap for the reflector tube system. That issue was the primary focus of this project, while a parallel project (the 14-047 project) was executed in conjunction and is referenced in this report. To clarify, it would have made no sense to build two separate prototypes for the two separate projects: one with the optimized receiver but with contract manufactured tubes; and a different one with the old receiver, but with Hyperlight manufactured tubes. This approach would have simultaneously doubled the cost to develop the system, while virtually guaranteeing useless results because the two systems developed would bear little resemblance to the eventual market-entry product.

For this reason, it was decided to integrate execution of this project (EPC-16-016) on a parallel path with the 14-047 project. This project was a contract for match funding for a United States Department of Energy (U.S. DOE) project, which was intended to advance Hylux[™] to the point of readiness for commercial adoption.

In addition to upgrading the Hylux[™] receiver subsystem through the 14-047 project, this project included increasing reflector surface area to maximize solar energy capture, designing a robust heat transfer fluid handling subsystem, validating production cost assumptions, and finally building and testing a demonstration system of suitable size to convince commercial customers to install it.

The Hylux[™] concentrated solar thermal project goals and objectives are summarized, as follows.

Project Goal

The goal of the project was to:

• Make a disruptively low-cost concentrated solar power collector ready for commercial adoption.

Project Objectives

The objectives of the project were to:

- Scale up production capability of Hyperlight.
- Design, build, and install a Hyperlight system at 750-kW scale.
- Operate the system and report on performance.
- Meet thermal performance to achieve:
 - Total system annual solar-to-thermal efficiency of a half-acre module plant greater than 50 percent.

• Total system cost (as-built system cost including equipment, logistics, and installation/commissioning) less than \$99 per square meter.

Project Approach

To achieve this goal and these objectives, the project approach addresses:

- Reflector design focused on design of the upgraded reflector subsystem
- Balance-of-plant design focused on design of the heat transfer fluid subsystem
- Third-party procurement procurement of equipment and supplies from equipment manufacturers necessary to construct a half-acre system
- Production run in-house production of the reflector subsystem
- Installation transport to the site of all components, and on-site construction of the finished system
- Commissioning testing, fine tuning, and operation of the system

Reflector Array Design and Test

As previously discussed, it was decided to conduct the receiver upgrade project (the 14-047 project), in parallel with the reflector work from this (16-016) project. For this reason, the reflector-related work is mentioned here, because it was part of the overall workflow.

The prior 10-063 project had a one-part endcap component that attached each reflector tube to the bulkhead as shown in Figure 7.

Figure 6: Actuation Mechanism for Hyperlight Energy First-Generation Installation



Photo shows several primary reflector tubes connected to a single linear actuator through a large fourbar mechanism (the "bulkhead").

Source: Hyperlight Energy

To facilitate unskilled labor installation, a two-part design was adopted to allow factory calibration and easy "click-in" assembly in the field.



Figure 7: Second-Generation Bulkhead Design

The calibration tool (left) used to accurately orient all 50 end caps (right) in the factory to enable reflector tubes to be quickly snapped into place in the field.

Source: Hyperlight Energy

The intent here was to minimize in-field calibration labor and effort, which is substantially more expensive than labor required for simple click-together assembly.

In addition to installation cost, the other element of reflector array cost is the tube manufacturing step. The challenge of the manufacturing step was that in purchasing materials in small batches, the large plastic extruders would not even talk to a small company, so small shops that are used to manufacture custom parts were left. For example, the team worked with an extruder that focused on the medical device market, where the margins charged for plastic tubing are high, but remain a small percentage of the overall value of the product sold. Because the plastic tubing is the main ingredient, and energy is a commodity market, high margins for this component made it difficult. The team assumed that based on plastic pricing they had seen, it was possible to produce the parts with a reasonable markup and still meet quality specifications for the application. However, there was no proof that this was possible. If it truly was very difficult to produce the parts, and the small shops really were spending a sizable fraction of the price they charged for labor and equipment to accurately and consistently produce the parts, then the entire assumption about price would have been false. This was a dilemma: the only shops the team could get parts from seemed to overcharge and eliminate any cost-saving advantage, and the shops where the team would be able to get good pricing wouldn't discuss business because the initial orders were too small. To solve this dilemma, it was decided to buy used plastic extrusion machinery, hire plastic extrusion expert consultants to train the staff, procure low-cost plastic pellets directly, and extrude the tubes in-house.

The pilot extrusion line the team established and used is shown in Figure 8.



Figure 8: Hyperlight Energy Extrusion Line

Extrusion line comprised (from right to left) of an extruder, vacuum chamber, and puller.

Source: Hyperlight Energy

The project team used the pilot line to extrude a single bed worth of tubes (50 tubes). These tubes were installed on a test bed in the Hyperlight facility in Lakeside and bulkheads were calibrated and installed. The completed test bed is shown in Figure 9.



Figure 9: Test Basin

Test basin comprised of 50 reflector tubes installed onto two second-generation bulkheads with clip-in end caps. The reflectors were extruded using Hyperlight Energy's extrusion line.

Source: Hyperlight Energy

This test bed was cycled 10,000 times to simulate 25 years' worth of life. Angular accuracy was measured at the start of life, at multiple steps along the way, and at end of life.

Results of this testing of in-house extruded tubing are presented in Chapter 3, Project Results.

Balance-of-Plant Design

This part of the project was focused on designing the heat transfer fluid handling subsystem, including pumps, heat exchangers, valves, and controls. While no fundamental innovation was involved here, it is still necessary to customize the various components and their configuration to match the thermal and other performance characteristics of the solar array. Further, it was necessary to plan for relevant market sectors in terms of temperatures, fluids, controls, and other considerations.

While not basic research, the design of a heat transfer fluid system is difficult and complex. The original intent of the project was to design a system capable of 752°F (400°C). This is the highest temperature that thermal oil can be used. The higher the temperature, the more commercial applications open up, and the more efficiently a power generation plant can be operated. A key issue is that the project team's core competence is reflector design, not heat transfer fluid system design. Although the team engaged relevant consulting help, no consultant could be familiar with the performance characteristics of a brand new linear Fresnel reflector system. Not exactly a dilemma as with the plastic extrusion manufacturing issue, but rather more like a chicken-and-egg problem. The team required a heat transfer fluid subsystem to be able to build a complete concentrated solar power system, but the precise characteristics of the new concentrated solar power technology was not known to be able to move through the design process of the heat transfer fluid system.

For this reason, it took longer to establish a baseline design suitable to obtain quotes. Up until that point, from proposal development up through final contract signature for the project, the team had estimated the cost of the heat transfer fluid system based on percentages of cost associated with other concentrated solar power plants built and documented in the literature. The team knew that these other plants were much larger than the one that was proposed for this project, so the percentages that should be used, should also be much larger. The percentages were increased, but there was no way to know how much of an increase would be enough. When the quote for the heat transfer fluid system eventually came in, it was more than twice as expensive as the highest original estimate.

This issue presented the project team with its first large problem. The project did not have sufficient budget to accommodate the quoted heat transfer fluid system. The solution was to switch to a less expensive design that would use a different heat transfer fluid limited to 572°F (300°C). This reduced the cost of the heat transfer fluid system such that it would be feasible to build, if other changes were also made. The key other change that was necessary was to reduce the demonstration site size from the originally planned one acre, down to a half acre. This change, along with every other cost saving strategy imagined, brought the budget back to a manageable level. The resulting heat transfer fluid system design is shown in Figure 10. This 572°F (300°C) design was much simpler than the original 752°F (400°C) design.

This process generated one of the key take-aways of this entire project. It is the project team's opinion that it is likely not feasible to go higher than 572°F (300°C) for projects on the

scale of one acre or less, for any concentrated solar power technology that uses thermal oil as a heat transfer fluid.



Figure 10: Heat Transfer Fluid Processing Skid

Engineering drawings show the general layout of the oil-processing skid, containing a pump, two control valves, two safety relief valves, inlet and outlet sensor arrays, and a large oil-air heat exchanger to vent heat when no other heat load is in operation.

Source: Hyperlight Energy

Third-Party Procurement

Although it may seem mundane, simply procuring parts from the global concentrated solar power supply chain and other industrial sectors is difficult for an emerging technology because the largest possible order size for a small-scale technology developer such as Hyperlight Energy is still a small fraction of the smallest order size vendors typically consider and are set up to service. Again, while not part of the fundamental technology development process, this step is still necessary to prove out the technology and so, it must be taken. Although this step is conceptually simple, the challenges are so daunting that they must be considered here, if even only briefly. Importantly, these challenges were identified and surmounted by the project team, though sometimes under very extreme difficulty and duress, but always with ingenuity.

Among the challenges faced by the project team were: a greater than 10 percent breakage rate of heat collection elements received from the supplier; a plastic pellet shipment of 26,000 pounds that was the wrong polymer; and a curved mirror supplier – that the team had been

working with for a year – deciding to leave the curved mirror business. It is difficult to quantitatively characterize the frustration these events caused. However, schedule slip is one result, and this project was no exception. Critically, these supply chain issues could not have been discovered, fleshed out, and addressed any other way than by actually trying to build a half-acre concentrating solar power system.

Production Run

The initial small production run project staff performed to produce the 50 reflector tubes for the test bed validation of optical accuracy, was a success. It took about two days to produce the tubes. As each tube came off the line, it was immediately placed in the test bed adjacent to the tube that preceded it off the line. The production run for 16 basins (used in Brawley) was conducted in two shifts per day (16 hours at a time) for approximately one month. As each tube came off the line, end caps were placed on it, and it was carried out to a 53-foot trailer and stored until the trailer was full. Each tube was put in the trailer adjacent to the tube that preceded it off the production line.

There were two production problems embedded in this process that were not identified until installation – and would have been difficult, if not impossible, to predict prior to installation. The first production problem was that the importance of having a good seal for the endcaps on the tubes was not stressed to production laborers. Hence, the PVC pipe cement used to seal the ends was not adequately applied and many of the tubes did not have water-tight seals. The solution is simple: better training of the laborers hired to do production and better quality control for the process. However, the lack of a seal led to a follow-on problem during installation that impacted the project and is discussed in the Installation section.

The second production challenge was temperature variation. The production plant is not, and cannot be, climate controlled. Operating during day and night hours, and over the course of a month means that temperatures varied substantially during a single production run. Although the tubes did not vary in length by much, relative to tubes produced immediately before or after them, they did vary substantially – by up to 2 inches in length – across an entire production run. The impact of this challenge and its solution is discussed in the Installation section of this report.

Installation

During the installation phase, three critical issues were discovered that the team could not have learned other than through experience.

- 1. Tube length
- 2. Rough handling of tubes while they are put on beds.
- 3. End cap seal.

The tube length issue mentioned previously in the production section was discovered because the truck was unloaded somewhat randomly by the unskilled labor hired to do the installation work. There was no unloading order, so the tubes were chosen based on what was closest at hand, which did not correspond to unloading in neat orderly rows. The result was that tubes ended up being placed on basins adjacent to other tubes that may have been produced days, or even weeks, earlier or later. This led to length differences of up to two inches between adjacent tubes. The two-part click-together design of the end caps had a tolerance of only 1/8 inch length difference. It is not clear that the project team could have realized this issue any other way. To correct for these length differences, it was necessary to measure each of the 800 tubes individually, then perform a sorting operation. Unfortunately, this caused weeks of delay. In the future, it will be a simple matter of unloading the truck row-by-row.

A more substantial issue was rough handling of tubes during placement on beds. The laborers hired did not have an intuitive understanding of the system they were helping install because they had no prior experience with it. Consequently, tubes were handled much too roughly, and the top sheets of several of the beds were punctured by tube end-caps. While an end-cap redesign to eliminate sharp edges will be done, another key part of the installation procedure will be training in proper tube handling for new laborers.

This rough-handling issue, combined with the tube end-cap seal issue already mentioned, created the most difficult problem for the project. The top sheet punctures caused very slow leakage into the top sections of the beds, which are supposed to be dry (except for rain events). During rain events, some water is expected, but is not a problem, because end cap seals are supposed to be water-tight and prevent water from getting into tubes until it evaporates away. Unfortunately, it rained the same week as the tube installation, so the slow leaks were not immediately identified. Additionally, because of the end cap seal issue, many of the tubes took on large amounts of water – to the point of total submersion. It took some time to diagnose the problem as something other than simply left over rainwater. It also took substantial time to locate and patch holes in top sheets. Ultimately, between a third to a half of all of the reflector tubes spent anywhere from a few days to multiple weeks submerged. During this time, substantial dust loads from surrounding farming activity were deposited on the beds. This led to a difficult form of soiling in which dust deposited on the submerged tubes formed very tight adhesions to the mirror surface. The soil ended up being nearly impossible to remove, even with aggressive cleaning.

There are multiple reasons for discussing this last issue in such depth. First, in scale up of any emerging technology, there are always unknowns that cannot be discovered through any means other than installation in the field. The discussion above is a discussion of knowledge gained through this work, that could not have been gained any other way – specifically, training the laborers not to puncture the top sheets. However, there is a second reason for the discussion. The punctured top sheets had an impact on mirror cleanliness. It is outside the design basis for the mirrors to be submerged and soiled for any length of time. Although there is no reason for future installations to have this same problem, the effects of the submersion are nevertheless real and must be understood. Two cleaning levels were established: "aggressive," involving use of a squeegee on each tube; and "thorough," involving a high pressure jet of distilled water. Each cleaning level was applied each in various measure. However, because of the nature of the soiling, it is unlikely the tubes will ever be as clean as they were at production. While unintentional, the submersion event actually did one positive thing, it established a worst-case scenario for cleanliness and, therefore, for thermal performance.

Results of the cleaning campaign are discussed at more length in Chapter 3, Project Results.

Figure 11: Tube Installation



Source: Hyperlight Energy

Commissioning

During commissioning of the system, sensors selected for closed-loop control of the solar tracking system were found to have a high incidence of poor signal to noise ratio. While this may be a sensor selection issue that is easily solvable going forward, the project team was faced with the challenge of how to collect data before the end of the project schedule, with the system as built. Project staff elected to use a one-minute smoothing algorithm to eliminate noise. Although this did work to generate a usable signal, the signal lagged behind the sun's position, so the tracking algorithm worked very poorly.

Sensor improvements are planned for future installations. However, these improvements were not feasible within the remaining schedule and budget. Instead, an alternative tracking approach was used. The team used a form of open loop control with closed loop correction on a limited number of beds. Data from this configuration are presented in Chapter 3, Project Results.

Figure 12: Commissioned 1/2-Acre System During Operation



Source: Hyperlight Energy

Test Bed Histograms

The data collected on the Lakeside test bed, to validate the tubes produced in-house, is substantial. The results have been summarized and are presented graphically to allow the data to be more easily understood. Each tube has a defined ideal angular position. Every mirror on that tube would be tilted in that position if the system had zero error. Ultimately, the goal of this part of the project approach was to prove that tubes produced in-house met the same accuracy achieved in the 10-063 project, summarized in Figure 13.



Figure 13: Sample Accuracy Results from CEC-10-063

Source: Hyperlight Energy



Figure 14: Light Flux on Receiver from Project CEC-10-063

Source: Hyperlight Energy

At this stage of the project, it was not possible to use the tubes "on-sun" and measure light flux distribution (as in Figure 14), so an alternative approach was used. The goal was to achieve the same distribution shape as in Figure 13. To calculate the actual system error an angle measurement was taken on each mirror segment and compared to the ideal position to create an angular delta in milliradians.

The team computed the maximum error that the collector assembly could tolerate and still achieve an acceptable overall pointing location. Because the lifecycle data were not normally distributed, a sample standard deviation could not be easily generated and compared. Instead, this allowance was used to define the acceptable bounds. In a normal distribution, 99.7 percent of the data points will fall within three standard deviations of the sample mean, so a passing rate of three standard deviations of the allowable error was used. Since the measurements are deviations from ideal (and therefore the mean is zero), this means that the allowable range was approximately 6.0 milliradians. Measurements with that tolerance would pass, while those outside of the three standard deviation failed. Figure 15 shows pass/fail (green/red) measurements at beginning (left) and end (right) of life for the reflector array. The shape of these graphs should be compared to the shape of the graphs in Figure 14. Importantly, in-house produced tubes proved to be as accurate as the 10-063 tubes, which were produced by a contract manufacturer, at much greater cost.

Figure 15: Plots Showing Distribution of Optical Errors on Hyperlight Energy Test Basin



The green boxes represent passing reflectors according to the U.S. DOE's three milliradians standard deviation requirement, while the red represent failures. The two vertical lines represent the allowable optical error according to Hyperlight's models that will still allow for near-peak performance.

Source: Hyperlight Energy

The results of this work established confidence in the project team's ability to extrude plastic tubing that met the required specifications for concentrated solar power application. This result establishes one of the most important parts of Hyperlight's low-cost thesis. It was possible to produce the tubes to the required specification without substantial additional expense beyond the raw material cost and low cost labor, plus supervision.

Thermal Performance

The second part of the Hyperlight low-cost thesis is low-cost installation. As discussed in previous sections, the project team learned important lessons that will be applied going forward. Also, sensor issues in the as-built system prevented correct functioning of the software algorithm throughout the entire solar field. To be able to collect data before the end of the project (due to schedule and budget constraints), it was decided to use a hardware/software fix on a limited subset of the solar field. It was possible to fix four of the 16 beds. One of these beds was cleaned aggressively, while the other three were cleaned thoroughly.

Figure 16: Layout and Flow Direction of Hyperlight Demonstration Facility in Brawley, California



Source: Hyperlight Energy

The bed that was cleaned aggressively (each tube of B13 was scrubbed with a squeegee) achieved 85 percent of modeled thermal performance. Next, the system was run with beds B9, B11, B13 and B15 on-sun. Beds B9, B11, and B15 were cleaned with a distilled water jet only. This configuration achieved 62 percent of modeled thermal performance. There are two key issues that led to the results coming in at these levels. First, the soiling issue described at length in the Installation section; and second, the sensor malfunction issue leading to sub-optimal tracking. The solution to the soiling issue is described in the Installation section, but can be summarized as: (1) better training of installation laborers, and (2) a small end-cap redesign to maintain water tightness. The solution to the sensor issue is simple, different sensor selection.

Importantly, the project team feels that this work establishes a worst-case scenario for future installations. Even if these issues are not resolved, then an operational approach can be used that at least achieves 60 percent or better of the modeled thermal performance, perhaps reaching up to 85 percent. This worst-case scenario forms a band that was used to project performance relative to the annual efficiency model for the system. This key graph is shown in Figure 17.





Assuming 100 percent, 85 percent, and 60 percent of modeled efficiencies, compared to 100 percent modeled efficiency of a traditional linear Fresnel reflector system.

Source: Hyperlight Energy

Results: Goals and Objectives

All of the project goals and objectives were achieved.

Project Goals

The goal of the project is to:

• Make a disruptively low-cost concentrated solar power collector ready for commercial adoption. Status: achieved.

Project Objectives

The objectives of the project are to:

- Scale-up production capability of Hyperlight. Status: achieved
- Design, build, and install a Hyperlight system at 750-kW scale; 60 percent to 85 percent of modelled efficiency. Status: partially achieved.
- Operate the system and report on performance. Status: achieved.
- Meet thermal performance to achieve:

- Total system annual solar-to-thermal efficiency of a half-acre module plant, greater than 50 percent. Efficiency of 60 percent to 85 percent. Status: partially achieved
- Total system cost (as-built system cost including equipment, logistics, and installation/commissioning) less than \$99 per square meter. Status: achieved.

Two important changes happened during the execution of this project relative to performance targets. First, as previously described, installation and sensor issues degraded the performance below modelled levels. This is the reason that the two objectives above relative to thermal performance and annual efficiency were only partially achieved. The second thing that happened is that a market opportunity for process heat materialized. For this reason, it is important to report on projections of delivered heat, in view of thermal performance achieved to date.

Results: Cost Projections

Cost projections for energy in the 60 percent and 85 percent performance cases are presented in Figure 18. The effects of scale are clearly seen, at increasing scale, the company can accept lower gross profit margins, which yields improvements in production cost. This, plus planned engineering design changes, yields competitive energy production costs, even in the 60 percent of modeled performance case.



Figure 18: Cost Projection of Hylux[™] Systems

Assuming 85 percent and 60 percent of modeled efficiency.

Source: Hyperlight Energy

Importantly, Hylux[™] is on track to reach cost parity with natural gas as shown in Figure 18, which is a projection of the cost of delivered heat from Hyperlight based primarily on increasing scale. Increasing scale lowers cost in multiple ways. First, with increased scale, the

gross profit margin that a company must charge is lower because the overhead and variable costs to operate a business do not increase proportionately with units sold. As units sold increases, less profit margin is necessary to support the business (that is, pay for fixed overhead and variable costs), and unit prices drop. Second, with increasing scale, the volumes of raw materials that are bought to produce a product increase, and because larger quantities are purchased their cost is less, lowering the base cost per unit sold. Figure 19 also includes product improvements that will increase performance and lower base cost, which are planned for future development. This cost reduction assumes large commercial, industrial, and utility-scale projects, not residential.

Figure 16 shows the levelized cost of heat of delivered heat for Hylux in two scenarios at various scales. The two scenarios represent the high and low end of the performance band for Hylux. The team is currently observing performance of the Brawley site in the range of 60 percent to 85 percent of the thermal model. The thermal model is for an idealized system that is perfectly aimed, perfectly clean, and tracking perfectly. The team eventually hope to achieve consistent results at about 90 percent of the model. However, results better than 60 percent are never realized, eventually the project will reach \$4.50 per MMBTU, once the system size reaches 3,000 acres. If 85 percent is achieved, then heat energy will be delivered at \$3.50 per MMBTU for a 3,000-acre project.

CHAPTER 4: Market Transfer Activities

Background

Commercializing an emerging technology is challenging. To date, business development efforts have been more successful in the food processing sector.

Concentrated Solar Power Commercialization Pathway

Commercializing a new concentrated solar power technology is uniquely challenging for multiple reasons. Chief among them is project size. Whereas, solar photovoltaic projects can be as small as a single one square meter panel, the absolute smallest commercial concentrated solar power projects are typically on the order of acres. For this reason, the first commercial project for a new concentrated solar power technology – even when heavily subsidized by grants and incentives – will always require substantial effort, land, and risk tolerance on the part of the first commercial customer. As an example of this, during the business development effort to find host sites for the Food Processing Investment Program, Hyperlight personnel were able to offer potential customers a no-cost system. The team learned in multiple cases that they were the second and sometimes third company to make such an offer based on this program. The obvious question of "why did you take a pass on the first offer[s]" was uniformly met with some version of the following: "we simply don't want to be first." This was irrespective of any cost, benefit, or feature discussion of any kind.

While grants or other incentives are necessary to commercialize emerging technologies, it is not sufficient by itself. Another necessary component to building a first commercial project, is finding a customer that is willing to be a first commercial customer. In the team's experience, those customer prospects that have shown the most willingness to consider such a prospect have typically been those businesses with the strongest commitment to sustainability. In addition to focusing on markets where grant and incentive support are applicable, Hyperlight Energy has further refined its focus to be direct outreach efforts to companies that have demonstrated a commitment to sustainability.

Beachhead Market

The food production and processing industry in California is a huge user of natural gas for process heat. Unlike many other industries, food processors are often located in or near agricultural areas where there is more access to land suitable for concentrated solar power facilities. Further, process heat is better served by solar thermal, as opposed to photovoltaic, because of the higher energy capture of solar thermal, and the conversion to heat vs. electricity. The CEC has recognized this, and released the Food Processing Investment Program.

Hyperlight Energy has secured a host customer site for a proposed first commercial customer through the Food Processing Investment Program. Crucial in the business development effort, was the demo site at Brawley, constructed through CEC agreements EPC-14-047, EPC-16-016 and with U.S. DOE and Southern California Gas Company (SoCalGas) support. Touring this site

gave the customer a solid sense of what they were committing to for their own site. Further, SoCalGas' continued staunch support in providing funding for a front end engineering and design study for the proposed site was also crucial. This funding allowed Hyperlight Energy to establish a preliminary project scope and budget, including the site layout and process and instrumentation diagram shown in **Error! Reference source not found.**.

Figure 19: Site Overview and Preliminary Process and Instrumentation Diagram for Proposed Installation at Saputo Cheese Plant in Tulare, California



Source: Hyperlight Energy

Lastly, and most importantly, the customer has expressed a willingness to engage with Hyperlight after a possible award to continue to improve the installation to maximize energy production, emissions reduction, and operational efficiency.

CHAPTER 5: Conclusions and Recommendations

Next Steps

The Hyperlight team plans to fix the sensor issue identified in the commissioning of the system and continue with data collection. Additionally, the team plans to continue to run the system to gather additional data. Having said this, there simply is not enough work still to be done on this technology to justify another research and development grant. Although improvements to the technology will always be advantageous, it is time to commercialize. It is instructive to note, that another concentrated solar power company, Solar Reserve, won a multi-million dollar research and development grant from the U.S. DOE to improve its tracking system. Solar Reserve has an enormous plant in Crescent Dunes, Nevada and is still doing research and development. Similarly, this may be a continuing activity for Hyperlight in the future, but with the Food Processing Investment Program, and a customer willing to be the first commercial customer, Hyperlight Energy is turning its focus to commercialization.

CHAPTER 6: Benefits to Ratepayers

This project had substantial benefits to California ratepayers by advancing the state-of-the-art of the concentrated solar power industry. In conjunction with project 16-016 the funding provided by this project allowed Hyperlight Energy to build a half-acre demonstration site in Brawley, California, to prove lower bounds on the performance and cost-effectiveness of Hyperlight's Hylux[™] solar technology. The data obtained as a result of this project demonstrate that Hylux[™], at scale, will be a cost-competitive alternative to natural gas for industrial process heat, enhanced oil recovery, and ultimately electricity generation. Future installations of the technology will be installed to replace current or planned fossil-fuel heat sources, reducing the state's greenhouse gas emissions and natural gas consumption.

Further, concentrated solar power in general, and as the cost leader Hyperlight Energy in particular, will be fundamental to reaching the state's goal of 100 percent clean energy generation by 2045. The largest impediment to reaching that goal is the unreliability or intermittency of most forms of renewable generation. A key solution is cost-effective energy storage. Currently, the only form of energy storage that is cheap enough to be practical is thermal energy storage: storing a hot fluid and converting it into electricity on demand. Concentrated solar power is the ideal partner for thermal storage, because it is an intermittent power source that can heat a storage medium to very high temperatures allowing for efficient storage. As the most cost-effective form of concentrated solar power, Hyperlight Energy can help achieve the renewable penetration deemed necessary by the state, while reducing energy costs to ratepayers.

In addition to the long-term environmental benefits to California, this project also generated short- and long-term economic benefits in the form of jobs. In conjunction with project EPC-16-016, Hyperlight Energy developed methods to produce many of the primary components of the concentrated solar power system locally, which will lead to local manufacturing jobs as project components are fabricated. Presently, all planned Hylux[™] installations are in California, leading to substantial additional employment for the installation of the various projects.

Quantitative Benefits

Jobs. The project generated nine jobs during execution, and has led to projects that will create 10 full-time jobs in California.

Energy Savings per Year. The project at Brawley is not a commercial project and will not lead to energy savings. However, it did lead directly to a commercial project win, which will lead to an estimated 18,000 MMBTU of thermal energy generated per year, offsetting approximately 1,800 tons of carbon dioxide emissions per year.

LIST OF ACRONYMS

Term	Definition
CEC	California Energy Commission
CSPConcentrated Solar PowerEPIC	Electric Program Investment Charge
kW	Kilowatts
LFR	Linear Fresnel Reflector
MMBTU	Million British Thermal Units
NREL	National Renewable Energy Laboratory
SoCalGas	Southern California Gas Company
U.S. DOE	(United States) Department of Energy