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Energy Research and Development Division

FINAL PROJECT REPORT

A Novel Low-Cost, High-Efficiency Solar Powered Micro-Combined Heat and Power System for Electricity, Hot Water, and Space Heating

Gavin Newsom, Governor

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PREFACE

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

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

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

A Novel Low-Cost, High-Efficiency Solar Powered Micro-CHP System for Electricity, Hot Water, and Space Heating is the final report for the A Novel Low-Cost, High-Efficiency Solar Powered Micro-CHP System for Electricity, Hot Water, and Space Heating project (Contract Number PIR-16-007) conducted by the University of California, Merced. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

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

ABSTRACT

The researchers developed and successfully demonstrated a proof of concept solar combined heat and power (CHP) collector. The novel low-cost, high efficiency solar CHP collector generates electricity and heat for space and water heating up to 60°Celsius (140°Fahrenheit). It uses non-imaging optics for solar concentration, aluminum mini-channels for thermal collection, and commercially available solar cells packaged in an inexpensive glass tube for electricity production. Prototypes were manufactured and tested outdoors over several months. Technical performance under standard operating conditions was verified, and the collector passed all extreme condition testing (stagnation, accelerated cycling, sub-zero temperatures, and hail testing) without degradation. The system has the potential to save 30 percent more roof space and $0.29 per Watt compared to a system combining conventional solar water heater with solar PV and reduces carbon emissions by $24/metric ton of CO_2. This research effort supports the industry in meeting California's greenhouse gas reduction targets, reducing energy consumption, promoting greater natural gas reliability, and lowering energy costs.

Keywords: solar; energy; photovoltaics; solar thermal; combined heat and power (CHP), photovoltaic / thermal (PV/T)

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Introduction

California is challenged to reduce natural gas consumption across all building sectors to lower energy costs, reduce greenhouse gas emissions, and increase safety. The residential and commercial sectors in California consume more than 5 billion therms (100,000 British thermal units) each year for space and water heating. California is exploring technologies that can enable zero-net energy buildings to alleviate demand on the electric and natural gas infrastructure.

Solar energy technologies are promising solutions for distributed generation of electricity and heat using photovoltaic (PV) and solar thermal technologies. Solar combined heat and power (CHP) systems combine these two technologies. They offer the potential to reduce natural gas consumption by providing thermal energy for applications such as building hot water and space heating, while also providing distributed electricity generation. While solar CHP collectors exist, they are either inefficient at temperatures required for building hot water and space heating or are too expensive to enable their widespread adoption. What is missing is an efficient and low-cost solar CHP collector with a similar price point as PV to access the market and capitalize on this distributed heat generating potential.

This project successfully incorporated a nonimaging optical design to provide visual access to both sides of the heat transfer element. Since both sides are used, no insulation or back sheet material is needed and the collector requires only half as much material as a flat plate collector. Expensive copper tubing is replaced with an aluminum mini-channel (made low-cost by the automotive and LED industries) for efficient collection of thermal energy. The ability to use solar cells in a less expensive package, and at the same time provide additional heat is key to lowering the levelized cost of energy from the system and reducing the payback time.

Project Purpose

The project developed a novel cost-competitive high-efficiency solar CHP system capable of producing electricity for building loads and heat for hot water and space heating. The solar CHP system will use commercially available solar cells to enable the development of arrays that can be tuned for optimal performance in California's 16 building climate zones. This will result in ratepayer benefits of lower costs, increased safety, reduced GHG emissions, and greater electricity reliability

Specific goals of the project were to:

1. Complete the design, prototyping and testing of a novel low-cost, high-efficiency solar CHP system for building electricity, hot water, and space heating;
2. Evaluate and quantify the cost and environmental benefits of the system to California natural gas ratepayers; and
3. License the collector design for commercial development.

Project Approach

During the past decade, the University of California, Merced research team successfully developed non-imaging optics, that do not produce any optical image of the source, to enable designing solar thermal collectors for medium for high temperature applications; aluminum and copper mini-channel thermal collectors for low to medium temperature applications; and integrated solar cell/mini-channel assemblies for solar cell cooling, enhanced efficiency, and thermal energy capture. It is a combination of these approaches that makes the novel low-cost, high-efficiency solar CHP collector possible.

The project was broken into the following tasks:

- Task 1: Model and simulate the solar CHP device performance;
- Task 2: Evaluate and select materials for the solar CHP device based on performance, cost-effectiveness, and long-term robustness;
- Task 3: Construct and test a solar CHP array assembly at the lab-scale;
- Task 4: Perform testing and data analysis to verify the simulation and improve its accuracy for future solar CHP products; and
- Task 5: Perform techno-economic and environmental analysis to simulate the benefits of solar CHP in 16 California building zones.

In the first task, a detailed performance model was developed based on optical and thermal simulations for a baseline estimate of the solar CHP collector. In the second task, different materials were investigated, sourced, and characterized for use in the CHP prototypes (heat collecting elements, solar cells, adhesives, and reflectors). In the third task, more than 20 solar CHP collector prototypes were assembled by the team at UC Merced.

In the fourth task, the 20 solar CHP tubes were mounted outdoors for real-world performance testing. Testing of the solar CHP collector prototypes was performed outdoors under typical conditions. Industry standard test procedures were used to produce accurate data for comparison with other products in the market. Additionally, two tubes were sent to a San Francisco Bay Area PV certification company for extreme condition and accelerated testing, including stagnation testing, accelerated temperature cycling, sub-zero atmospheric temperature exposure, 100 hours continuous testing, and hail testing. Experimental results were used to confirm the electric and thermal models, thus demonstrating the technical performance of the CHP collector. Long term performance and corresponding emissions reductions could then be estimated for California’s 16 building climate zones.

Multiple challenges were encountered during the project. Several different adhesives for the PV per thermal interface were tried before a stable solution was found. Tube assembly was time consuming and meticulous. The best procedure and techniques for assembling the tubes were discovered after many iterations of trial and error. The team performed around 10 iterations of tube and assembly development until a final stable manufacturing procedure was found.

Technology costs were estimated using the prototype material costs as a guide, and discussions with manufacturers and suppliers. Performance characteristics were measured according to standard practices in the solar thermal and PV industries. A suite of standard certification tests was performed by a third party to confirm prototype stability.

Project Results

The project successfully demonstrated a proof of concept solar CHP collector. Prototypes were manufactured and tested outdoors over several months. Technical performance under standard operating conditions was verified, and the collector passed all extreme condition testing (stagnation, accelerated cycling, sub-zero temperatures, and hail testing) without degradation.

The solar CHP collector generates 150 Watts of electricity and 400 thermal Watts per square meter. The collector reaches a maximum temperature of 93°Celsius (C) (199°Fahrenheit), and a single square meter of collector can heat 25 gallons of water to 60°C (140°Fahrenheit) by the end of the day. Measured thermal and electric efficiencies were approximately 86 percent of the module, since most solar cell modules packing factors, the ratio of cell area to the aperture area of a module, are less than 90 percent compared to the thermal absorber, an integral component of a solar air collector. Improving this, however, would be easy to implement in the next generation, especially with a production line. When combined with a low production cost of $81 per square meter as determined by a bottom-up cost analysis, the collector yields a very low-cost product. The solar CHP system will reduce greenhouse gas emissions in California by $24 per metric ton of $CO2$. The total avoided $CO2$ emissions are determined using 0.18 kg $CO2$ per kWh of natural gas and 0.331 kg $CO2$ per kWh electric. Multiplying these values by the kWh of heat generation and kWh of electric generation from the PVT collector yields a total kg of $CO2$ avoided per m2 per year. At an estimated mass-production cost of $81/m^2 (Table 3), a module will cost $0.54/WDC and is only $0.07/WDC more expensive than residential PV in the United States. The additional cost can be associated with the 400 Watts of thermal generation, which is added at less than $0.01 per Watt thermal.

The UC Merced team believes that such cost metrics are sufficient to merit further development of this technology which has a high potential for being cost competitive with residential PV. As such, it has the potential to access the residential and commercial markets on a scale which is unprecedented compared to other solar CHP technologies.

Some additional research and development is necessary to improve the technology maturity to commercial readiness. Materials and construction of the solar cell thermal interface should be optimized and undergo accelerated testing to confirm electrical isolation, high thermal conductivity, and stability over a 20-year lifetime. In addition, optimizing the solar cell subassembly could improve the electric output and rate of manufacturing success. In the prototypes, approximately 5 percent of the solar cell area is deactivated or lost by the cutting process. At large scale the supplier has indicated it would be possible to produce cells with custom back-contact grids to eliminate this issue. In its current stage, there are numerous connections made for a small cell area, and when manufactured by hand, this is a long and arduous process and a small error may destroy an entire string or tube. This process can be improved with machinery and automation. The UC Merced research team is seeking funding to (1) confirm stability of the solar cell per thermal absorber interface over 20-year lifetime and (2) optimize the assembly procedure with the assistance of machinery and automation.

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

The research team made numerous public presentations and had face-to-face meetings with stakeholders at industry meetings and conferences, publications in trade press and open access peer-reviewed publications (listed under Publications Section below).

The prototype collector system will also be maintained outdoors for long-term operation and will be available for users to view during site-visits. This is to enable a long-term study and make the system available for further discussion of the project, challenges, and results. To date the operating demonstration has been shown to solar energy researchers from Spain and Chile, and to several Central Valley businesses and industries.

Near-term markets for the CHP technology are building owners and commercial businesses who require electricity and heat. Within commercial buildings, the health (hospitals, health care centers) and lodging (hotels) sectors have been identified as optimal candidates. Mid- and long-term markets include both the residential and commercial building sectors.

The UC Merced research team has reached out to the California League of Food Producers to discuss the CHP collector and its potential for use in the food processing industry. The team has also connected with the Renewable Energy Test Center which oversees the standardized testing of PV modules.

Benefits to California

The project team developed, prototyped, and field tested a new solar CHP collector. This provided the health, lodging and food processing industry with a potentially cost-effective, lightweight, modular, and scalable solar CHP collector that can be installed on rooftops to provide electricity and thermal energy for space or water heating. This research effort supports the industry in meeting California's greenhouse gas reduction targets, reduces energy consumption, and promotes greater natural gas reliability, lower costs and increased safety for all Californians.

Annually, each square meter installed in California will generate an average 205 kilowatt-hours (kWh) of electricity and 547 kWh (19 therms) of heat, reducing natural gas consumption (locally and at power plants) by 1163 kWh (40 therms), and eliminating 167 kilograms (368 pounds) of CO_2 emissions. Over a 20-year lifetime, the estimated investment cost for greenhouse gas savings is approximately $24/metric ton of avoided CO_2. Achieving one million metric tons of avoided CO_2 emissions over a 20-year lifetime will require 265,565 square meters of CHP collector installation and will cost approximately $24 million.

Each square meter installed in California will save the end-user a total of $56 each year in energy costs. The module cost is approximately $81 per meter square. This results in a module-based simple payback time of about 1.4 years. Using this as a guide, a full installation of the solar CHP collector should pay back in 5-8 years.

CHAPTER 1: Introduction

California is faced with the challenge of reducing natural gas consumption across all building sectors in order to lower energy costs, reduce greenhouse gas (GHG) emissions, and increase safety. In addition, California is seeking technologies which can enable zero-net energy (ZNE) buildings to further reduce demand on the electric and natural gas infrastructure.

One technique for reducing consumption is through combined heat and power (CHP), or cogeneration, which is the simultaneous generation of electrical and useful thermal energy from a single fuel source. CHP systems use thermal energy that would have otherwise gone to waste for process loads, and space and water heating/cooling. If widely implemented, CHP technologies possess vast potential for natural gas conservation and reduced greenhouse gas emissions. CHP systems are most commonly large commercial or industrial electric power generating systems; however, the same principles can be applied to distributed solar photovoltaic (PV) systems.

California currently has more than 8,000 MW[1] of distributed photovoltaic generating capacity deployed on rooftops across the state. These technologies convert sunlight into electricity with efficiencies approaching 20 percent, with the remainder either reflected (about 5 percent) or lost as waste heat (about 75 percent). At a ratio of more than 3:1 (heat to electricity), there exists a significant opportunity for recovery and reuse. For example, more than 5 billion therms are consumed by the residential[2] and commercial[3] sectors in California each year for space and water heating below 60°Celsius (C) (140°Fahrenheit[F]). Additionally, nearly 100 billion therms are consumed annually by residential[4] and commercial[5] buildings in the U.S. for space heating and water heating. This is a large market space and source of emissions, about 80 percent of which is provided by high quality fossil fuels (natural gas, propane, and fuel oils) with combustion temperatures above 1000°C (1,832°F). The temperatures required for space and water heating, however, are readily achieved by existing solar collectors as shown in Figure 1 and it is not uncommon for PV modules to reach these temperatures by sitting outdoors. Therefore, it should be technically possible for a large portion of this market space

[1] https://www.californiadgstats.ca.gov/.

[2] KEMA, Inc. 2010. 2009 California Residential Appliance Saturation Study. California Energy Commission. Publication number: CEC - 200 - 2010 - 004 - ES.

[3] Itron, Inc. 2006. 2006 California Commercial End-Use Survey. California Energy Commission. Publication number: CEC - 400 - 2006 - 005.

[4] 2015 Residential Energy Consumption Survey (RECS) - https://www.eia.gov/consumption/residential/.

[5] 2012 Commercial Building Energy Consumption Survey (CBECS) - https://www.eia.gov/consumption/commercial./

to be served by distributed and renewable solar CHP systems, especially in states with a high solar resource such as California.

Solar combined heat and power (CHP) or hybrid photovoltaic/thermal (PV/T) solar collectors combine PV and thermal technologies into a single system. They generate distributed electricity while simultaneously providing thermal energy for hot water or space heating needs. These are enabling technologies of distributed zero-net-energy buildings, which reduce natural gas consumption on-site and at natural gas-fired power plants. They also reduce loads on both the electric and natural gas grids.

In addition, they offer several benefits over side-by-side PV + thermal systems. By recovering waste heat, there is increased production from the same collector area and an improvement in space efficiency. Where previously two systems needed to be installed, now only a single system needs to be installed, reducing total installation time and cost. Furthermore, since installation costs are amortized over the electric and thermal generation of the collector, CHP technologies promise faster returns on investment.

Figure 1: Existing Solar Combined Heat and Power Collectors

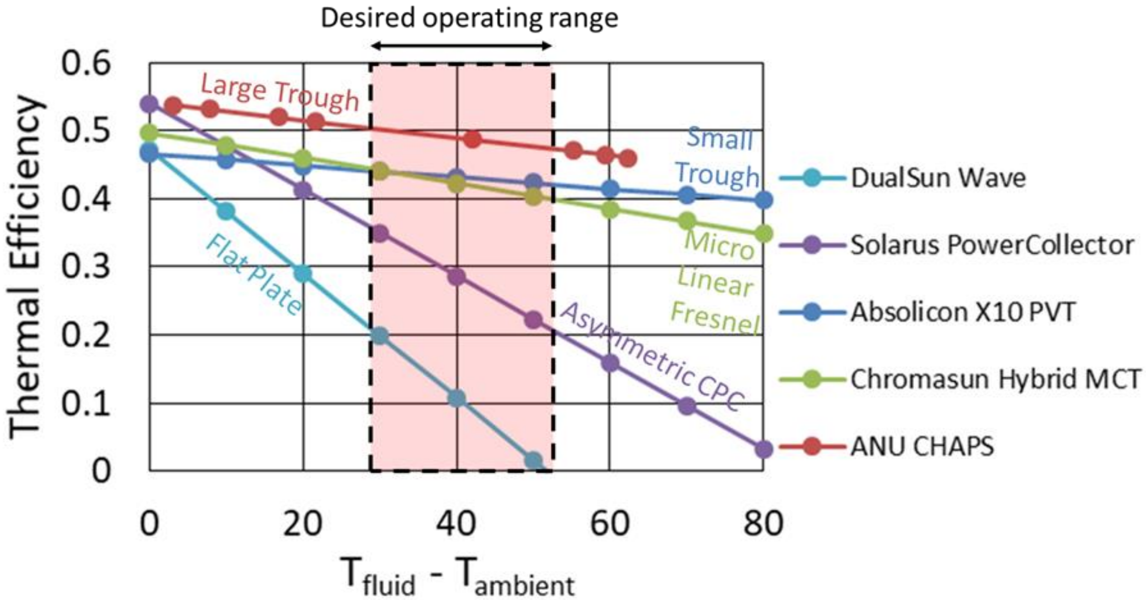
(Left) PowerTherm collector, (Middle) Solarus PowerCollector, (Right) Absolicon X10 PVT

Source: (Left) Powertherm, (Middle) Solarus, (Right) Absolicon

Most PVT technologies (about 75 percent of the market) are simple flat plate style collectors which combine traditional PV panel architectures with traditional flat plate thermal collectors (Figure 1, left). These have high electric efficiencies similar to PV panels, but low thermal efficiencies at the temperatures required for space and water heating. Other PV/T collectors (Figure 1, middle, right) incorporate optical systems to provide solar concentration. These systems sacrifice a small amount of electrical efficiency (due to additional optical losses) for improved thermal outputs at higher temperatures (Figure 2).

Most current commercially available solar CHP systems combine traditional photovoltaic (PV) panel architectures with traditional thermal collector models, making them just as expensive per square meter (m^2) as side-by-side PV + thermal installations. A price survey conducted in 2018 revealed an average flat plate PV/T module price of approximately \$350/m^2 or \$2/WDC (de Keizer et al. 2018). Without innovations combining the two technologies (PV and thermal), the capital costs are high and payback times can reach 14 years (Tse et al. 2016).

Figure 2: Thermal Efficiencies of Some Existing Solar CHP Collectors



Source: UC Merced

While technically feasible, existing solar CHP systems (Table 1) have failed to penetrate the market because their high capital costs ($2/WDC)[6] and are too expensive to justify the additional heat generation compared to standalone PV panels ($0.47/WDC)[7]. What is really needed is an efficient and low-cost solar collector which can harvest electricity and heat for use by residential and commercial end users. To be relevant, CHP collectors must achieve a similar low cost as PV.

Table 1: Properties of Some Existing Solar Combined Heat and Power Collectors

Company/Author	Collector	Type	Concentration	Aperture Area (m^2)	$\eta_{0,th}$	$\eta_{0,el}$
DualSun (Brottier et al. 2016)	DualSun Spring	FPC	1X	1.65	0.47	0.15
Solarus (JM Puerto 2014)	PowerCollector	CPC	1.5X	2.21	0.64	0.11
Absolicon (Fiorenza et al. 2016)	X10 PVT	PTC	17.8X	10.37	0.55	0.07
Chromasun (Vivar et al. 2013)	Hybrid MCT	cLFR	20X	3.50	0.59	0.08
J. Coventry 2005	CHAPS	PTC	37X	1.875	0.64	0.11

Source: UC Merced

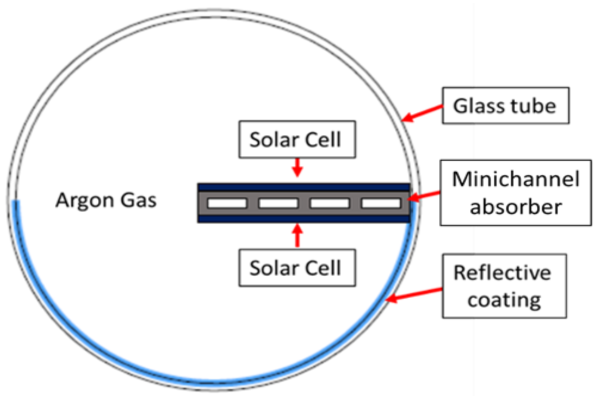
[6] de Keizer, C., Bottse, J., de Jong, M., 2018. PVT Benchmark: An overview of PVT modules on the European market and the barriers and opportunities for the Dutch Market. PVT inSHaPe benchmark 2017.

[7] Fu, R., Margolis, R.M. and Feldman, D.J., 2018. US Solar Photovoltaic System Cost Benchmark: Q1 2018 (No. NREL/TP-6A20-72399). National Renewable Energy Lab.(NREL), Golden, CO (United States).

The incredible price drop of PV panels in the past 10 years has completely changed the market, requiring all competitors to be at or near the same price point. This has essentially eliminated the once-burgeoning CPV market and is making it difficult for CHP (or PV/T) collectors to compete, despite their additional heat generation. Therefore, new radical designs are needed to drastically improve efficiencies while simultaneously lowering costs to match commercial PV.

New collector paradigms and novel techniques are required to optimally combine thermal and photovoltaic technologies to maintain high efficiencies without sacrificing on cost. Development of new technologies such as these, while of vast potential benefit to society, is typically too risky for the private sector especially in such an early stage. Therefore, initial proof-of-concept research and development typically requires public support. Support for this project was provided by the California Energy Commission's Natural Gas Research Program[8], which invests in technologies and solutions that help the natural gas sector support California's energy and environmental goals.

Figure 3: Solar Combined Heat and Power Collector Schematic



Source: UC Merced

To achieve such a target the solar team at University of California, Merced (UC Merced) proposed a new solar CHP collector (Figure 3) which uses non-imaging optics for solar concentration, aluminum mini-channels for thermal collection, and commercially-available solar cells for electricity production. By replacing the packaging material cost of traditional PV and flat-plate collectors with a low-cost optic and using aluminum mini-channels for efficient thermal collection, a much lower cost solar CHP collector can be created. At an expected module cost around the same price point as residential PV, it is likely this collector could see greater market penetration, allowing end users to capitalize significant heat generating capacity of distributed rooftop PV systems.

[8] GFO-16-503 – Novel solutions to accelerate deployment of small and micro-scale combined cooling heating and power systems.

CHAPTER 2: Project Approach

In 2017, the CEC awarded $935,131 in funding to the University of California, Merced to develop and demonstrate performance of their novel low cost and high-efficiency solar powered micro-CHP system for electricity, hot water, and space heating.

During the past decade, the UC Merced solar team has successfully developed multiple non-imaging optics-enabled solar thermal collectors. These have been developed for medium temperature applications,[9] low temperature applications with mini-channels,[10] and integrated solar cell/mini-channel assemblies for solar cell cooling and energy recovery.[11] A combination of these approaches makes the novel low-cost, high-efficiency solar CHP collector possible.

The UC Merced team consists of principal investigator Dr. Roland Winston, an expert in non-imaging optics and solar concentration, and Dr. Gerardo Diaz, an expert in heat transfer with experience using mini-channels for efficient solar thermal collection. Project scientist Dr. Lun Jiang and post-doctorate Dr. Bennett Widyolar provided expertise on manufacturing, fabrication, and assembly of the solar CHP collectors. In addition, two doctoral students Jordyn Brinkley and Sai Kiran Hota worked on the project, along with several other graduate and undergraduate students. Ron Durbin acted as project manager and Robyn Lukens served as the point of contact between the research team and the UC Merced staff. In many ways the success of this project can be attributed to the success of this team.

The CHP collector incorporates a non-imaging optical design to provide optical access to both sides of the heat transfer element (Figure 4). Since both sides are used, no insulation or back sheet material is needed and the collector requires only half as much material as a flat plate collector. Expensive copper tubing is replaced with an aluminum mini-channel (made low-cost by the automotive and LED industries) for efficient collection of thermal energy. The ability to use solar cells in a less expensive package, and at the same time provide additional heat is key to lowering the levelized cost of energy from the system and reducing the payback time.

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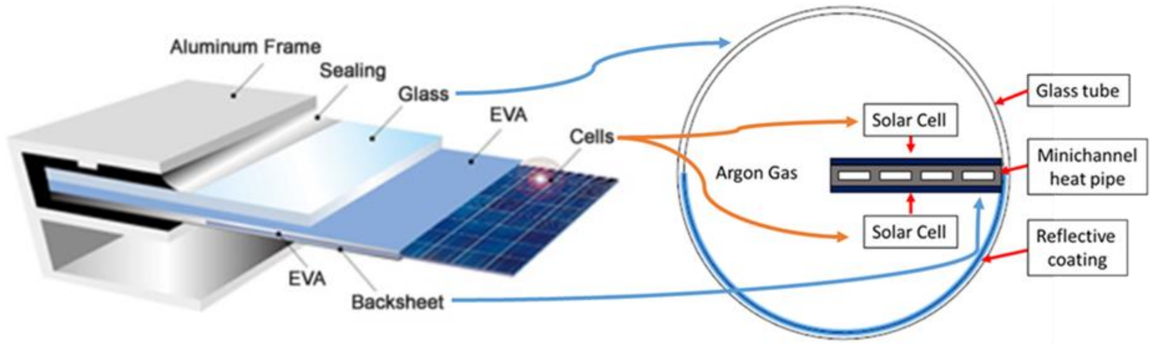
[9] Widyolar, B., Jiang, L., Ferry, J. and Winston, R., 2018. Non-tracking East-West XCPC solar thermal collector for 200 celsius applications. Applied energy, 216, pp.521-533.

[10] Diaz, Gerardo. (University of California-Merced). 2015. Mini-channel Technology to Improve Solar Water Heaters. California Energy Commission. Publication number: CEC-500-2019-008.

[11] Widyolar, B., Jiang, L., Ferry, J., Winston, R., Kirk, A., Osowski, M., Cygan, D. and Abbasi, H., 2019. Theoretical and experimental performance of a two-stage (50X) hybrid spectrum splitting solar collector tested to 600° C. Applied Energy, 239, pp.514-525.

Figure 4: Comparison between Typical Photovoltaic Module and Solar Combined Heat and Power Collector

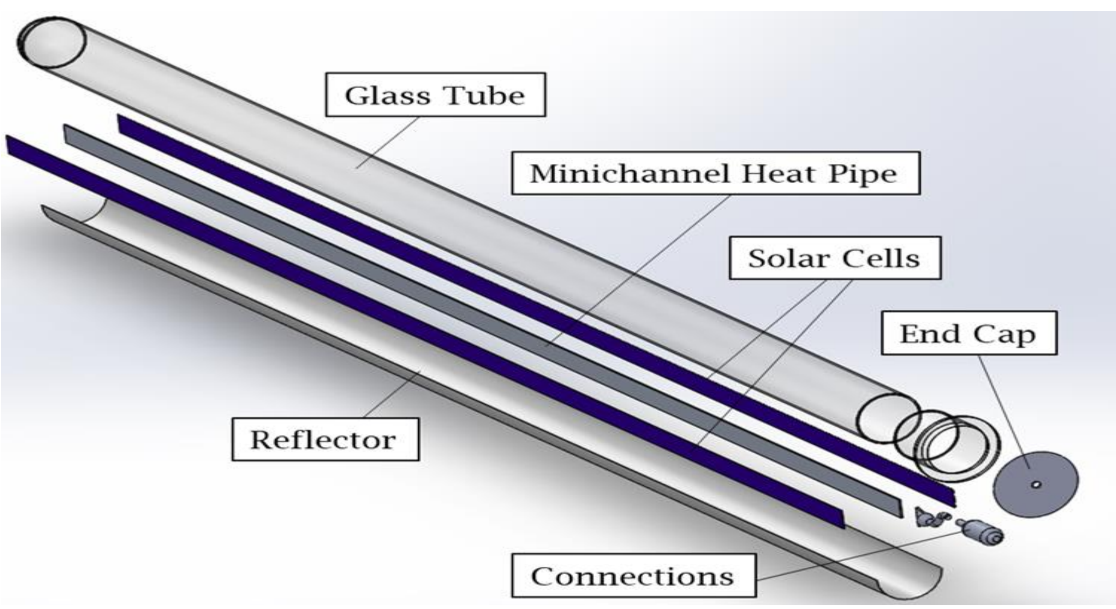


(Left) Typical PV module, (Right) Solar CHP collector

Source: UC Merced

The collector consists of (1) a glass tube, (2) mini-channel absorber, (3) half-circle reflector, and (4) solar cells applied to the top and bottom of the absorber (Figure 5). The half-circle reflector provides optical access from the aperture to both top and bottom surfaces of the absorber. Compared to conventional PV/T solar collectors, no insulation material is needed for the back of the heat sink on the solar cells, and no back sheet is needed for the collector assembly. Additionally, both sides of the heat transfer element are utilized instead of one. The absorber is an aluminum mini-channel heat pipe mounted horizontally in the 3'oclock position. It is both the substrate for mounting the solar cells and the thermal absorber.

Figure 5: Exploded View of Solar Combined Heat and Power Collector



Source: UC Merced

The unique solar cell/mini-channel interface allows for the collection of thermal energy, while simultaneously cooling the solar cells and enhancing their efficiency. Waste heat generated by the cells is transferred to a working fluid circulated through the mini-channel absorber. The cells are attached to the mini-channel with a thermally conductive and electrically isolating adhesive to isolate the cells from the aluminum mini-channel absorber (prevents shorting), as shown in Figure 6, while also allowing heat to be transferred into the absorber. The glass tube is filled with argon gas to reduce the internal convection coefficient inside the tube and minimize heat loss from the hot solar cells.

Figure 6: Solar Cell Strip Assembly

(Left) Adhesive applied to heat pipe, cells, tabbing ribbons, and low melting point solder applied and prepared for (Middle) Soldering of the strip. (Right) A fully soldered string of cells which is then applied to the heat pipe.

Source: UC Merced

This project developed a proof-of-concept collector and experimentally confirmed the technical performance.

The goals of this two-year research project were to (1) complete the design, prototyping, and testing of the proof-of-concept CHP collector prototype, (2) evaluate and quantify the cost and environmental benefits to California natural gas ratepayers, and (3) license the technology for commercialization.

To achieve these goals, the project was broken into the following tasks:

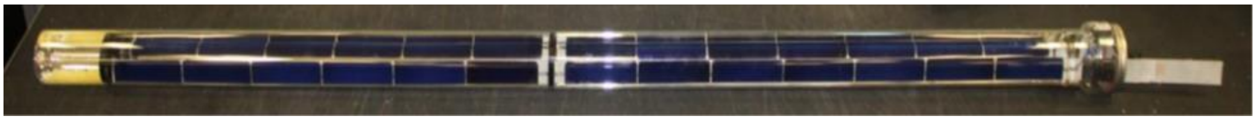
1. Model and simulate the solar CHP device performance;
2. Evaluate and select materials for the solar CHP device based on performance, cost-effectiveness, and long-term robustness;
3. Construct and test a solar CHP array assembly at the lab-scale;
4. Perform testing and data analysis to verify the simulation and improve its accuracy for future solar CHP products; and
5. Perform techno-economic and environmental analysis to simulate the benefits of solar CHP in 16 California building zones.

In the first task a detailed performance model was developed based on optical and thermal simulations for a baseline performance estimation of the solar CHP collector. This was performed using ray tracing and finite element analysis (FEA) thermal simulation software.

In the second task, different materials were investigated, sourced, and characterized for use in the CHP prototypes (heat collecting elements, solar cells, adhesives, and reflectors). The major focus in this task was the selection of solar cells and adhesives for the cell / thermal interface.

In the third task, the team assembled many prototype CHP collector tubes. Several different adhesives for the PV / thermal interface were tried before a stable solution was found. Tube assembly (Figure 7) was time consuming and meticulous. The best procedures and techniques for assembling the tubes were discovered after many iterations of trial and error. Assembly of the collector required multiple steps and multiple solder joints to string the cells together, all of which were performed manually. Each solder joint, if done improperly, could potentially ruin the entire assembly. The team went through approximately 10 iterations of tube and assembly development until a final stable manufacturing procedure was found. The minimum array size which could be accurately characterized required approximately 20-tubes, and a significant amount of effort was put into assembling these.

Figure 7: Assembled Heat Pipe Tube



Source: UC Merced

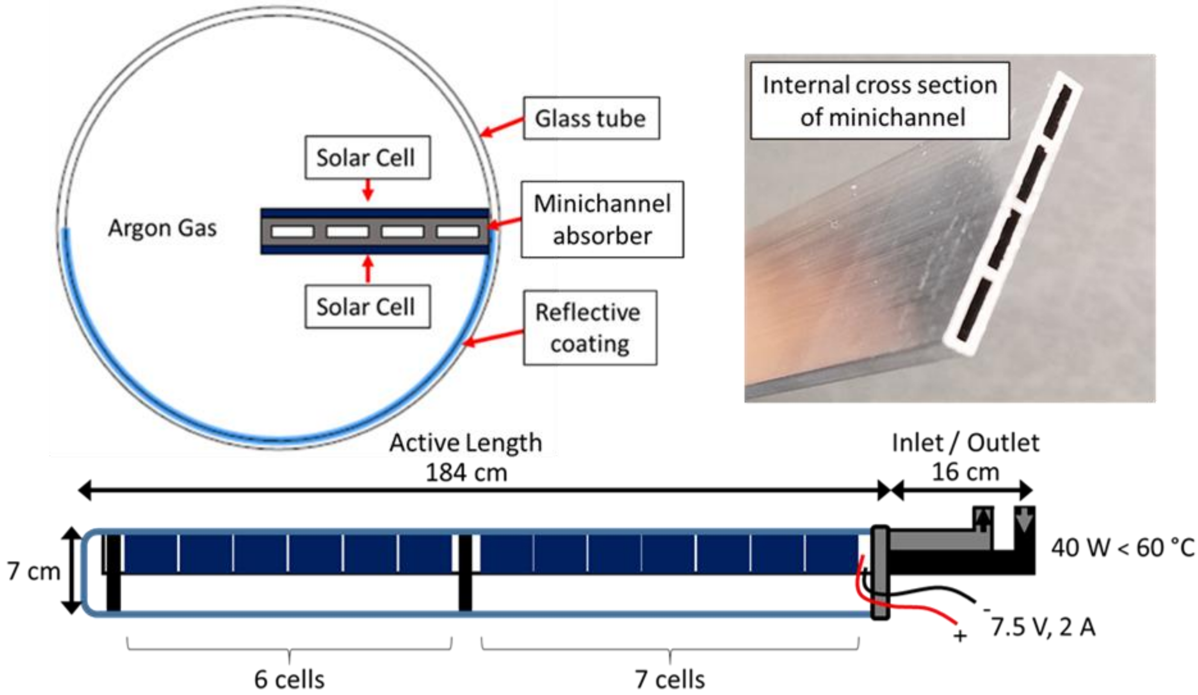
In the fourth task, the twenty solar CHP tubes were assembled into an array and mounted outdoors for testing under typical conditions. Industry standard test procedures were used to produce accurate data for comparison with other products in the market. Additionally, 2 tubes were sent to a bay-area PV certification company for extreme condition and accelerated testing, including stagnation testing, accelerated temperature cycling, sub-zero atmospheric temperature exposure, 100-hour continuous testing, and hail testing. Experimental results were used to confirm the electric and thermal outputs, thus demonstrating technical performance of the CHP collector. Long term performance of systems and corresponding emissions reductions could then be estimated for California’s 16 building climate zones.

Technology costs were estimated by a bottom-up cost analysis using the cost of materials for the prototypes as a guide, and through discussions with manufacturers and suppliers. The economic and environmental benefits were then estimated.

CHAPTER 3: Project Results

The project was a success in delivering the proof of concept solar CHP collector test results. The prototype solar CHP collector (Figure 8) was manufactured and tested outdoors, on-sun over the course of several months. Technical performance of the solar CHP collector under standard operating conditions has been verified, and the collector passed all extreme condition testing (stagnation, accelerated cycling, sub-zero temperatures, and hail testing) without degradation.

Figure 8: Prototype Solar Combined Heat and Power Collector Schematics



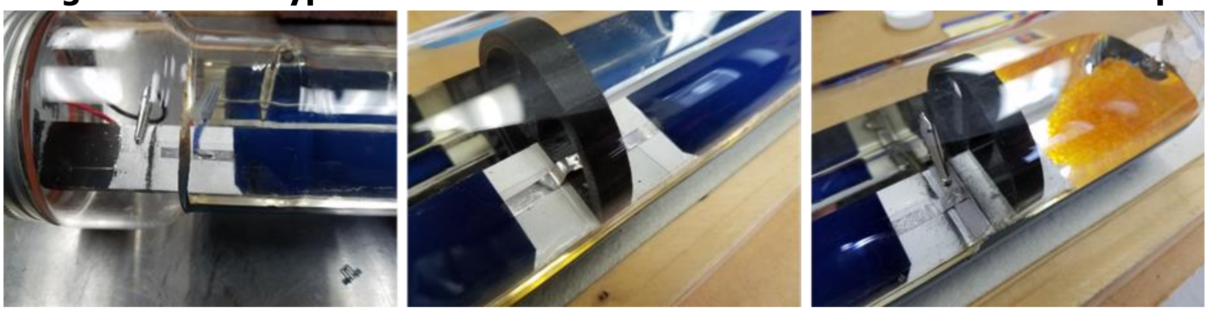
(Top left) cross-sectional schematic of the CHP collector tube, (Top right) internal cross-section of aluminum mini-channel, (Bottom) top-down schematic of solar CHP collector with dimensions, cells, and outputs.

Source: UC Merced

More than 20 prototype CHP collector tubes were fabricated and tested. The glass tubes are 2 meters long with 66 milimeters (mm) and 70 mm ID and OD, respectively, and were made using borosilicate glass. At one end they are sealed shut with a half-spherical glass cap. At the other end they transition to a 90 mm OD glass tube with outer threads to allow the end caps to be screwed into place, similar to a mason jar, and re-sealed. The exterior bottom half of the tubes were silver-coated and painted to protect the coating from the environment. Two-meter-long aluminum mini-channels extruded with a width of 32 mm, height of 3 mm, and four inner channels (6 mm x 1 mm) were used as absorbers. At one end they were cut and welded into an inlet and outlet, allowing the working fluid to enter through two of the channels and exit from the other two. At the opposite end, the mini-channels were sealed so that the flow from the first two channels was forced into the other two channels (u-tube configuration).

SunPower Maxeon Gen II solar cells were used for their high efficiency, robustness and durability. These cells have inter-digited back contacts, meaning there is no front contact shading. The cells ($bin\ Jp$) have open circuit voltages (Voc) of 0.68 V and short circuit currents of about 6.32 A. They are roughly 125 mm x 125 mm and are about 22 percent efficient at converting solar energy into electricity. To apply them to the absorber, the cells were cut into three strips around each of the contact pads so that each strip was approximately 30 mm x 125 mm. They were then interconnected using SunPower's strain-relieving interconnect tabs and a small amount of low melting point solder. Only 13 cells could fit inside the tube, so they were divided into two distinct sections of 6 cells and 7 cells with space for an absorber support in the middle (Figure 9, middle). The cells were attached to the mini-channel absorber using a double-sided silicone tape with a reported thermal conductivity of 1.5 W/m-K, breakdown voltage of 4 kV, and long term 120 °C temperature stability.

Figure 9: Prototype Solar Combined Heat and Power Collector Close-up



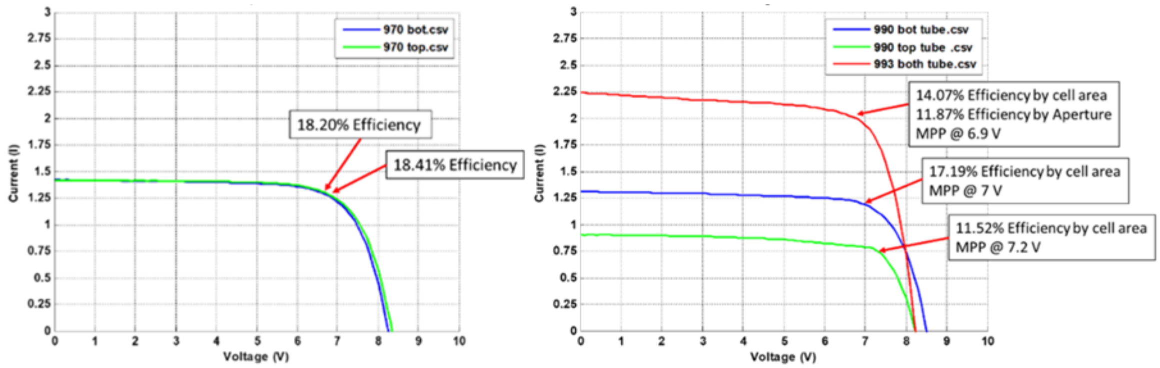
(Left) End cap and wires, (Middle) Absorber support and tabbing wire interconnects, (Right) End of tube with orange desiccant beads.

Source: UC Merced

Rather than running a wire along the length of the tube, it was decided to use the aluminum mini-channel itself as the negatively charged electrode. An alligator clip provided the mechanical contact to press the long tabbing wires into the aluminum absorber (Figure 9, right). In the middle two long tabbing wires were soldered to bridge the 6 cell and 7 cell sections. At the top of the tube, the positive electrodes from each strip were wired in parallel and passed through the end cap outside the glass tube (left). Also at the top, a second alligator clip was attached to the aluminum absorber, and in a similar manner passed to the outside of the glass tube.

The end caps were provided by the glass tube manufacturer with locking rings to press the cap against the glass tube (similar to a mason jar). Slots were drilled in the end caps to accommodate the mini-channel absorber and both electrodes. All gaps were epoxied shut to make an air-tight seal. A small amount of desiccant was added to the bottom of the glass tube to absorb any moisture as a precaution. A layer of silicone vacuum grease was applied to the inside gasket of the end cap. The tube was positioned vertically and argon gas was added to the glass tube from a tank. Since argon is heavier it displaces the air in the tube. A lighter was used to determine when the tube had been filled with argon (once the lighter would no longer stay lit). Once determined to be filled, the cap was sealed shut. Standard PV MC4 connectors were attached to the positive and negative electrode wires on the outside of the tube and the solar CHP collector tube assembly was complete.

Figure 10: IV Curve Tracing



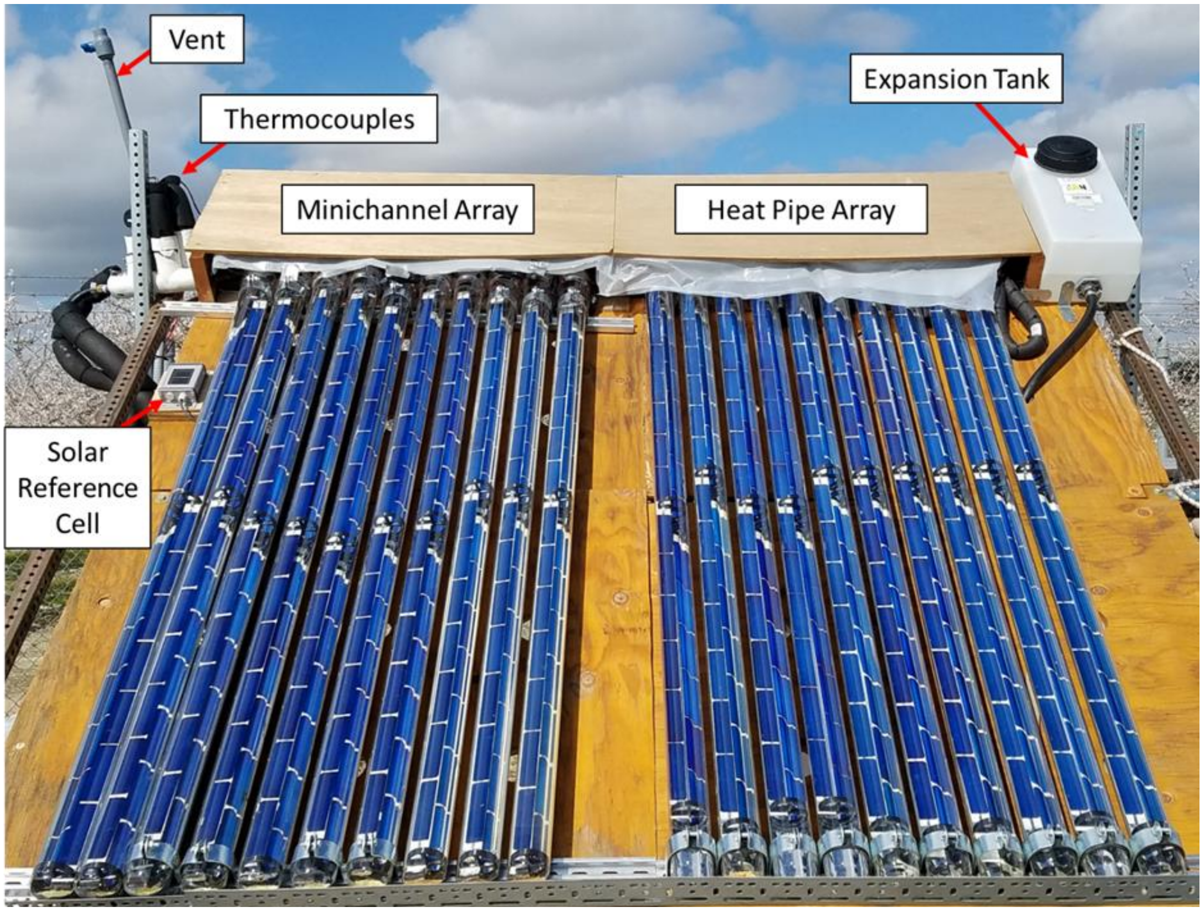
(Left) Bare strips exposed to sunlight, (Right) Strips inside a solar CHP collector.

Source: UC Merced

IV curve testing was performed on the tubes during and after assembly. The IV curves of bare top and bottom strips (taken outside, on-sun, and without a glass tube) are shown in Figure 9 (left). Both strips have nearly identical on-sun IV curves with maximum power point efficiencies of about 18.3%. The IV curves from a finished collector are shown in Figure 10 (right). The top strip inside the CHP collector (blue) is reduced compared to a bare strip due to the transmission loss through the glass tube. The bottom strip inside the CHP collector (green), however, is reduced $2/3$ of the top strip which is more than expected from just an additional reflection loss. This may be due to uneven illumination of the solar cells (for example via shading from one of the absorbers supports) which may be current limiting the entire strip. When the two strips are wired in parallel in the CHP collector (red) the resulting IV curve is the sum of the top and bottom strips as expected.

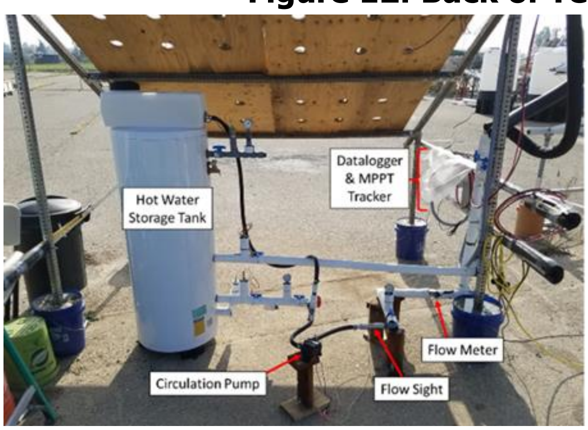
Twenty fully working CHP collector tubes were then assembled into an array and mounted on an outdoor test platform at the UC Merced Castle Research Facility in Atwater, California Ten tubes were constructed in the flow-through configuration. using direct-flow mini-channels, and the remaining ten were built using heat pipes. Thermal and electrical performance of the array was quantified up to 90 °C and the incident angle modifier (IAM) experimentally generated. An image of the CHP test array is shown in Figure 11, with the direct-flow mini-channel array on the left and the heat pipe array on the right.

Figure 11: Solar Combined Heat and Power Collector Undergoing Experimental Testing



Source: UC Merced

Figure 12: Back of Test Loop and Datalogger



Source: UC Merced

The test loop can be run in open and closed configurations (Figure 12). It includes a circulating pump, flow meter, and thermocouple clusters located at the inlet and outlet of the collector. The solar collector is mounted at a fixed latitude ($37°$) tilt facing solar south to simulate performance under typical installation conditions. The test stand includes a solar reference cell mounted on the same plan as the collector to measure the incoming solar irradiance and a thermocouple located behind the collector is used to measure the ambient temperature.

Solar efficiencies are calculated based on the amount of useful energy captured divided by the total solar energy input. Since the solar CHP collector generates two useful outputs, it is characterized by both the solar-to-thermal efficiency ($\eta_{thermal}$) and solar-to-electric efficiency ($\eta_{electric}$), which are given in the following equations.

$$\eta_{thermal} = \frac{Q_{thermal}}{Q_{solar}} = \frac{mC_p(T_{out} - T_{in})}{A * G}$$

$Q_{thermal}$ is the useful thermal power (Watts) captured in the heat transfer fluid and is measured by the mass flow rate of the fluid ($\dot{m}$), heat capacity of the fluid (C_p), and temperature difference of the fluid at the inlet (T_{in}) and outlet (T_{out}) of the collector. The heat capacity of the working fluid (water) is assumed to be a constant 4.184 kJ/kg-K.

Q_{solar} is the incoming solar radiation which is available to the collector. It is calculated based on the area of the collector (A) and the normal global irradiance (G).

$$\eta_{electric} = \frac{Q_{electric}}{Q_{solar}} = \frac{I_{MPP}\ x\ V_{MPP}}{A * G}$$

The solar-to-electric efficiency $\eta_{electric}$ is calculated from the electric power generation ($Q_{electric}$) which is a result of the current I multiplied by the voltage V at the maximum power point (MPP).

The defining area (A) for the calculation of incoming solar power varies depending on the type of test performed. For the solar-to-thermal efficiency tests, the aperture area of the module (the area of the collector that is actively capturing incoming solar energy) is used. The aperture width of each tube is 66 mm, however, the heat pipe and flow-through versions each have a different amount of active collecting length inside the glass tube. This averages to 1.75 meters for the heat pipe collectors and 1.84 meters for the flow-through collectors. The aperture area per tube is calculated according to the equations below:

$$A_{tube} = W_{aperture}\ x\ L_{absorber} = 0.116\ m^2\ for\ heat\ pipes$$

$$A_{tube} = W_{aperture}\ x\ L_{absorber} = 0.121\ m^2\ for\ flow - through$$

The aperture area of the multi-tube module is simply calculated by multiplying the aperture area of each tube by the number of tubes in the module.

$$A_{module} = A_{tube}\ x\ \#_{tubes}$$

Solar-to-electric efficiency can be calculated in two ways. The first way is similar to the solar-to-thermal efficiency, using the aperture area of the collector being tested. The second way is using the total active cell area in the collector being tested. The ratio of cell area to the aperture area of a module is called the packing factor, and is typically maximized to improve the relative efficiency of the module. Due to constraints constructing manual prototypes, the tubes produced in this project have slightly reduced packing factors. The total active cell area in a tube (two sides, 13 cells each strip) is given by the following equation

$$A_{cells} = 2\ sides\ x\ 13\ cells\ x\ 0.125\ m\ x\ 0.03\ m = 0.0975\ m^2$$

Therefore, the packing factor is

$$Packing\ Factor\ = \frac{0.0975\ m^2}{0.116\ m^2} = 0.84\ for\ heat\ pipes$$

$$Packing\ Factor\ = \frac{0.0975\ m^2}{0.121\ m^2} = 0.81\ for\ flow - through$$

Solar-to-electric efficiencies are reported as a function of aperture area.

Once the efficiency data has been collected, calculated, and graphed as a function of the reduced temperature T*, the collector performance is generalized for comparison with other collectors using a linear coefficient a1 determined by a linear curve fit.

$$\eta_{collector} = \eta_0 - a_1 T^*$$

Where

η_0 is the optical efficiency

T^* is the reduced temperature, $T^* = \frac{T_{in} - T_{amb}}{G}$

a_1 is the coefficients determined from a linear curve fit.

Several different test types were performed to quantify the full performance of the CHP collector. These are broken down into:

- Open-loop optical efficiency: The city water line is connected directly to the supply side of the loop using a garden hose. Water can then be circulated through the system at temperatures close to the ambient, providing a good measurement of optical efficiency.
- Open-loop thermal efficiency: A thermal bath is filled with city water and the desired temperature set point is placed. The suction hose from the water circulation pump is disconnected from the loop and instead draws from the thermal bath while the outlet of the loop now discharges into the bath. In this way, the thermal bath provides a temperature control and the pump circulates this heated water through the system. This allows for control and steady operation of the loop at a desired temperature set point.
- Closed-loop typical daily performance: The pump remains connected to the piping system. Water in the loop is circulated through the collector continuously, causing it to heat up over time. This simulates a typical daily performance. The amount of water in the hot water storage tank can be varied to simulate different sized domestic hot water loads.
- Individual tube IV-curve tracing: Each individual tube is connected to the IV curve tracer to generate an instantaneous IV curve. This is typically done tube-by-tube in quick succession to gather more detailed electric performance on each tube. Upon triggering a sweep, the 2460 System SourceMeter®[12] takes 5-10 seconds to perform the sweep, after which the data was saved to a .csv file and marked with the average

[12] The System SourceMeter® 10 µsec Pulser/Source Measure Unit (SMU) Instrument combines the power of a high current/high speed pulser with measure and the full functionality of a traditional SMU in a single instrument.

solar flux during the test period. The power at each point along the IV curve is calculated and the maximum power point (MPP) is used to calculate the electric efficiency of that tube.

- Full module active MPPT + PV load consumption: All of the tubes in a module are connected in series and the output of the full module is connected to the maximum power point tracker (MPPT). The MPPT tracker monitors and controls the voltage of the system for maximum power output. The maximum power current and voltage are then directly measured by the datalogging system.

The data logger records data from 8 channels every second. These channels include:

- The voltage recorded by the solar reference cell which is then converted to W/m2.
- The ambient temperature measured by a K-type surface thermocouple mounted in the shade of the collector test stand.
- A single inlet thermocouple which is inserted into the flow path of the HTF.
- Three outlet thermocouples inserted into the flow path of the HTF.

Note: It was noticed early that the inlet stream to the collector is well-mixed after passing through the flex hoses and bends of the loop. The outlet stream from the collector is typically not well-mixed, so multiple thermocouples are used to accurately measure the bulk temperature of the fluid stream.

- The current measured from the PV combined output.
- The voltage measured from the PV combined output.

The output is stored in a comma separated variable file which is then analyzed to calculate the desired quantities.

The test conditions reported in Table 2 were required to be met for data to be used.

Table 2: Standard Test Conditions

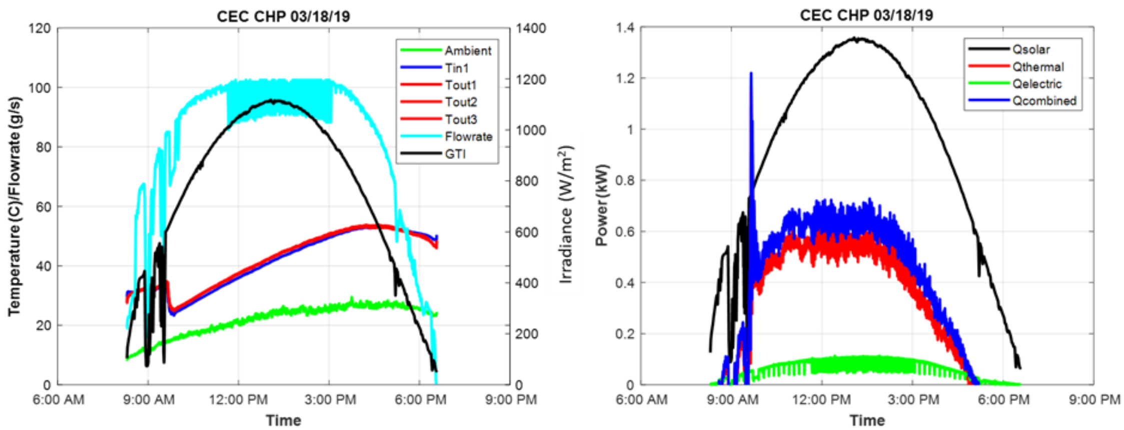
Test Parameter	Standard test condition
Duration of test	30 minutes
T_{in}	Must not vary by more than ±1 °C during course of test
$\dot{m}$	Must not vary by more than ±8 g/s during course of test
GTI	Must be ≥ 800 W/m^2 during course of test
GTI	Must not vary by more than ±50 W/m2 during course of test

Source: UC Merced

Outdoor test results were gathered between February-June of 2019. Due to the nature of the CHP collector, it easy to develop an autonomous demonstration loop for the collection of long-term data. In the morning the sunlight which is incident on the solar cells provides the necessary power to drive the pump and circulate the working fluid. Data is collected automatically as soon as the solar irradiance reaches above 100 W/m2. As a result, months of data have been collected, including several weeks of continuous operation.

Test data is shown for March 18, 2019 (Figure 13), when the direct flow mini-channel array was undergoing testing. At about 10:00 AM, 25 gallons of cold water were filled into the hot water storage tank, causing the temperatures to drop to about 20°C (68°F). By the end of the day, the temperatures had reached about 55°C (131°F). This scenario simulates a typical home installation and shows the system can reach desired hot water temperatures at the end of a single day.

Figure 13: Experimental Testing of Direct Flow Minichannel Array



(Left) Temperatures, flowrate, and solar resource. The flow from the pump is automatically powered by the electricity generated by the collector. (Right) Calculated solar, thermal, electric, and combined power in kW.

Source: UC Merced

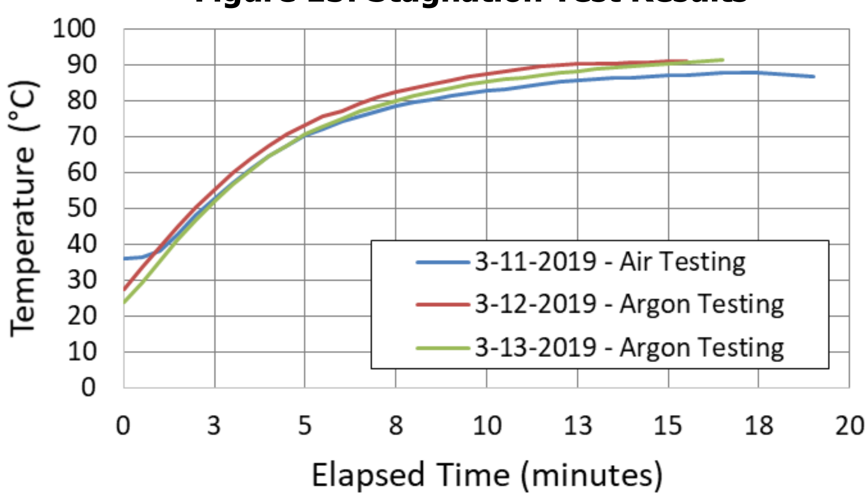
Stagnation tests were performed using a single heat pipe CHP collector. Two thermocouples were attached to the condensing section of the heat pipe and subsequently wrapped with two 1″ thick pieces of insulation (Figure 14). The CHP collector was then placed outdoors on the same plane as the solar reference cell and uncovered. The temperatures were recorded every 30 seconds for about 15 minutes until the temperature levelled off.

The maximum temperature recorded at the condenser was 93°C (199°F). The temperature rise of three stagnation tests are plotted in. The first test data (3/11/2019) in Figure 15 was performed when the tube was filled with air, after which it was filled with argon and subsequently tested two more times. The argon does increase the maximum temperature by a few degrees.

Figure 14: Stagnation Test Setup

Source: UC Merced

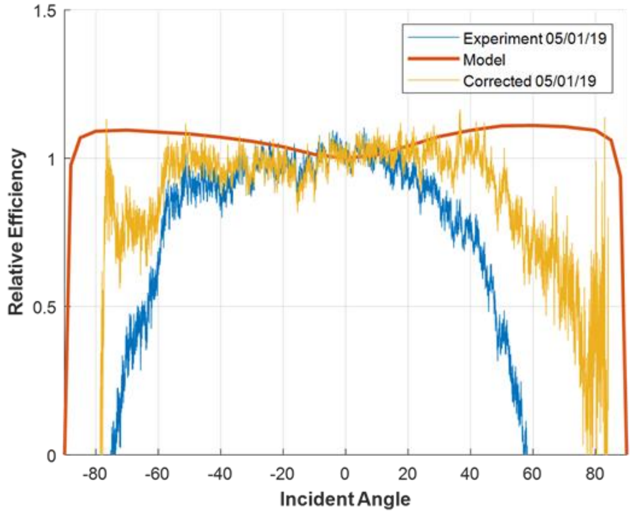
Figure 15: Stagnation Test Results



Source: UC Merced

The incidence angle modifier was quantified on May 1, 2019. This was down by allowing the sun to pass over the collector the entire day while monitoring the efficiency. This efficiency is plotted in Figure 16: Incidence Angle Modifier in blue, relative to the efficiency recorded at solar noon. At this point, the relative efficiency is 1. Since the solar irradiance changes over time (due to the cosine effect, specifically the daily motion of the sun) and the collector and ambient temperature slowly increase throughout the day, all the efficiencies were then T* corrected. This way they reflect the efficiency at the same T* as the efficiency at solar noon. This curve is plotted in yellow and captures a wider range of incidence angles. It is difficult to quantify the extreme angles because the incident solar energy is so low, that most of it is lost as heat prior to being quantified by the thermocouples. Overall, however, the experimental IAM is fairly close to the expected for ±60°.

Figure 16: Incidence Angle Modifier

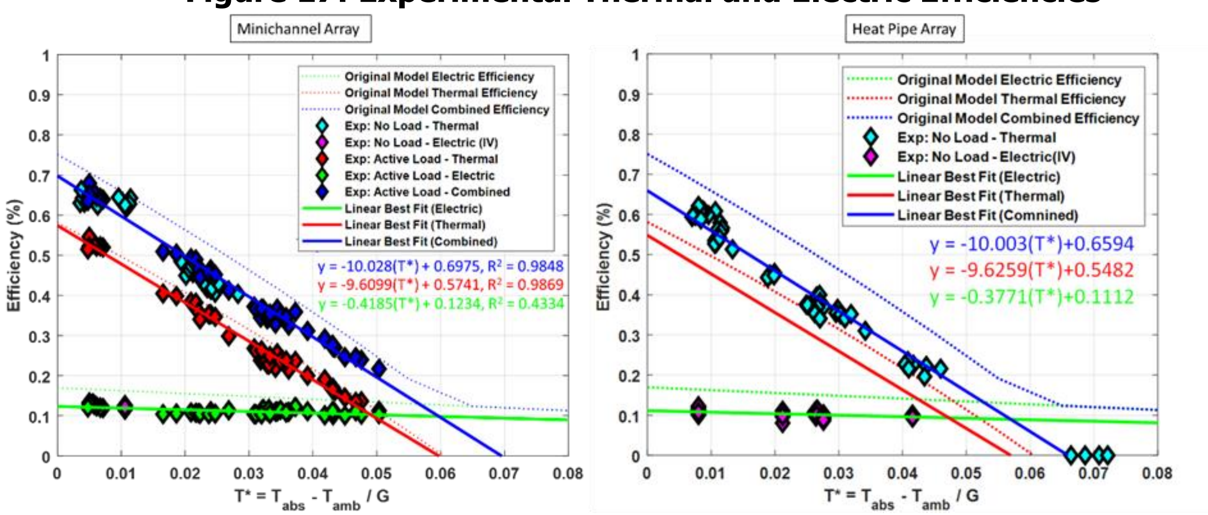


Source: UC Merced

Accelerated temperature cycling (-40°C [-40°F] to 90°C [194°F)]cycled twenty times) and hail testing (1” ice ball shot at 23 m/s) was performed on two additional tubes, the results are shown in Appendix A.

Data which fits the test criteria from Table 2 was used to populate the charts in Figure 17. The solar-to-thermal, solar-to-electric, and combined (Solar-to-Thermal+Electric) efficiencies are plotted as a function of T* in Figure 17.

Figure 17: Experimental Thermal and Electric Efficiencies



(Left) Mini-channel array, (Right) heat pipe array

Source: UC Merced

The diamonds in Figure 17 represent experimental data points which meet the test criteria from Table 2. The cyan diamonds are the thermal efficiency points measured while the solar cells have no active load on them. The magenta diamonds are the individual IV curve traces of each tube. After these tests, the CHP collector tubes were series-connected electrically and connected to a maximum power point tracker (MPPT). The MPPT tracker was connected to the circulation pump and a series of resistors to dump the excess electric load into the environment. As a result, the green diamonds are the electric efficiencies calculated using the current and voltage measurements with an active load. The red diamonds are the thermal efficiencies calculated during these same tests, and the blue diamonds are artificially calculated by adding the red and green diamonds together.

As a result of experimental testing, the models have been updated and a detailed techno-economic analysis performed for the 16 California climate zones. The annual electric and thermal generation from CHP collector systems installed in these regions and corresponding natural gas and CO2 emission reductions have been calculated.

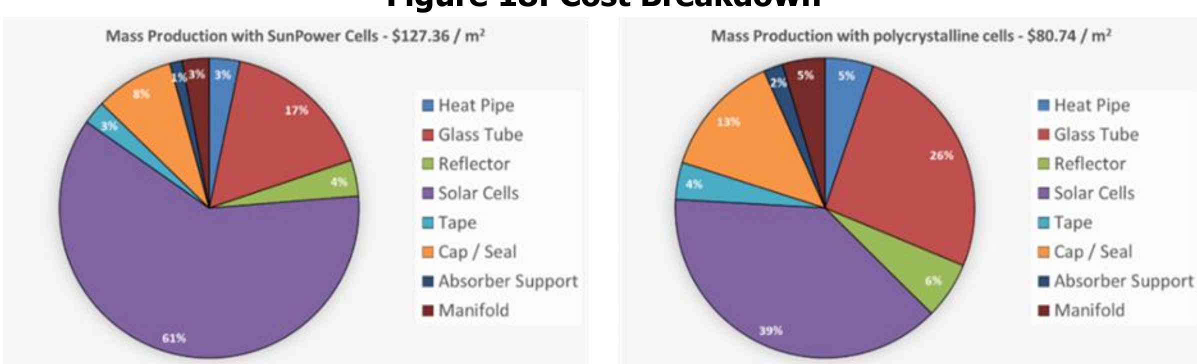
A bottom-up cost analysis of the CHP collector in Table 3 and Figure 18, was performed for the prototype system which then guided an estimation of mass-production costs for the CHP collector.

Table 3: Bottom-Up Costs of Combined Heat and Power Collector

Component	Prototype System	Mass production SunPower cell	Mass production polycrystalline cell
Mini-channel	$3.53	$0.50	$0.50
Glass Tube	$2.50	$2.50	$2.50
Reflector	$0.59	$0.59	$0.59
Solar Cells	$13.69	$9.23	$3.69
Tape	$2.83	$0.38	$0.38
Cap / Seal	$1.29	$1.29	$1.29
Absorber Support	$1.00	$0.20	$0.20
Manifold	$0.88	$0.44	$0.44
Total $/tube	$26.31	$15.13	$9.59
Total $/m^2	$221.48	$127.36	$80.74

Source: UC Merced

Figure 18: Cost Breakdown



(Left) Mass-production cost breakdown of the CHP collector using SunPower cells, (Right) Mass-production cost breakdown of the CHP collector using polycrystalline silicon cells

Source: UC Merced

The CHP collector prototypes have experimentally demonstrated 15 percent solar-to-electric efficiency as a function of cell area or about 13% as a function of module area. This is a 76 percent reduction over the 20 percent bare cell efficiency as a result of the following:

- Cutting commercial cells deactivates ~93 percent of the inter-digited back contact area
- Series resistance and contact losses (~97 percent)
- Transmission losses through the glass tube (~92 percent)
- Reflection losses from the bottom half-circle reflector (~92 percent)
- Packing factor losses, with cell area covering only about 83 percent of the aperture area

The solar-to-electric efficiency of future CHP collector models can therefore be improved from 76 percent of the bare cell efficiency to 86 percent by 1) using properly designed cells to increase the area utilization from 93 percent to 100 percent, 2) using an AR-coated glass tube (typical of PV panels) to increase transmission from 92 percent to 96 percent, and 3) increasing the packing factor of the cells on the absorber to 95 percent. Furthermore, the starting cell efficiency can be improved by using SunPower's latest 22 percent efficient cells, or the latest 19 percent efficient polycrystalline cells. With this the solar-to-electric efficiency of future mass-production SunPower models is estimated to be 19 percent by cell area and 18 percent by module area, and 16 percent by cell area and 15 percent by module area for the mass-production polycrystalline model.

The prototypes demonstrated 60 percent optical efficiencies and 30 percent solar-to-thermal efficiencies at design operating temperatures about 50°C (122°F). The daily average solar-to-thermal efficiency is about 40 percent as the fluid is heated from 20°C (68°F) to 60°C (140°F). during the operation.

The electric and thermal generation is estimated for the 16 California climate zones by assuming a 40 percent solar-to-thermal efficiency, an 18 percent solar-to-electric efficiency for the mass production SunPower model, and a 15 percent solar-to-electric efficiency for the mass production poly-crystalline model.

Each tube has an aperture area of 0.132 m^2 and therefore 7.6 tubes are required to scale up to a 1 m^2 aperture area. A performance ratio of 75 percent is assumed, so that only 75 percent of the generating capability of the module (both PV and thermal streams) actually contributes to generation. This accounts for cable, inverter, and PV losses as well as heat losses in an installed system.

The solar resource per climate zone is given in global horizontal irradiance. The electric and thermal generation in kWh/m^2/year are then calculated using the collector efficiencies.

The natural gas consumption avoided by the CHP collector is calculated as follows. The thermal generation component of the CHP collector is converted to therms. The electrical generation component of the CHP collector is multiplied by 3 to estimate the amount of natural gas used at the power plant to generate an equivalent amount of electricity. It is then converted to therms and added to the therms of natural gas offset by the thermal component of the CHP collector for a total NG reduction in therms/m^2/year.

The CO_2 emissions avoided by the CHP collector are calculated using the emission factors for kg CO_2 per therm of natural gas and kg CO_2 per kWh electric (Table 4) as provided in the solar

CHP cost calculator excel sheet (Table 5 & 6). Note these are also provided in California Energy Commission: GFO-16-502: Attachment 13-Energy Efficiency Data. Multiplying these values by the therms of heat and kWh of electric generation from the CHP collector yields a total kg of CO_2 avoided per m^2 per year.

Table 4: Emission Factor Assumptions

Emission Factor	Units	Value
Emission Factor ($CO_{2\text{-}e}$) Natural gas in California	kg/therm	5.3
Emission Factor ($CO_{2\text{-}e}$) electricity grid in California	kg/kWh	0.331

Source: UC Merced

Finally, a cost of 1 MMt CO2 avoided is calculated, assuming the module cost of the collector from Table 3 for the mass-production cost of the different collector models.

Table 5: Annual Generation, Emissions Reductions, and Cost Targets for the Mass-Production SunPower Model

Model: Mass-Production SunPower											
CA Climate Zone		Solar Resource	CHP - Electrical		CHP - Thermal		Avoided NG		Avoided Emissions	1 MMt CO2 Avoided Targets	
Climate Zone number	Area name	GHI (kWhr/day/m2)	Electric Generation (kWh/m2/year)	Electric Generation Therm Equivalent (therm/m2/year)	Thermal Generation (kWh/m2/year)	Therm Equivalent (therm/m2/year)	Total NG Reduction (therms /m2/year)	Total CO2 Emissions Reduction (kg/m2/year)	Total CO2 Emissions over 20 years (Ton CO2 /m2)	Required CHP collector area to avoid 1 MMt CO2 (m2)	Cost for 1 MMt CO2 avoided over 20 years ($)
1	Arcata	3.93	193.65	19.83	430.34	14.69	34.51	141.94	2.84	352,260.77	$ 44,863,577.13
2	Santa Rosa	4.64	228.64	23.41	508.08	17.34	40.75	167.58	3.35	298,358.80	$ 37,998,676.32
3	Oakland	4.63	228.14	23.36	506.99	17.30	40.66	167.22	3.34	299,003.21	$ 38,080,746.89
4	San Jose	4.96	244.40	25.02	543.12	18.54	43.56	179.14	3.58	279,109.85	$ 35,547,148.81
5	Santa Maria	5.19	255.74	26.18	568.31	19.40	45.58	187.45	3.75	266,740.82	$ 33,971,841.64
6	Torrance	5	246.38	25.23	547.50	18.69	43.91	180.59	3.61	276,876.97	$ 35,262,771.62
7	San Diego	5.09	250.81	25.68	557.36	19.02	44.70	183.84	3.68	271,981.31	$ 34,639,264.86
8	Fullerton	5.04	248.35	25.43	551.88	18.84	44.26	182.03	3.64	274,679.53	$ 34,982,908.36
9	Burbank	5.21	256.72	26.29	570.50	19.47	45.76	188.17	3.76	265,716.86	$ 33,841,431.50
10	Riverside	5.21	256.72	26.29	570.50	19.47	45.76	188.17	3.76	265,716.86	$ 33,841,431.50
11	Red Bluff	4.87	239.97	24.57	533.27	18.20	42.77	175.89	3.52	284,267.94	$ 36,204,077.64
12	Sacramento	4.91	241.94	24.77	537.65	18.35	43.12	177.34	3.55	281,952.11	$ 35,909,136.07
13	Fresno	5.23	257.71	26.39	572.69	19.55	45.93	188.89	3.78	264,700.74	$ 33,712,018.76
14	Palmdale	5.78	284.81	29.16	632.91	21.60	50.76	208.76	4.18	239,512.95	$ 30,504,127.70
15	Palm Springs	5.74	282.84	28.96	628.53	21.45	50.41	207.31	4.15	241,182.03	$ 30,716,700.02
16	Blue Canyon	4.98	245.39	25.13	545.31	18.61	43.74	179.86	3.60	277,988.92	$ 35,404,389.18
	Min	3.93	193.65	19.83	430.34	14.69	34.51	141.94	2.84	239,512.95	$ 30,504,127.70
	Average	5.03	247.64	25.36	550.31	18.78	44.14	181.51	3.63	277,508.10	$ 35,342,515.50
	Max	5.78	284.81	29.16	632.91	21.60	50.76	208.76	4.18	352,260.77	$ 44,863,577.13

Source: UC Merced

Table 6: Annual Generation, Emissions Reductions, and Cost Targets for the Mass-Production Polycrystalline Silicon Model

Model: Mass-Production PolyCrystalline Si											
CA Climate Zone		Solar Resource	CHP - Electrical		CHP - Thermal		Avoided NG		Avoided Emissions	1 MMt CO2 Avoided Targets	
Climate Zone number	Area name	GHI (kWhr/day/m2)	Electric Generation (kWh/m2/year)	Electric Generation Therm Equivalent (therm/m2/year)	Thermal Generation (kWh/m2/year)	Therm Equivalent (therm/m2/year)	Total NG Reduction (therms/m2/year)	Total CO2 Emissions Reduction (kg/m2/year)	Total CO2 Emissions over 20years (Ton CO2 /m2)	Required CHP collector area to avoid 1 MMt CO2 (m2)	Cost for 1 MMt CO2 avoided over 20years ($)
1	Arcata	3.93	161.38	16.52	430.34	14.69	31.21	131.26	2.63	380,931.39	$ 30,755,998.37
2	Santa Rosa	4.64	190.53	19.51	508.08	17.34	36.85	154.97	3.10	322,642.32	$ 26,049,800.34
3	Oakland	4.63	190.12	19.47	506.99	17.30	36.77	154.64	3.09	323,339.17	$ 26,106,063.41
4	San Jose	4.96	203.67	20.85	543.12	18.54	39.39	165.66	3.31	301,826.68	$ 24,369,168.06
5	Santa Maria	5.19	213.11	21.82	568.31	19.40	41.22	173.34	3.47	288,450.93	$ 23,289,224.20
6	Torrance	5	205.31	21.02	547.50	18.69	39.71	166.99	3.34	299,412.07	$ 24,174,214.72
7	San Diego	5.09	209.01	21.40	557.36	19.02	40.42	170.00	3.40	294,117.95	$ 23,746,772.81
8	Fullerton	5.04	206.96	21.19	551.88	18.84	40.03	168.33	3.37	297,035.78	$ 23,982,355.87
9	Burbank	5.21	213.94	21.90	570.50	19.47	41.38	174.01	3.48	287,343.64	$ 23,199,822.19
10	Riverside	5.21	213.94	21.90	570.50	19.47	41.38	174.01	3.48	287,343.64	$ 23,199,822.19
11	Red Bluff	4.87	199.97	20.48	533.27	18.20	38.68	162.65	3.25	307,404.59	$ 24,819,522.30
12	Sacramento	4.91	201.62	20.64	537.65	18.35	38.99	163.99	3.28	304,900.28	$ 24,617,326.60
13	Fresno	5.23	214.76	21.99	572.69	19.55	41.53	174.68	3.49	286,244.81	$ 23,111,103.94
14	Palmdale	5.78	237.34	24.30	632.91	21.60	45.90	193.04	3.86	259,006.98	$ 20,911,950.45
15	Palm Springs	5.74	235.70	24.13	628.53	21.45	45.58	191.71	3.83	260,811.91	$ 21,057,678.33
16	Blue Canyon	4.98	204.49	20.94	545.31	18.61	39.55	166.33	3.33	300,614.53	$ 24,271,299.92
	Min	3.93	161.38	16.52	430.34	14.69	31.21	131.26	2.63	259,006.98	$ 20,911,950.45
	Average	5.03	206.36	21.13	550.31	18.78	39.91	167.85	3.36	300,089.17	$ 24,228,882.73
	Max	5.78	237.34	24.30	632.91	21.60	45.90	193.04	3.86	380,931.39	$ 30,755,998.37

Source: UC Merced

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The success of this project has demonstrated the technical readiness of the technology for commercialization. The knowledge gained from this project has been made available in the following ways.

Publications

Project-related information will be made available to the public via the publication of peer-reviewed journals, conference papers, and chapters of student PhD dissertation and Masters Theses. This will allow both the academic community as well as prospective commercial partners and end-users to see data regarding the technical performance of the CHP collector. It will also give insight into the stages of prototyping which were undertaken over the course of this project, and the major learnings that resulted.

- Brinkley, J., Jiang, L., Widyolar, B. and Winston, R., 2018, September. Flowline analysis of eténdue transfer of a wide-angle solar concentrator. In Nonimaging Optics: Efficient Design for Illumination and Solar Concentration XV (Vol. 10758, p. 107580K). International Society for Optics and Photonics.
- (Pending) Widyolar, B., Jiang, L., Brinkley, J., Hota, S.K., Ferry, J., Hassanzadeh, A., Bhusal, Y., Durbin, R., Diaz, G., Winston, R., 2019. A Low-Cost, High-Efficiency Solar CHP (PV/T) System for Electricity, Hot Water, and Space Heating. Applied Energy
- (Pending) Hota, S.K., Brinkley, J., Widyolar, B., Hassanzadeh, A., Jiang, L., Winston, R., Diaz, G., 2019. Experimental Performance of a Hybrid PV/T Collector. Solar World Congress / Solar Heating & Cooling 2019 Conference. November. Santiago, Chile.
- (Pending) Brinkley, J., Widyolar, B., Jiang, L., Hota, S.K., Ferry, J., Bhusal, Y., Durbin, R., Diaz, G., Winston, R., 2019. ADvanced Optical Photovoltaic Thermal System (ADOPTS) Applied Energy

UC Solar Webpage

Project description located at the UC Solar website gives a brief synopsis of the project need and goals and directs the user to a press release located at the UC Solar website (https://news.ucmerced.edu/news/2017/new-uc-solar-project-produces-both-heat-and-power). Contact information located on the website gives the public an access point for further inquiry on the project.

UC Merced Press Release

A press release was released May 28, 2019 (http://bit.ly/2QCxgxr) which discusses the project, the technology, and its benefits.

Conference Presentations & Posters

Several presentations have and will be given at conferences and symposia (notably the International Solar Energy Society conference, Solar Heating and Cooling conference, annual SPIE photonics conference, the annual UC Solar symposium), with additional material presented in posters at other events. This allows for a much wider dissemination of project results to a number of stakeholders (utilities, commercial entities, entrepreneurs).

- "The Solar Thermal Energy Program at UC Merced," Dr. Roland Winston, UC Solar Symposium 2018, Conference presentation.
- Combined Solar Power and Heat for Electricity, Hot Water, and Space Heating - Ali Hassanzadeh, Bennett Widyolar, Jordyn Brinkley, Sai Phani Kiran, Lun Jiang, Roland Winston, University of California, Merced, UC Solar Symposium October 2018
- Novel Solar Hybrid System for Producing Heat and Electricity - Ali Hassanzadeh, Sai Phani Kiran Hota, Lun Jiang, Gerardo Diaz, Dr. Roland Winston, University of California, Merced, UC Solar Symposium October 2017

Site Visits

Prototype collector system will also be maintained outdoors for long-term operation and will be available for users to view during site-visits. This is to enable a long-term study and make the system available for further discussion of the project, challenges, and results. To date the operating demonstration has been shown to solar energy researchers from Spain and Chile, and to several Central Valley businesses and industries who require electricity and heat at about 60°C (140°F).

Stakeholder Engagement

The UC Merced research team has reached out to the California League of Food Producers to discuss the CHP collector and its potential for use in the food processing industry. The team has also connected with the Renewable Energy Test Center which oversees the standardized testing of PV modules.

Information resulting from this project can be used by: (1) commercial entities who may be interested in licensing the technology, (2) policymakers, and (3) researchers, and (4) interested end-users.

Near-term markets for the CHP technology are building owners and commercial businesses who require both electricity and heat. Within commercial buildings the health (hospitals, health care centers) and lodging (hotels) sectors have been identified as optimal candidates which have high electricity and thermal energy needs. Mid and long-term markets include the full residential and commercial building sectors.

Each year, residential buildings in California consume 72,422 GWh of electricity and 4 billion therms of natural gas, of which 86 percent used for space or water heating[13]. Commercial buildings consume an additional 67,077 GWh of electricity and 1.2 billion therms of natural

[13] KEMA, Inc. 2010. 2009 California Residential Appliance Saturation Study. California Energy Commission. Publication number: CEC - 200 - 2010 - 004 - ES

gas, with 68 percent used for space and water heating[14]. In total this is a consumption of about 5 billion therms of natural gas and 140,000 GWh of electricity each year. Meeting 100 percent of thermal energy demand will require more than 263 million square meters of collector and cost roughly $21 billion. This would eliminate nearly 1 million metric tons of equivalent CO2 emissions over a 20-year lifetime.

The cost of equivalent carbon reduction of this technology is cheaper than residential and commercial PV. Residential customers are often roof constrained for PV (the area of the roof that is oriented in an acceptable direction without significant shading is not enough to provide the electricity the customer wants). If the customer also wants solar thermal for their water use and/or their pool heating, the problem is even more severe. Therefore, it is very promising for the CHP technology which improves space utilization and provides both outputs.

At the culmination of the project, the UC Merced team is seeking a commercialization partner and is continuing to apply for funding to advance the solar CHP collector to the next stage of commercialization.

[14] California Commercial Saturation Survey, Prepared for the California Public Utilities Commission by Itron, Inc. 2014

CHAPTER 5: Conclusions and Recommendations

As a result of this project the technical potential of the proof-of-concept solar CHP collector prototype has been confirmed. The solar CHP collector generates 150 WDC (Direct Current Watts) electricity and 400 $W_{thermal}$ per square meter. The collector reaches a maximum temperature of 93°C (199°F). A single square meter of collector can heat 25 gallons of water to 60°C (140°F)by the end of the day. Experimental thermal and electric efficiencies are approximately 86 percent of the initial model. This is largely the result of a non-100 percent packing factor of the solar cells over the thermal absorber, however, improving this would be easy to implement in the next generation and especially with any form of production line. These high-performance metrics, when combined with the low production costs determined by a bottom-up cost analysis, yield a very low cost for carbon reductions. Based on our analysis the solar CHP system installed in California will reduce GHG emissions at a cost of $24/metric ton CO_2. At an estimated mass-production cost of $81/$m^2$, a module would cost $0.54/WCD, compared to $0.47/WDC for the 2018 residential PV benchmark. This is an important result as it means this solar CHP collector could be installed for only slightly more than existing PV panels.

The UC Merced team believes that such cost metrics are sufficient enough to merit further pursuit of this technology which has a high potential for being cost competitive with residential PV. It is much more likely to enjoy adoption on a similar scale to residential PV which is unprecedented compared to existing solar CHP technologies. Without incentives, the solar CHP collector should have a simple payback time on the order of seven years in a residential scenario. In a commercial setting where balance of system (BOS) costs are a smaller fraction of the total installed system cost and with incentives the simple payback times should be much less. As a result, this technology can provide significant value to customers, and demonstrates significant value for policymakers who are looking for technologies with low cost carbon emission reductions.

Some additional research and development is necessary to improve the technology maturity to commercial readiness. The materials and construction of the solar cell / thermal interface should be optimized and undergo accelerated testing to confirm that it maintains electrical isolation, high thermal conductivity, and stability over a 20+ year lifetime. In addition, optimization of the solar cell subassembly could be performed to improve the electrical performance and rate of manufacturing success. In the prototypes, approximately 5% of the solar cell array is deactivated due to the cutting process. At a large scale, however, the supplier has indicated it would be possible to produce custom cells to eliminate this issue. Furthermore, in its current stage there are a significant number of connections to be made for such a small solar cell area. When manufactured by hand, this is a long and arduous process and a small error may destroy an entire string or tube. Improvements to this process should be made through the introduction of machinery and automation. The UC Merced research team is now actively seeking funding to (1) confirm stability of the solar cell / thermal absorber interface over 20+ year lifetime and (2) optimize the assembly procedure with the assistance of machinery and automation.

CHAPTER 6: Benefits to Ratepayers

This solar CHP technology is lightweight, modular, and scalable. It can be installed on residential, commercial, or industrial rooftops to provide electricity and thermal energy for space or water heating up to 60°C (140°F). Each square meter installed in California will save the end-user a total of $56 each year in energy costs[15]. The module cost for a square meter is approximately $81/m^2. This results in a module-based simple payback time of about 1.4 years. Today, module costs account for only about 17 percent of the total investment cost for residential PV systems, and 26 percent for commercial PV systems (Fu et al. 2018). Using this as a guide, a full install of the solar CHP collector should pay back in 5-8 years.

Annually each square meter installed in California will generate an average 205 kWh of electricity and 547 kWh (19 therms) of heat, reducing natural gas consumption (locally and at power plants) by 1163 kWh (40 therms), and eliminating 167 kg of CO_2 emissions. Over a 20-year lifetime, the estimated investment cost for GHG savings is approximately $24/metric ton of avoided CO_2. Achieving 1 million metric tons of avoided CO_2 emissions over a 20-year lifetime will require 265,565 square meters of CHP collector installation and will cost approximately $24 million.

Successful deployment of solar CHP technology will result in the ratepayer benefits of lower costs, increased safety, reduced natural gas consumption, reduced GHG emissions, and enabling ZNE buildings, as follows:

- Lower costs: System affordability is a key ratepayer benefit. The proposed solar CHP system offers the potential to provide sufficient thermal energy to meet building hot water and space heating needs while also providing distributed electricity generation. With a projected module cost of $81 per square meter, the system would generate the same amount of electricity per square meter as a standalone rooftop PV)panel, with an additional amount of thermal energy per square meter as a standalone rooftop thermal panel.
- Increased safety: By reducing building natural gas and electricity consumption, solar CHP systems will reduce California's dependence on natural gas infrastructure, while also reducing the need for large-scale transmission and storage.
- Reduced natural gas consumption: Each installed per square meter of the proposed solar CHP system should reduce total natural gas consumption by approximately 40 therms in California.
- Reduced GHG emissions: By reducing both the natural gas consumption used by typical water and space heaters, as well as grid-supplied electricity generated by natural gas, the proposed system should offset 0.17 metric tons of equivalent CO_2 emissions annually per installed square meter.

[15] For 5 kWh/m2/day average California solar resource, natural gas cost of $1/therm, and electricity cost of $0.18/kWh.

- Enabling ZNE buildings: Given the amount of natural gas used in California's buildings for hot water and space heating, and in the electrical grid for energy generation, it will be challenging to meet California's aggressive GHG-reduction goals without the introduction and large-scale adoption of distributed solar CHP technologies like the one described in this project.

When commercialized, this system will be a reliable and cost-effective choice for reducing natural gas consumption and increasing electricity reliability in single and multi-family residential, commercial, institutional, and industrial building sectors. System affordability, and the ability to take advantage of solar PV and thermal incentives, should accelerate system payback time and make the solution attractive in all geographic areas—including disadvantaged communities. Used on a large scale, the solar CHP collector can significantly reduce emissions locally and at natural gas-fired power plants and contribute to cleaner air quality across the state.

The success of this project has proven the technical viability of the CHP collector concept. At this stage it is very near commercial readiness. The main areas for further study are:

- Addition of low-cost reflector panels between tubes can increase outputs almost 30%
- Improved material and component testing needed to ensure longevity of adhesive and solar cell / mini-channel interface
- Development of a production line with fully or semi-automated cell cutting, stringing, soldering, and application.

LIST OF ACRONYMS

Term	Definition
A	Ampere is a unit to measure electric current
CHP	Combined Heat and Power
PV	Photovoltaic
PV/T	Photovoltaic/ thermal
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
UCM	University of California Merced
ZNE	Zero Net Energy
WDC	Direct Current Watts is an electric power unit to measure solar system size.

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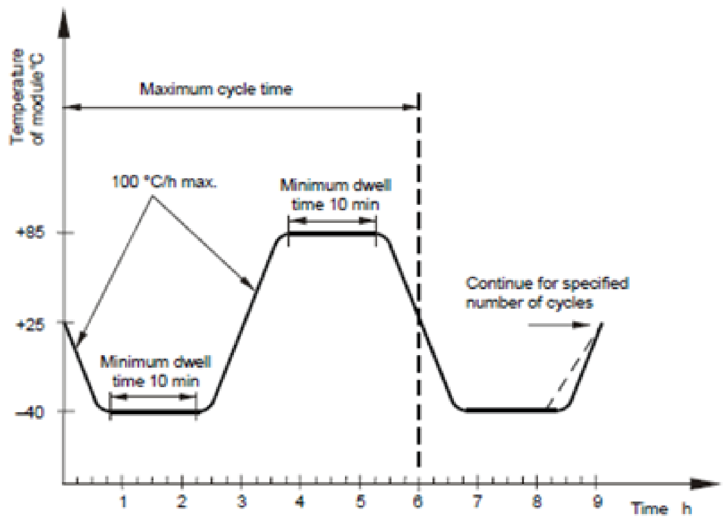
APPENDIX A: Accelerated Temperature Cycling and Hail Testing

Accelerated temperature cycling and hail testing was performed by the Renewable Energy Test Center (RETC) in San Jose, CA on two sample tubes. The tests and results are described in Figure A-1 and Figure A-2 below. Temperature cycling was performed between -40°C and approximately 90°C at an average rate of six cycles per day. Twenty cycles in total were performed, after which the tube was returned and tested at UC Merced.

Figure A-1: Temperature Cycle Profile



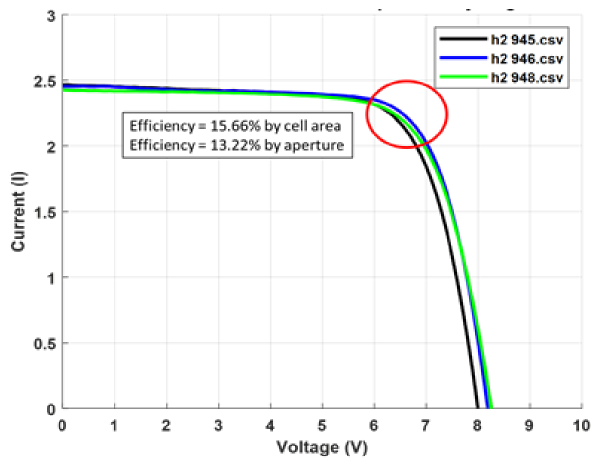
Source: Renewable Energy Test Center (RETC)

Figure A-2: Heat Pipe Tube Sent to RETC for Thermal Cycle Testing

Source: Renewable Energy Test Center (RETC)

After testing, there was no evidence of any damaged circuitry or visual deformation of the tube noticed by Renewable Energy Test Center. Upon being returned to UC Merced, the tube (designated H2) was taken outside on May 9, 2019 under clear sunny conditions and its electrical performance was measured using an IV curve tracer. The results for three consecutive tests are shown in the IV curves (Figure A-3). The average efficiency by cell area was 15.66 percent and 13.22 percent by aperture, indicating normal operation of the tube. Therefore the tube is capable of withstanding sub-zero atmospheric temperatures and thermal cycling up to 90°C (the stagnation temperature of the tube) for at least 20 cycles without degradation.

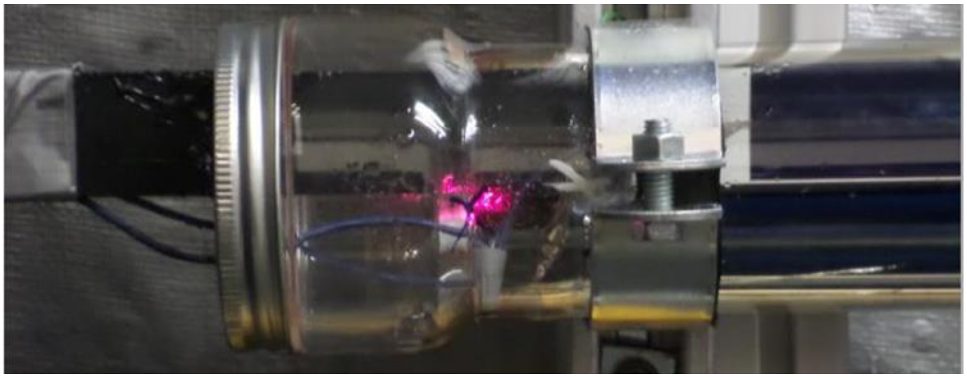
Figure A-3: IV Curve Trace of Tube after Thermal Cycling



Source: UC Merced

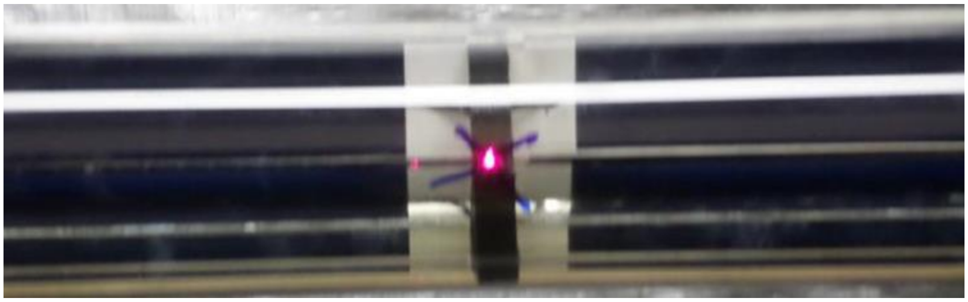
Hail testing was also performed by the Renewable Energy Test Center (RETC). The test and results are summarized here, as well as in the attached Renewable Energy Test Center report. A nominal 1" diameter ice ball (~8 gram) was shot at a velocity of 23 m/s at three locations (top, middle, bottom) on a sample tube as shown in the Figure A-4, Figure A-5 and Figure A-6.

Figure A-4: Laser Point of First Hail Test Location (top)



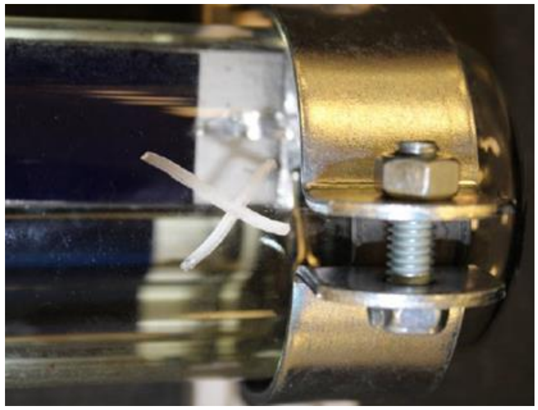
Source: Renewable Energy Test Center (RETC)

Figure A-5: Laser Point of Second Hail Test Location (middle)



Source: Renewable Energy Test Center (RETC)

Figure A-6: Third Hail Test Location (bottom) Designated by the X



Source: Renewable Energy Test Center (RETC)

After testing there was no indication of faulty circuitry or visual degradation observed by the Renewal Energy Test Center, indicating a PASS of the hail testing. The tube has been returned to UC Merced.