CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Manufacturing Scale-up of Record-Breaking Solid-State Heat Engine for Deep Decarbonization in California

February 2024 | CEC-500-2024-011

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Acknowledgements

Antora Energy is very grateful for the support of Antora's Commission Agreement Manager, Anthony Ng, and everyone else at the CEC. Antora's operational TPV fabrication facility would not have been possible without CEC. Antora Energy also acknowledges the support of the Advanced Research Projects Agency–Energy for providing sustained financial support that has been crucial in getting Antora to the position it is in today.

The research team would like to further acknowledge the support of the Technical Advisory Committee (TAC), namely Professor Sarah Kurtz, Dr. Jose Corbacho, and Mr. Stephen Horne. The TAC provided valuable insight into reliability test programs, working toward product bankability, and system techno-economics, within the scheduled TAC meetings as well as in emails and other communications outside of those meetings.

The team acknowledges the support of our suppliers. The team would also like to acknowledge the support of the consultants and contractors who assisted on this project.

The team further acknowledges the contributions made to this project by former Antora Energy employees and interns, including Alex Young, Amy Chi, Anna Clark, Remy Dennis, Matías Filloy, Scott Lambert, Tuheen Manika, Mateo Massey, JD Pruett, Rajagopalan Ramesh, D'Arcy Seamon, Robert Stallman, and Emily Stein. Last, but certainly not least, the research team acknowledges the entire team at Antora Energy for contributing to and supporting this project in many large and small ways.

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 EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities — Pacific Gas and Electric Company, San Diego Gas and 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.

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

ABSTRACT

Antora Energy has developed a new type of solid-state heat engine that is a critical tool in achieving a reliable, affordable, and zero-carbon energy system in California. The operation of Antora's thermophotovoltaic (TPV) heat engine is similar to that of a solar photovoltaic panel; it converts electromagnetic radiation directly into electricity.

Production and deployment of Antora's TPV-enabled thermal batteries will improve both ratepayer safety and electricity reliability. They will enable faster deployment of energy storage systems to power communities during public safety power shutoff events, which will reduce the risk of catastrophic wildfires without endangering vulnerable populations; and, given their extremely low capital and operating costs (Antora's storage medium, carbon blocks, are ~50x cheaper than traditional battery materials), they can provide safe, reliable, and inexpensive electricity storage to support deeper penetrations of renewables on the California grid — helping the state meet the state's statutory energy goal of 100 percent renewable retail electricity by 2045.

Antora Energy's purpose in conducting this project was to demonstrate Manufacturing Readiness Level (MRL) 8 for these TPV heat engines by building a low-rate initial production pilot production (LRIP) line for TPV cells. The production goal was a capacity of at least two megawatts (MW)/year. To achieve this goal, the TPV cell fabrication had to be performed with batch processing of full wafers, and the TPV cell characterization had to be automated.

We have scaled up our equipment and processes to a production line with a 2 MW/year capacity and demonstrated MRL 8. Also, during the project, the team confirmed a diversified, robust, and qualified supply chain for TPV manufacturing at and above the LRIP.

Keywords: Long-duration Energy Storage, Thermophotovoltaic Heat Engine, Thermal Batteries, TPV Converter, Low-Rate Initial Production (LRIP), Full-Wafer TPV Fabrication

Please use the following citation for this report:

Kayes, Brendan, Haley Gilbert, Tarun Narayan, David Bierman, Sally Espiritu, Amit Gupta, Ben Johnson, Leah Kirkland, Leah Kuritzky, Moritz Limpinsel, Cece Luciano, Dustin Nizamian, Emmett Perl, John Perna, Andrew Ponec, Rubén Rodríguez Lopez, Ry Storey-Fisher, Jason Tolentino, Geordie Zapalac, and Justin Briggs. 2024. *Manufacturing Scale-up of Record-Breaking Solid-State Heat Engine for Deep Decarbonization in California*. California Energy Commission. Publication Number: CEC-500-2024-011.

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Executive Summary

Background

Antora Energy has developed a new type of solid-state heat engine that unlocks multiple renewable energy applications critical to achieving a reliable, affordable, and zero-carbon energy system in California and beyond. Antora's low-cost, zero-maintenance thermophotovoltaic (TPV) heat engine operates like a solar photovoltaic panel; it converts thermal electromagnetic radiation directly into electricity with high efficiency. Antora has leveraged funding from the U.S. Department of Energy, the National Science Foundation, and private investors, as well as partnerships with the National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, and the University of California Santa Barbara to develop a prototype TPV converter with higher efficiency than any other type of solid-state heat engine. This TPV converter has the potential to outperform all other heat engines, including internal combustion engines and steam- or gas-combustion turbines.

Antora's TPV heat engine supports multiple applications. These include a thermal battery that will enable a low-cost, zero-emissions public safety power shutoff solution while supporting deep decarbonization on the California grid. Further, Antora's potential customers have expressed interest in directly purchasing Antora TPV converters, including customers in concentrating solar power, high-efficiency residential and commercial furnaces, industrial waste heat recovery, bioenergy, and unmanned aerial vehicles. However, Antora's current production capacity limits Antora's ability to deliver products to these customers. This project helps Antora scale up the TPV manufacturing to a low-rate initial production (LRIP) pilot plant to meet demand for TPV in Antora's thermal batteries and other applications.

Project Purpose and Approach

Antora's objective is to build an LRIP pilot line in California that has a capacity of 2 megawatts of TPV cells per year, thus demonstrating Manufacturing Readiness Level (MRL) 8. This target initial production rate was chosen based on current customer demand. MRL is assessed by examining many factors, including production variability, performance, and yield compared with similar materials produced by a supplier, supply chain maturity, staff, as well as equipment risks. Production capacity is assessed by comparing the time to complete key process steps in the manufacturing sequence with the takt time — that is, the process time required to achieve Antora's manufacturing capacity target. Performance and yield were assessed by measuring several standard characteristics of photovoltaic performance, including current-voltage curves, external quantum efficiency, and reflectance, and by extracting relevant figures of merit from these data, for example, TPV efficiency.

Key Results

The primary key result from this work is the demonstration of an LRIP-capable production line for TPV cells. The production line is located in Silicon Valley, California — a strategic location with a strong network of workforce, suppliers, and services for semiconductor materials processing. These regional advantages provide a platform for further cost reductions in TPV cells, which will enable Antora Energy to be the world leader in TPV manufacturing for both its thermal batteries as well as supplying external customers. Antora's site is the world's first dedicated manufacturing line for TPV cells.

This project specifically completed the following three technical tasks.

Thermophotovoltaic Cell Full-Wafer Process: Prior to this work, Antora TPV cells were typically processed on wafer fragments that fit only four cells per fragment. This wafer-fragment process substantially increased the labor hours and costs per cell and limited throughput. Semiconductor materials are typically manufactured in the form of full wafers — circular discs of semiconductor material that are subsequently patterned and formed into arrays of devices, that is, "cells." Antora's first step toward an LRIP manufacturing line was developing a full-wafer TPV fabrication process and demonstrating that TPV cells from the LRIP line achieved performance parity with TPV cells from Antora's previous wafer-fragment process. The project team successfully converted Antora's wafer-fragment process to a full-wafer process, which enables the use of standardized and automated equipment and higher production throughput.

Thermophotovoltaic Cell Fabrication and Characterization Toolset: The team then specified, ordered, and installed the required wafer fabrication equipment and developed a method to run the full-wafer process at Antora's facility in Sunnyvale, California. To support TPV performance characterization for the full-wafer process, the team also specified and ordered a custom characterization tool that will enable high throughput measurement of the finished TPV cells.

Low-rate Initial Production of Thermophotovoltaic Cells: The team has performed all the full-wafer process steps on Antora's new fabrication tools and has demonstrated process takt times that meet or exceed Antora's 2 megawatt per year requirement. As part of this task, the team prepared a final *Low-Rate Initial Production Demonstration Report* that discusses the details of tools and process flow and demonstrates sufficient process stability to begin LRIP.

These results demonstrate that:

- The materials, staffing, tooling, test equipment, and facilities are sufficient to meet the planned LRIP; manufacturing and quality processes and procedures have been proven, are under control, and are in active production.
- Known producibility risks pose no significant challenges for LRIP, which documents the qualification of the supply chain for TPV cell manufacturing.
- Antora's supply chain is qualified for TPV cell manufacturing.

Knowledge Transfer and Next Steps

The team already used the LRIP capability developed in this project to produce market-ready TPV cells. Antora sees broad value in these devices for a range of applications. In future work, the team will seek to continue to drive down the cost of TPV manufacturing using this fabrication capability, which will further expand the market for TPV applications.

To support scientific knowledge transfer within the industry, Dr. Brendan Kayes (Principal Investigator) served on the Program Committee for the 14th World Conference on Thermophotovoltaic Generation (TPV-14) in 2023. Through this platform, there was a mutual exchange of ideas regarding future research and development and manufacturing directions for TPV development and deployment.

In the future, research should focus on cost reductions in TPV cell manufacturing processes, efforts to make these processes compatible with existing manufacturing processes and equipment, integration of TPV cells into modules and products, additional technoeconomic analysis, and additional customer research to better understand the pain points of the users of TPV devices.

Benefits to California

A successful LRIP line of Antora's TPV devices and their deployment in Antora's thermal batteries will provide considerable benefits to investor-owned utility ratepayers while helping surmount major barriers to achieving California's statutory energy goals.

- *Ratepayer safety and electricity reliability will simultaneously be improved* — An LRIP line of TPV cells will enable faster deployment of energy storage systems that will power communities during PSPS events, which will reduce the risk of catastrophic wildfires without endangering vulnerable populations by shutting off their power completely.
- *Costs to ratepayers will be reduced* — Antora's TPV-enabled thermal batteries have extremely low capital and operating costs and are one of the lowest-cost options for

providing long-duration power during PSPS events. In addition, they can provide valuable, year-round grid services outside of PSPS events.

In the near term, these safety, reliability, and cost benefits will be realized by cost-effectively enabling safer, less-disruptive PSPS events. Over the longer-term, Antora's thermal batteries will provide safe, reliable, and inexpensive electricity storage to support deeper penetrations of renewables on the California grid and help the state meet the goals of Senate Bill 100.

The ultimate results of deployment of Antora's products will be:

- Improved local air quality (in disadvantaged communities and beyond) through the elimination of over 100 kilotons (kt) of nitrogen oxide (NO_x) emissions and substantial reductions in carbon monoxide and particulates.
- Substantial job growth and new economic opportunities in the energy sector.
- Increased reliability and resiliency of California's energy infrastructure.
- Elimination of nearly 26 million metric tons of carbon dioxide annually in California alone.
- A clear path — for the first time — to reaching 100 percent carbon-free electricity by 2045.

CHAPTER 1: Introduction

Antora's thermal battery consists almost entirely of standard industrial materials and components with well-established supply chains. The only novel component that has not yet been produced at massive scale is the thermophotovoltaic (TPV) cell itself. The emergence of the public safety power shutoff (PSPS) market — as well as other major markets demanding TPV cells today — has created an urgent need to reach commercial readiness. Commercial availability will also enable key energy and emissions benefits in California and around the globe. Funding support from the California Energy Commission (CEC) to scale Antora's TPV manufacturing to the LRIP stage will allow Antora to meet these immediate market needs and serve as a launching pad towards much larger-scale production.

Benefits for California: A successful LRIP line of Antora's TPV devices and their deployment in Antora's thermal batteries will provide considerable benefits to investor-owned utility ratepayers while helping surmount major barriers to achieving California's statutory energy goals.

- *Ratepayer safety and electricity reliability will simultaneously be improved* — An LRIP line of TPV cells will enable faster deployment of energy storage systems that will power communities during PSPS events, which will reduce the risk of catastrophic wildfires without endangering vulnerable populations by shutting off their power completely.
- *Costs to ratepayers will be reduced* — Antora's TPV-enabled thermal batteries have extremely low capital and operating costs and are one of the lowest-cost options for providing long-duration power during PSPS events. In addition, they can provide valuable, year-round grid services outside of PSPS events.

In the near term, these safety, reliability, and cost benefits will be realized by cost-effectively enabling safer, less-disruptive PSPS events. Over the longer-term, Antora's thermal batteries will provide safe, reliable, and inexpensive electricity storage to support deeper penetrations of renewables on the California grid and help the state meet the goals of Senate Bill 100.

The need for long-duration storage in the coming decades will be immense. Consistent with other state and national analyses, Strategen Consulting has found that **40 gigawatts (GW) of long-duration storage will be required to meet California's goal of carbon-free electricity by 2045, and that this storage will result in $1.5 billion per year of savings for California ratepayers**. This staggering number is almost double California's current average statewide power usage of approximately (~) 23 GW. The lack of a storage technology to meet this need is a tremendous barrier to achieving California's statutory energy goals. By successfully scaling up the manufacturing of Antora's core TPV technology, Antora will be poised to deploy thermal batteries across the state at ultra-low cost, thus surmounting this barrier and supporting the deep decarbonization of the electricity sector at the lowest possible cost to ratepayers. Selling standalone TPV converters into additional markets — including concentrating solar power, bioenergy, micro-combined heat and power, industrial waste heat recovery, and unmanned aerial vehicles — will further reduce emissions, improve air quality, and reduce costs for Californians.

The ultimate results of deployment of Antora's thermal batteries will be:

- Improved local air quality (in disadvantaged communities and beyond) through the elimination of over 100 kilotons (kt) of nitrogen oxide (NO_x) emissions and substantial reductions in carbon monoxide and particulates.
- Substantial job growth and new economic opportunities in the energy sector.
- Increased reliability and resiliency of California's energy infrastructure.
- Elimination of nearly 26 million metric tons of carbon dioxide annually in California alone.
- A clear path — for the first time — to reaching 100 percent carbon-free electricity by 2045.

CHAPTER 2: Project Approach

Research Objectives

The purpose of this project was to design and build out an LRIP pilot production line for TPV cells that convert thermal radiation into electricity, with a capacity of at least 2 megawatts (MW)/year. The TPV cells are combined with inexpensive, high-temperature thermal storage media to produce a cost-effective long-duration energy storage (LDES) system. The team defined production capacity in terms of a target for individual process takt times. Antora's definition accounted for TPV cell yields of less than 100 percent as well as the fact that some production tools perform multiple processing steps. The input to the pilot line is thin-film III/V foils, and the output of the pilot line is that same III/V foil form factor processed into TPV devices.

Overall Approach

The project was divided into three technical tasks: TPV Cell Full-Wafer Process (Task 2), TPV Cell Fabrication and Characterization Toolset (Task 3), and Demonstration of LRIP of TPV Cells (Task 4).

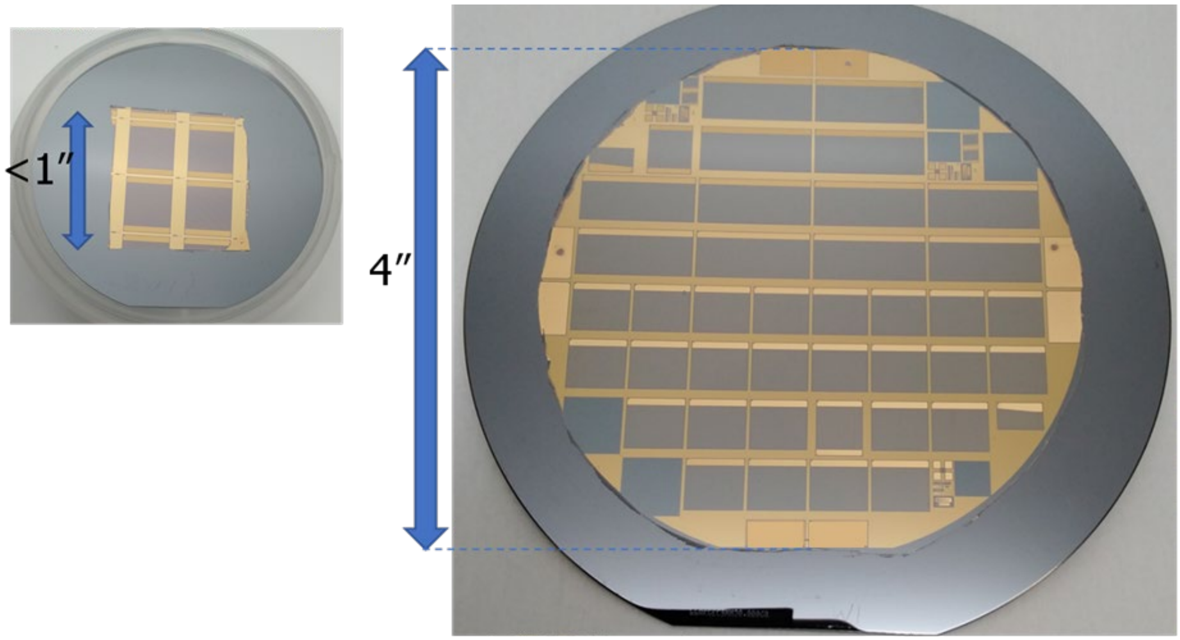
Task 2: TPV Cell Full-Wafer Process

Full-Wafer Process Development: The critical first step in achieving a TPV LRIP capability is to convert Antora's wafer-fragment process up to a full-wafer process. The benefits of this conversion include:

- A more than 10x increase in the number of TPV cells per process step, which improves equipment and labor efficiency and improves statistics when evaluating new designs.
- Compatibility with automated fabrication tools, which increases the processing throughput and is a pre-requisite to even larger batch sizes in future cassette-to-cassette processing.
- Elimination of wafer cleaving and the associated particle generation that typically results in reduced cell yield.

Figure 1 shows the results of Antora's full-wafer process. Antora's previous wafer-fragment process (left) yields only 4 TPV cells per processing step. The full-wafer process (right) allows the use of a 4-inch-diameter III/V film, which keeps the fabrication area out of the standard “keep-out” zone around the edge of the wafer. The larger format increases the number of TPV cells by more than 10 times.

Figure 1: Example of How a Full-wafer Process Enables More Devices per Processed Unit



This increases labor efficiency and production capacity, and it enables a more controlled comparison between different device layouts through the same process (for example, note the variety of TPV cell layouts in the right-hand image).

Full-Wafer Process Flow: The wafer example in Figure 1 forms the basis for the full-wafer fabrication and characterization process flow. This process flow is the basis for Antora’s LRIP design estimates in Task 3 and for Antora’s scale-up to LRIP on standardized and automated equipment in Task 4.

Task 3: TPV Cell Fabrication and Characterization Toolset

Daily Production Requirements: To reach Antora’s 2 MW/year capacity production target, the team made assumptions (updated since the 3.2 TPV Cell Toolset Plan) on TPV cell electrical power densities and yields per wafer that are conservative estimates based on demonstrated production. Further, the team assumes:

- All process stations are operated simultaneously.
- Tool downtime is minimal.
- The time to move lots between tools is minimal.

Under these assumptions, Antora's LRIP system must process approximately 40 wafers per day to achieve 2 MW/year capacity.

Process Tooling Requirements: Each of the processes is performed by a specific fabrication tool, with some tools being used more than once. Knowing the required throughput of the line allowed us to specify minimum required throughputs of each tool.

Characterizing TPV devices in high-volume manufacturing: Antora uses multiple self-consistent methods to measure thermophotovoltaic (TPV) efficiency. TPV efficiency differs from solar photovoltaic (PV) efficiency in one fundamental way. The solar PV radiation environment is essentially "open," and light below the bandgap is simply lost, which corresponds to a reduction in efficiency. In TPV, the thermal radiation source is enclosed. Thermal radiation below the bandgap is reflected back to the emitter, where it is absorbed, thermalized, and re-emitted. Conservation of energy requires that $Q_i - Q_e = P + Q$, where: P is the electrical power produced; Q_i and Q_e are the thermal radiation power incident on and re-emitted by the TPV cell, respectively (with the latter then incident on the emitter); and Q is the heat ultimately rejected to ambient temperature by the TPV cell. Under these enclosed conditions, the TPV cell efficiency is the electrical power produced, P, divided by net thermal radiation absorbed, (Q_i-Q_e), that is,

$$\eta_{TPV} = \frac{P}{Q_i - Q_e} = \frac{P}{P+Q}, \qquad (1).$$

Task 4: Demonstration of LRIP of Thermophotovoltaic Cells

Having verified Antora's processes on the toolset, the team was then able to track the time taken for each process step and compare it against the takt time required to achieve a capacity of 2 MW/year. The team measured the time taken for each step and sub-step in the fabrication process across eight process lots, varying in size from two wafers to eight wafers in the lot. Characterization was performed via the methods described in the 3.3 report, and in the future will be performed with a new High Throughput Characterization Tool.

With the data in hand to account for the process time for each sub-step of each lot, the takt time per wafer for each sub-step as a function of lot size could be calculated. Some tools need to be used twice for this process. The team therefore calculated the maximum allowable process times per wafer per step.

These numbers assume 4-inch device wafers. By comparing measured takt time against the maximum allowable takt time, the team could determine whether a capacity of 2 MW/year had been achieved.

CHAPTER 3: Results

Summary

During this project, the team:

- (Task 2) Transferred the TPV cell fabrication process from wafer fragments to full wafers, with no loss in performance.
- (Task 3) Specified, purchased, installed, and used a toolset in Antora's facility in Sunnyvale, California to run the full-wafer process and produce TPV cells with the same performance level.
- (Task 4) Quantified the takt time of each process step and demonstrated a capacity for running the TPV cell process of more than 2 MW/year in Antora's facility.

Each of these results is discussed in more detail in the subsections below.

Task 2: TPV Cell Full-Wafer Process

TPV Cell Performance and Yield — Full-wafer Versus Wafer-fragment Process

The data from cells tested in Task 2 (including yield, Open-circuit voltage (V_{OC}), Voltage at maximum power point (V_{MPP}), Fill factor (FF), median Series resistivity (R_S), and Below-bandgap reflectivity (R_{BBG})) demonstrated that Antora's new full-wafer process can produce cells with high yield and high performance relative to the previous wafer-fragment process.

Processing Improvements, Barriers, and Lessons Learned

Scaling up Antora's wafer-fragment process to full-wafer processing involved scaling up the area of the process steps, which required some changes to the fixturing and labware. None of these changes were conceptually challenging. More subtle challenges arose in process steps where the change in area resulted in a change in the requirements or outcomes of a given process. Data collected as part of Task 2 yielded important insights on uniformity and bonding that Antora has incorporated into its production process.

Task 3: TPV Cell Fabrication and Characterization Toolset

Fabrication Equipment Selection

The team engaged with multiple consultants to help the team select a toolset and specific vendors, brands, and models that would fit Antora's throughput requirements and budget constraints. The consultants had deep experience in equipment engineering, selection, installation, and maintenance, as well as cleanroom construction and management, and process development.

Antora’s considerations for tool selection included:

- Minimum throughput/capacity requirements — with a preference for higher levels of automation, when needed, to improve labor efficiency.
- Budget constraints for the total toolset, as per the CEC RAMP agreement — with a preference for used and refurbished tools, with refurbishment done by the original equipment manufacturer (OEM) when possible.
- California-based vendors per CEC requirements.
- Warrantied tools, with a preference for OEM warranties.
- Vendors located or with operations in the San Francisco Bay Area to simplify service visits.

Characterization Equipment Selection

To enable high throughput measurements of the cells, the team specified and ordered a custom high-throughput characterization tool. The measurements from this tool yield parameters that allow for the calculation of TPV efficiency.

Site Selection

In April 2021 the team executed a lease on Antora’s current headquarters at 1244 Reamwood Avenue in Sunnyvale, California with a move-in date of June 1, 2021. The previous tenant of this location was Akamai Solar, and the cleanroom here has been used for prototyping copper indium gallium diselenide (CIGS) solar panels. Prior to that, the site was occupied by EnerVault Corporation and Unidym, Inc., among others. The facilities work was fast-tracked by the prior existence of much of Antora’s needed facilities infrastructure.

Sunnyvale was a strategic choice for the team, as it is: central compared with where many of Antora’s employees were already living; convenient to many of the capital equipment and consumables vendors the team works with (in the “heart of Silicon Valley”); and a convenient location for attracting talent with appropriate backgrounds in the semiconductor industry for future hires.

Tool Installation

The team worked with various local consultants on facility layout, facility upgrades, and Sunnyvale permit planning. The team also opened a new position for a Director of Facilities and Equipment, hiring John Perna for this role starting August 9, 2021.

Comparison of TPV cells — Antora's LRIP Toolset Versus Control Toolset

Prior to development of Antora's LRIP full-wafer process in Sunnyvale, the TPV cells were manufactured by one of Antora's suppliers. In the fourth quarter of 2022, the team tested the performance of Antora's LRIP toolset by comparing several figures of merit for TPV cells produced on the LRIP toolset with the "controls" — TPV cells produced by Antora's supplier. In this test, the fabrication of the control TPV cells was fully done by this supplier.

Quantitative TPV Assessment of TPV Cell Performance

Samples were quantitively assessed by using a "1-sun light" current-voltage (I-V) mapping tool to measure the TPV cell's current-voltage. In the long term, the team will replace this 1-sun test with the high throughput tool.

The Antora frontside process produces yielding cells with I-V parameters that are generally very similar to those produced by the control process, demonstrating the quality of the Antora process.[1] While there is room for continued performance and yield improvement in Antora's Sunnyvale process, the fact that the team has achieved comparable performance (and a slightly better yield) at Sunnyvale than with the controls gives the team confidence that the process is ready to ramp up.

Discussion of Available Component Suppliers or Associated Partners

During this project the team has prioritized equipment suppliers local to the San Francisco Bay Area. Fortunately for Antora, the San Francisco Bay Area has no shortage of manufacturing expertise, particularly on the LRIP or prototyping scale. The characterization tools are the only examples of vendors where the team had to look beyond California, or even beyond the Bay Area. As a result, the team enjoys rapid response service for all Antora's CEC RAMP equipment, often from the OEMs themselves.

[1] Note that V_{OC} is a function of illumination light intensity and will typically be at least 100 millivolts (mV) higher in the hundreds-of-suns equivalent conditions in Antora's thermal battery.

Task 4: Demonstration of Low-Rate Initial Production of Thermophotovoltaic Cells

Antora measured takt times for all the steps in the process across eight lots, ranging in size from two to eight wafers per lot. While not all lots achieved the takt time goal for all steps, sufficiently low takt time was observed for lots of six wafers or more. All steps tend to have a larger takt time with smaller lots, as there is set-up and shut-down time associated with beginning and ending the process step. This effect is particularly severe for very long batch process steps, where the process takes the same amount of time independent of the number of wafers in the batch. In production, the team would intend to run larger lot sizes than those tested, and therefore in production the team would anticipate takt times equal to or lower than those the team saw in 6-8 wafer lots. Taking this assumption and the measured takt time data, the team asserts that **Antora's line has demonstrated > 2 MW/year capacity.**

Note that a 6-inch foil can hold more than twice as many devices as a 4-inch foil. Therefore, the capacity of Antora's LRIP line will more than double when the team transitions from 4-inch wafers to 6-inch wafers, as the team intends to do in the future.

Table 1: Project Performance Metrics

Performance Metric	Benchmark Performance	Performance at Project Start	Low Target Performance	High Target Performance	Achieved during this project
MRL	7	7	8	9	8
LRIP pilot line nameplate capacity (MW/yr)	0.01	0.01	2	10	>2
LRIP TPV cell yield	Unknown	N/A	50%	80%	>75%
TPV cell median R_S (mΩ cm^2)	<100	<50	<40	<5	5
TPV cell median R_{BBG}	80%	>90%	>90%	>95%	95%

Discussion

Herein (as well as in the Task 3.3: TPV Cell Fabrication and Characterization Toolset Report) the team demonstrated that Antora materials, equipment, and facilities are proven and are available to meet the planned LRIP.

In running the trial lots required to demonstrate Antora's tool capacity, the team found Antora tools and processes to be sufficiently stable to enter LRIP. Furthermore, Antora yields indicate processes that are under control and ready for LRIP production (see also Task 3.3: TPV Cell Fabrication and Characterization Toolset Report).

During the course of this project, the team confirmed a diversified, robust, and qualified supply chain for TPV manufacturing at the LRIP scale (and larger).

Knowledge Transfer

The team already used the LRIP capability developed in this project to supply TPV customers. Their positive response to Antora's products validates that there is broad value in these devices for a range of applications. In future work, the team will seek to drive down the cost of TPV manufacturing using this fabrication capability, which will further increase customer interest.

To support scientific knowledge transfer within the industry, Dr. Brendan Kayes (Principal Investigator) served on the Program Committee for the 14th World Conference on Thermophotovoltaic Generation (TPV-14) in 2023. Through this platform, there was a mutual exchange of ideas regarding future research and development and manufacturing directions for TPV development and deployment.

CHAPTER 4: Conclusion

During this project Antora Energy has demonstrated an LRIP-capable production line for TPV cells. The production line is located in Silicon Valley, California — a strategic location with a strong network of workforce, suppliers, and services for semiconductor materials processing. These regional advantages provide a platform for further cost reductions in TPV cells, which will enable Antora Energy to be the world leader in TPV manufacturing for both internal use as well as supplying external customers.

The team has demonstrated all of the process steps on Antora's tools and has quantified the takt time per wafer and compared it against what is required for 2 MW/year production. All steps and tools have been shown to be compatible with the 2 MW/year requirement. During this project, the team also confirmed a diversified, robust, and qualified supply chain for TPV manufacturing at the LRIP scale and larger.

Antora Energy is extremely grateful for the opportunity that the CEC has provided to develop an in-house process for TPV devices. The team was able to work with excellent advisors and local equipment suppliers to bring a new capability to the San Francisco Bay Area. With continued time and funding, the team will expand the number of processes that can be run at Antora's facility, as well as the scale of Antora's production. As the team increases headcount and makes deeper connections with local vendors, it looks forward to contributing to the vibrant climate tech hardware ecosystem in this region.

In the future, research should focus on further cost reductions in TPV cell manufacturing processes, efforts to make these processes compatible with existing manufacturing processes and equipment, integration of TPV cells into a larger area and higher-power modules and products, additional technoeconomic analysis, and additional customer research to better understand the pain points of the users of TPV devices.

Glossary and List of Acronyms

Term	Definition
I-V	current-voltage
GW	gigawatts
kt	kilotons
LRIP	low-rate initial production
MRL	manufacturing readiness level
MW	megawatt
NOx	Nitrogen oxide
PV	photovoltaics
R_{BBG}	below bandgap reflectivity
R_S	series resistivity
TPV	thermophotovoltaic

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Project Deliverables

- 1.6.2 Final Report
- 2.1 TPV Cell Informational Materials
- 2.2 TPV Cell Full-Wafer Process Report
- 3.1 Critical Project Review Report
- 3.2 TPV Cell Toolset Plan
- 3.3 TPV Cell Fabrication and Characterization Toolset Report
- 4.1 TPV Cell LRIP Demonstration Report
- 5.1 Initial Project Benefits Questionnaire
- 5.2.1 Annual Survey #1
- 5.2.2 Annual Survey #2
- 5.2.3 Annual Survey #3
- 5.3 Final Project Benefits Questionnaire
- 5.4 Documentation of Project and Organization Profile on EnergizeInnovation.fund
- 6.5 Final Project Case Study

Project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.