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ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

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

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PREFACE

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

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The 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 thermal radiation emitted from any high-temperature source directly into electricity.

Production and deployment of Antora's TPV-enabled thermal batteries will improve both rate-payer 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 (they cost 10 times less than lithium-ion batteries), they can provide safe, reliable, and inexpensive electricity storage to support deeper penetrations of renewables on the California grid and help 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 8 for these TPV heat engines by building a low-rate initial production pilot production line for TPV cells. The production goal was a nameplate 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.

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, and MRL 8 was achieved. Also, during the project, the team confirmed a diversified, robust, and qualified supply chain for TPV manufacturing at the low-rate initial production scale (and larger).

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

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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 radiation from any high-temperature source directly into electricity with high efficiency. Antora has leveraged funding from the 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 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 costs 10 times (10x) less than lithium-ion batteries that will enable a low-cost, zero-carbon 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. This interest has led to initial sales and further customer requests from multiple sectors; 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 Antora's immediate customer demand.

Project Purpose and Approach

Antora's objective is to build an LRIP pilot line in California that has a nameplate 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 based on the semiconductor material indium gallium arsenide. 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 uses as well as supplying external customers.

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 wafer process times compatible with the process takt times for Antora's 2 megawatt per year requirement.[1] 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,[2] 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 ready for LRIP
- 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.

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[1] The high-volume characterization tool has not yet been received; however, it has been designed to achieve the required throughput.

[2] The team has not yet staffed up to run the Antora facility at full LRIP level, but it sees no barrier to doing so.

Knowledge Transfer and Next Steps

The team already used the LRIP capability developed in this project to supply TPV customers such as Mesodyne and the Army Research Lab. 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 Thermo-photovoltaic 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 a larger area and higher-power modules and products, more refined technoeconomic analysis, and customer outreach 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 into all these markets 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 components from well-established supply chains. Only the thermophotovoltaic (TPV) cell itself is not manufactured at scale. Antora's nominal plan was to fill this gap by building out TPV low-rate initial production (LRIP) capabilities in the mid-2020s — a timeline consistent with the growth in the long-duration storage market. However, 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 earlier. Earlier 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.

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 rate-payers 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 for less than $10 per kilowatt-hour (kWh) of energy, 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 into all these markets 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 nameplate 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 nameplate 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 indium gallium arsenide (InGaAs) foils bonded on silicon (Si) wafers, and the output of the pilot line is that same InGaAs 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 steps in Antora's previous wafer-fragment process, which yields only 4 TPV cells per processing step. Figure 2 shows the results of Antora's full-wafer process. The larger 6-inch silicon (Si) wafer allows the use of a 4-inch-diameter InGaAs 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 Wafer-fragment Cell Fabrication Process

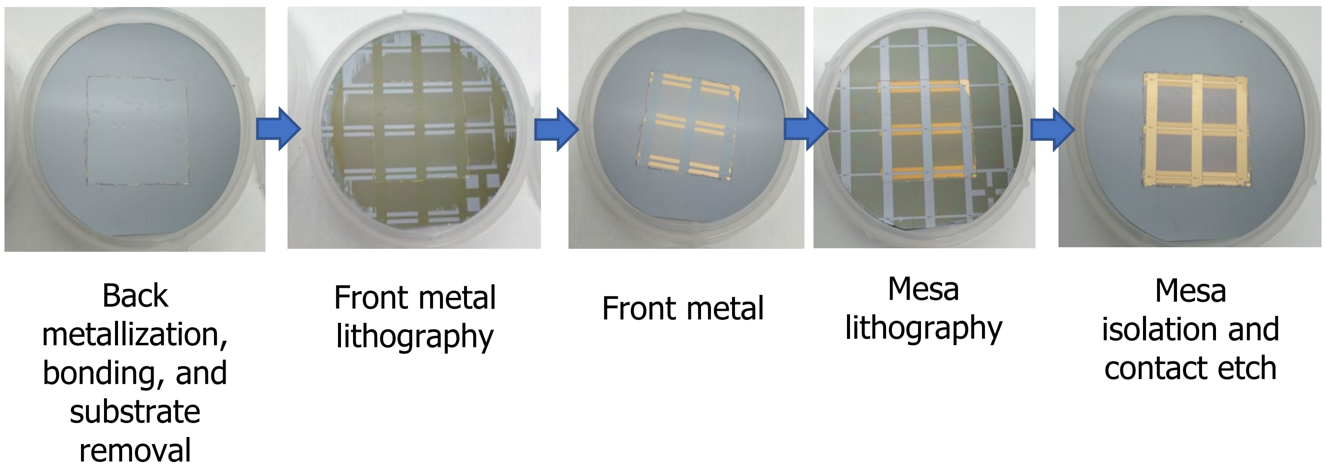
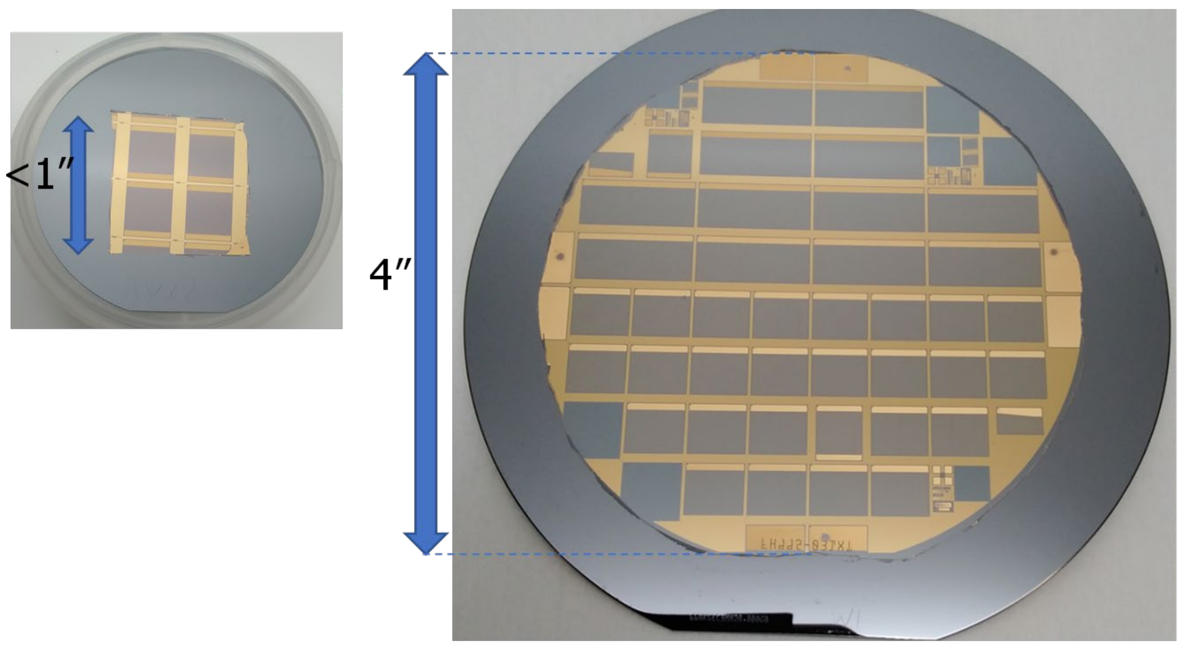


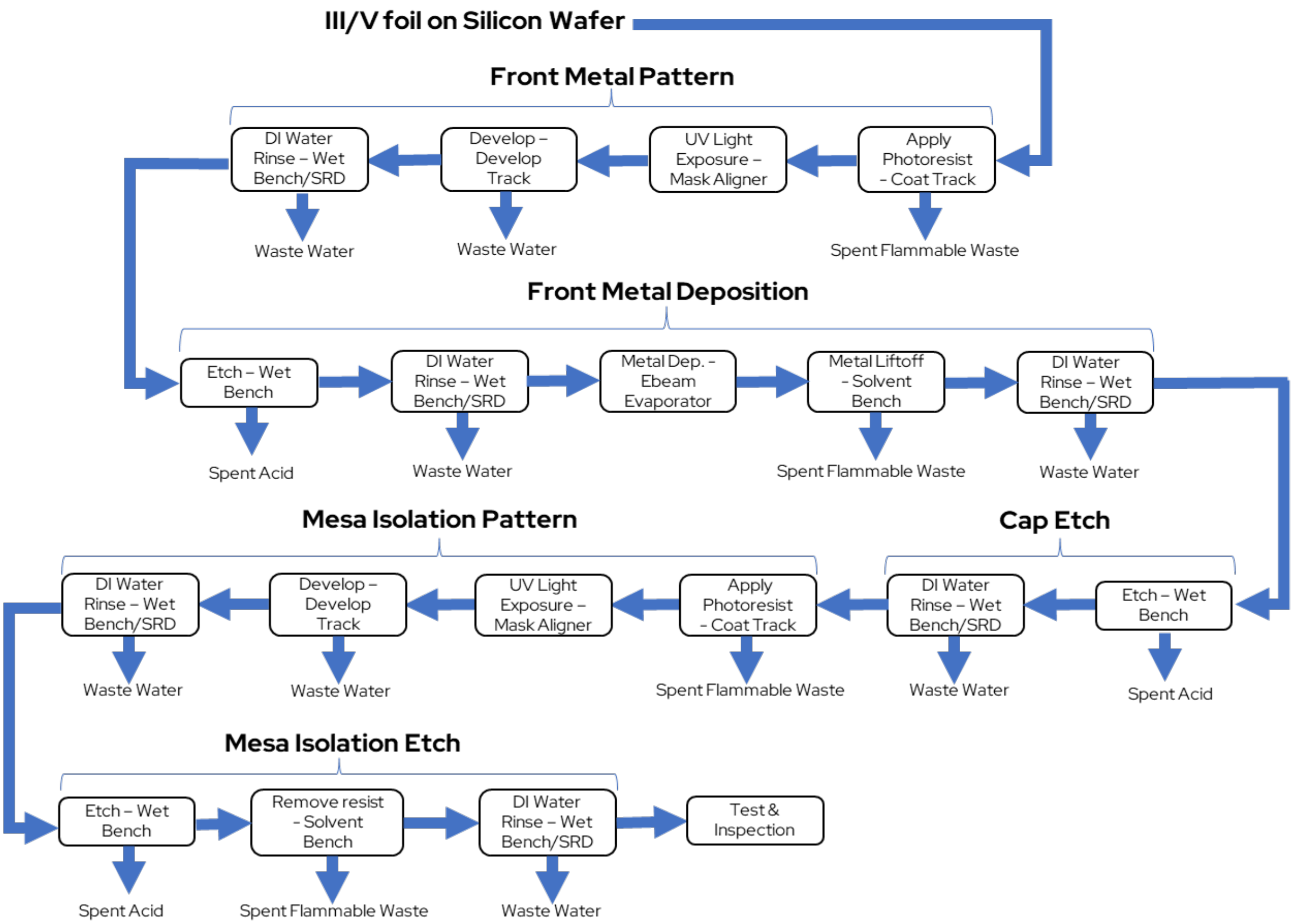
Figure 2: Example of How a Full-wafer Process Enables More Devices per Processed Unit



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 2 forms the basis for the full-wafer fabrication and characterization process flow in shown schematically in Figure 3. The schematic indicates each step in the fabrication process and the waste streams generated by each step. 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.

Figure 3: Schematic of the Process Flow From a Bonded InGaAs Foil to Completed Cells



DI = deionized
SRD = spin rinse dryer

Task 3: TPV Cell Fabrication and Characterization Toolset

Daily Production Requirements: To reach Antora's 2 MW/day capacity production target, the team made the following assumptions (updated since the 3.2 TPV Cell Toolset Plan):

- The emitter temperatures in Antora's thermal batteries will range from 1500–1600°C (2732-2912°F), which results in TPV cell electrical power densities (output) of 4–7 watts per square centimeter (W/cm^2).
- Using the conservative 4 W/cm^2 requires 500,000 cm^2/year of TPV cells.
- A 6-inch Si wafer with a 4-inch-diameter InGaAs foil[3] can fit approximately (~) 43.5 cm^2 of TPV cells (74 cells with a 0.588 cm^2 active area).

[3] In this document the team will refer to the indium phosphide (InP) growth substrates as "substrates", the thin-film III/V epi-on-metal device foils as "foils," the Si handle substrates as "wafers," and the bonded foil-on-Si stack as "bonded foils."

- The team further assumes:
  - The TPV cell fabrication yield is 80 percent.
  - All process stations are operated simultaneously.
  - Tool downtime is minimal.
  - The time to move lots between tools is minimal.
  - The tools are operated 24 hours/day, 365 days/year.

Under these assumptions, Antora's LRIP system must process approximately 40 wafers per 24-hour day.

Process Tooling Requirements (takt times): Each of the processes carried out in Figure 3 is performed by a specific fabrication tool, with some tools being used more than once. Table 1 maps each full-wafer process step to its associated fabrication tool, which yields the required daily throughput and the takt time for each fabrication tool.

Table 1: Fabrication Tools and Required Throughput for the Full-wafer Process in Figure 3 to Achieve 2 MW/Day of TPV Cell Capacity

Tool/process	Number of times used in process flow	Required throughput (4" foils)	Required takt time (4" foils)
Lithography (coat)	2	~ 80 per day	< ~ 18 mins per wafer
Lithography (expose)	2	~ 80 per day	< ~ 18 mins per wafer
Lithography (develop)	2	~ 80 per day	< ~ 18 mins per wafer
Etching (pre-metal dep and contact etches)	2	~ 80 per day	< ~ 18 mins per wafer
Etching (mesa isolation)	1	~ 40 per day	< ~ 36 mins per wafer
Front metal deposition	1	~ 40 per day	< ~ 36 mins per wafer
Solvent bench (metal liftoff, resist removal)	2	~ 80 per day	< ~ 18 mins per wafer
Characterization	1	~ 40 per day	< ~30s per cell

Characterizing TPV devices in high-volume manufacturing: Thermophotovoltaic (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; 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, $(Q_i\text{-}Q_e)$, that is,

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

where conservation of energy has been used, write the last expression on the right-hand side. The team contrasts this with the definition of solar PV efficiency, where the denominator is typically the total power incident on the PV device.

The team characterizes the efficiency of Antora's TPV cells using two different approaches, which are detailed below. The first approach directly leverages Equation 1 by measuring heat rejected, *Q*, and electric power, *P*. Although straightforward, this approach is limiting in both speed and flexibility. The calorimetric measurements require waiting a sufficient time to reach steady — too long to implement for quality assurance in Antora's LRIP system. Also, the calorimetric measurements are valid only for the thermal emitter used in the test — temperature, emissivity, and configuration (for example, view factor). In contrast, the second approach builds an operational model of the TPV cell from secondary optical and electrical measurements that can be used to compute TPV cell efficiency for any thermal emitter. Also, these measurements can be performed rapidly on automated equipment.

Approach #1: The first approach to TPV efficiency measurement uses the calorimetry apparatus[4] shown in Figure 4. The TPV cell is illuminated with a resistively heated graphite emitter through a water-cooled aperture. The aperture serves to protect the electronics and other sensitive components from the intense irradiation. The TPV cell sits on a copper post, or cutbar, with holes drilled for thermocouples. The mass. *M*. and specific heat capacity, c_p, of the copper cutbar are known, and the simple relation

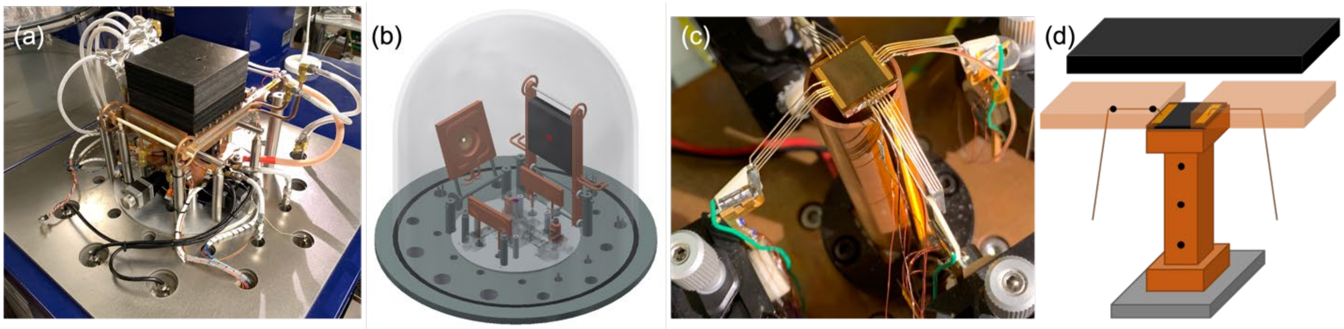
$$Q = mc_p \Delta T \quad (2)$$

can be used to calculate the heat deposited into the cutbar, that is, the heat rejected by the TPV cell to ambient temperature. Here, ΔT is the increase in average temperature of the cutbar over the time period of the measurement.

The electrical power output, *P,* of the TPV cell is determined from measurements of the voltage across and current through a load resistor attached to the TPV electrical terminals. Electrical connections to the TPV cell busbars are made with multi-pronged probes to reduce the power dissipated at this interface. The probes are metallic and conduct some heat away from the TPV cell, which affects Antora's measurement of *Q*. To mitigate this effect, thermoscouples are installed on the probe fingers to quantify this heat in a similar manner to those on the cutbar.

[4] See also: T.C. Narayan et al., "Platform for Accurate Efficiency Quantification of > 35% Efficient Thermophotovoltaic Cells," 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 2021, pp. 1352-1354, DOI: 10.1109/PVSC43889.2021.9518588.

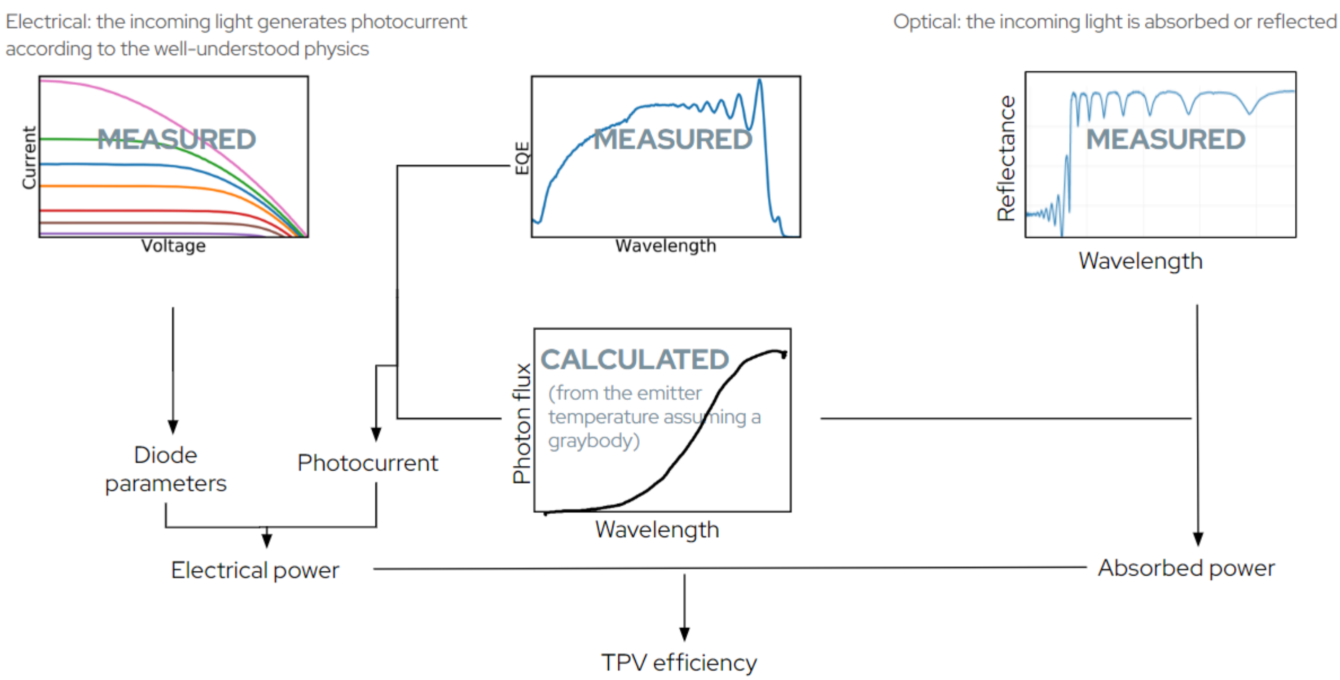
Figure 4: Depictions of Antora's Experimental TPV Efficiency Measurement Setup



(a) Fully assembled with insulation covering the emitter. (b) CAD showing the emitter (black) and aperture that folds down on top of the cell. (c) Cell stage and cutbar with electrical probes. (d) Simplified cartoon of the experimental setup; the black circles signify points of temperature measurement.

Approach #2: The second approach to TPV efficiency measurement is shown schematically in Figure 5. Instead of measuring *P* and *Q* in Equation 1 using calorimetric methods, this approach uses secondary characterization methods and modeling to extract *P*, Q_i, and Q_e in Equation 1.

Figure 5: Schematic Representation of How TPV Efficiency Can Be Quantified



TPV efficiency can be quantified by Combining Measurements of Current-voltage (I-V) Performance Under High-Intensity Illumination (for Example, Using a Flash Tester), External Quantum Efficiency (EQE), and Reflectance Across a Broad Spectrum of Relevant Wavelengths (for Example, in the Range of 300–20,000 nanometers), Using Fourier-transform Infrared Spectroscopy (FTIR)

To estimate the total absorbed thermal radiation (Q_i - Q_e) in Equation 1:

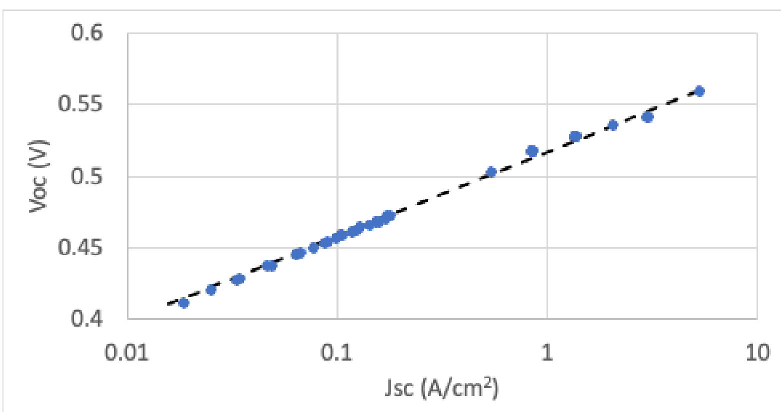
- The spectrum of the incident photon flux, Q_i, is calculated from a graybody model of the thermal emitter that will be used in the final configuration of the device. The team believes this modeling step is an improvement over the calorimetric approach (from above) because it allows determination of η_{TPV} for any configuration of thermal emitter.

- The reflectance spectrum of the TPV cell is measured via Fourier-transform infrared spectroscopy (FTIR) using a Bruker Invenio X with an integrating sphere that collects light scattered at all angles. These spectra are referenced to the reflectance standards of the National Institute of Standards and Technology (NIST), which are calibrated to better than ±0.5 percent uncertainty.
- The reflectance spectrum and the incident photon flux, Q_i, are combined to give the photon flux that is reflected back to the thermal emitter, Q_e. The team notes that a slight correction is applied to account for multiple reflections, depending on the view factor between the TPV cell and the thermal emitter inherent in a particular system to be modeled. The steps up to this point enable quantification of the absorbed thermal power (Q_i - Q_e) in Equation (1).

To estimate the electrical power, *P*, in Equation (1):

- The TPV cell's short-circuit electrical current, I_{SC}, is estimated by integrating the product of the cell's measured external quantum efficiency (EQE) and the modeled incident thermal radiation spectrum from the thermal emitter. The EQE is measured at near-normal incidence and referenced to silicon and germanium reference cells using a PV Measurements QEX10 system. Note that the EQE undergoes slight modification to account for multiple reflections, depending on the view factor between the TPV and the thermal emitter inherent in a particular system to be modeled.
- The TPV cell's operating output current and voltage, and therefore the TPV cell's electrical power output, *P*, are estimated from the TPV cell's diode curve, which is constructed from the TPV cell's diode parameters and short-circuit electrical current, I_{SC}. The TPV cell's diode parameters are estimated as follows:

Figure 6: Fit Showing Agreement of the Cell Diode Characteristic to an Ideality Factor n=1



The dotted line corresponds to n = 1. These data were acquired under continuous illumination in the low current range and by a flash in the high current range. Cell heating effects are minimized during flash experiments performed at higher currents.

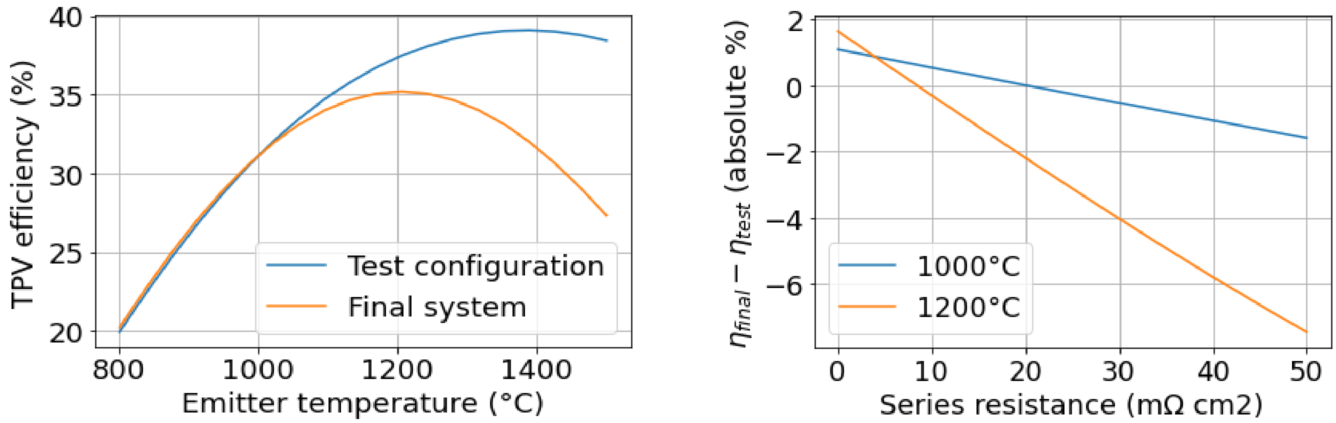
- The TPV cell's I-V curves are measured using a Sinton Instruments FMT-500 flash tester.
- The TPV cell's series resistance is obtained by comparing the flash I-V curve with a suns-V_{OC} curve taken at a comparable illumination intensity to that expected in the final application. The cells have been found to be in the n=1 ideality factor regime at and above 100 milliamperes per square centimeter (mA/cm^2) (see Figure 6).
- The saturation current density, I_0, is calculated assuming a 1-diode model using the I_{SC} and V_{OC} values of the highest available current I-V curve.
- The shunt resistance is obtained from dark I-V and other low intensity I-V curves.

Comparison of Approach #1 and Approach #2: The team believes Approach #2 is far superior to Approach #1 for multiple reasons.

First, the careful calorimetric measurements in *Approach #1* are time-intensive and labor-intensive — so much so that the team does not see an easy path to scaling Approach #1 to the LRIP setting. In contrast, *Approach #2* uses standard characterization techniques to construct a model of the TPV cell and calculate its efficiency. The team is currently working with Tau Science to develop a high-throughput tool that combines all of the required techniques (I-V, EQE, and FTIR) into a single tool for automated operation.

Second, *Approach #2* enables the TPV cell efficiency to be estimated for a wide range of thermal emitter temperature, emissivity, and configuration (for example, view factor). In contrast, the calorimetric method in *Approach #1* determines the efficiency for one particular thermal emitter, which does not necessarily apply to other emitters. For example, the calorimetric test system in *Approach #1* has a view factor of about 30 percent, which is approximately one-third of that expected in most real-world applications. For the same emitter temperature, a real-world system would experience approximately 3x more incident thermal radiation and 3x more output current. The ohmic losses in the TPV cell's series resistance would be approximately 10x higher while its output would only be approximately 3x higher — a situation that results in lower TPV cell efficiency. This reduction in TPV cell efficiency is larger at higher incident thermal radiation flux, that is, at higher emitter temperatures. In Figure 7 (left), the "test configuration" line shows that using the results from the calorimetric test system (*Approach #1*) results in a significant and growing overestimate of TPV cell efficiency at higher emitter temperatures relative to the "final system" estimates from *Approach #2*. Figure 7 (right) demonstrates the sensitivity of this efficiency estimation error as a function of the TPV cell's series resistance. Larger series resistance values predictably cause larger deviations between the test and final configuration efficiencies for higher emitter temperatures (that is, higher output currents).

Figure 7: (left) Calculated TPV Efficiency for the Test and Final System Configurations as a Function of Temperature; (right) Difference in TPV Efficiency of Test and Final System Configurations for Cells With Different Series Resistances



More generally, the above discussion highlights the importance of a versatile means to determine TPV efficiency. It is possible that different applications require different view factors and emitters. Calculating TPV efficiency from secondary characterization data is agnostic to the environment. The team can simply perform a new ray tracing simulation or view factor calculation in conjunction with an emissivity measurement to adjust Antora's efficiency to a new geometry.

Despite the shortcomings of *Approach #1* (particularly in a manufacturing context), the team views calorimetric TPV efficiency measurements as an important step in understanding TPV cells. The team expects uncertainties in the heat measurement, but they are not so great as to completely invalidate the calorimetric method. A close correspondence between the calorimetric measurement and the calculated TPV efficiency (based on secondary characterization data) would suggest that the different physical processes contributing to that value are correctly accounted for in these calculations. The team found that the measured and calculated TPV efficiencies are in quite good agreement, as seen in the plots (see Figure 7). The close correspondence suggests that the team indeed understands the physics of the TPV cells and that secondary characterization data can be used to determine TPV efficiency without danger of misrepresenting the results.

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 theoretical throughput of 2 MW/year (see Table 1). 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. The steps are as shown in Table 2.

Table 2: List of Steps and Sub-steps in Antora's Process Flow

Step name	Sub-step name	Tool/process
Front Metal Lithography (FML)	FML coat	Lithography (coat track)
	FML expose	Lithography (expose using mask aligner)
	FML develop	Lithography (develop track)
	FML inspect	Inspection
Front Metal Deposition (FMD)	FMD oxide strip	Etching (pre-metal deposition/contact etch)
	FMD excl. oxide strip	Front metal deposition
Front Metal Liftoff (FMLO)	FMLO liftoff	Solvent bench (metal liftoff, resist removal)
	FMLO inspect	Inspection
Contact Etching (CE)	CE etch	Etching (pre-metal deposition/contact etch)
	CE inspect	Inspection
Mesa Isolation Lithography (MIL)	MIL coat	Lithography (coat track)
	MIL expose	Lithography (expose using mask aligner)
	MIL develop	Lithography (develop track)
	MIL inspect	Inspection
Mesa Isolation Etching (MIE)	MIE etch	Etching (mesa isolation)
	MIE inspect	Inspection
	MIE resist strip	Solvent bench (metal liftoff, resist removal)
Final Inspection	Final Inspection	Inspection
Characterization	External Quantum Efficiency (EQE)	High Throughput Characterization Tool
	Fourier Transform Infrared Spectroscopy (FTIR)	High Throughput Characterization Tool
	Current-voltage (I-V) Testing	High Throughput Characterization Tool

The High Throughput Characterization Tool that was developed in collaboration with Tau Science is, unfortunately, not yet available (its delivery is anticipated before the end of 2023). Furthermore, an FTIR spectroscopy function was unable to be included into that tool due to budgetary limitations and rising prices (as described in the 3.3 TPV Cell Fabrication and Characterization Toolset Report. Therefore, the team continues to do the characterization of Antora's cells via the methods described in the 3.3 report, namely using a flash tester combined with a home-built mapping stage for current-voltage (I-V) testing and sampling the external quantum efficiency (EQE) and FTIR using manual research and development (R&D) tools. Therefore, the team does not discuss the characterization steps in this report.

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. For example, Antora Energy has a single coat/develop track tool with a coating lane and a developing lane; but there are two coating and two developing steps, so the coat lane and the developing lane need to be used twice in the process. Similarly, Antora has a single mask aligner tool but there are two exposure steps. Antora currently has a single etch bench but enough baths that the pre-metal deposition etch and contact etch can be run on one side of the tool, while the mesa isolation etch is run on the other side, effectively decoupling these. Finally, Antora has a single solvent bench tool in which both the metal liftoff process and the mesa isolation resist removal steps are run. The team therefore calculated the following maximum allowable process times per wafer per step, as shown above in Table 1.

These numbers assume 4-inch device wafers, an 80 percent yield, 24/7 operation, and no tool downtime. By comparing measured takt time against the maximum allowable takt time, the team could determine whether a nameplate 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 theoretical 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

Table 3 shows a summary of several figures of merit for the TPV cell performance and for the fabrication process for Antora's new full-wafer process versus the previous wafer-fragment process.

Table 3: Comparison of Figures of Merit for Wafer-fragment and Full-wafer TPV Cells

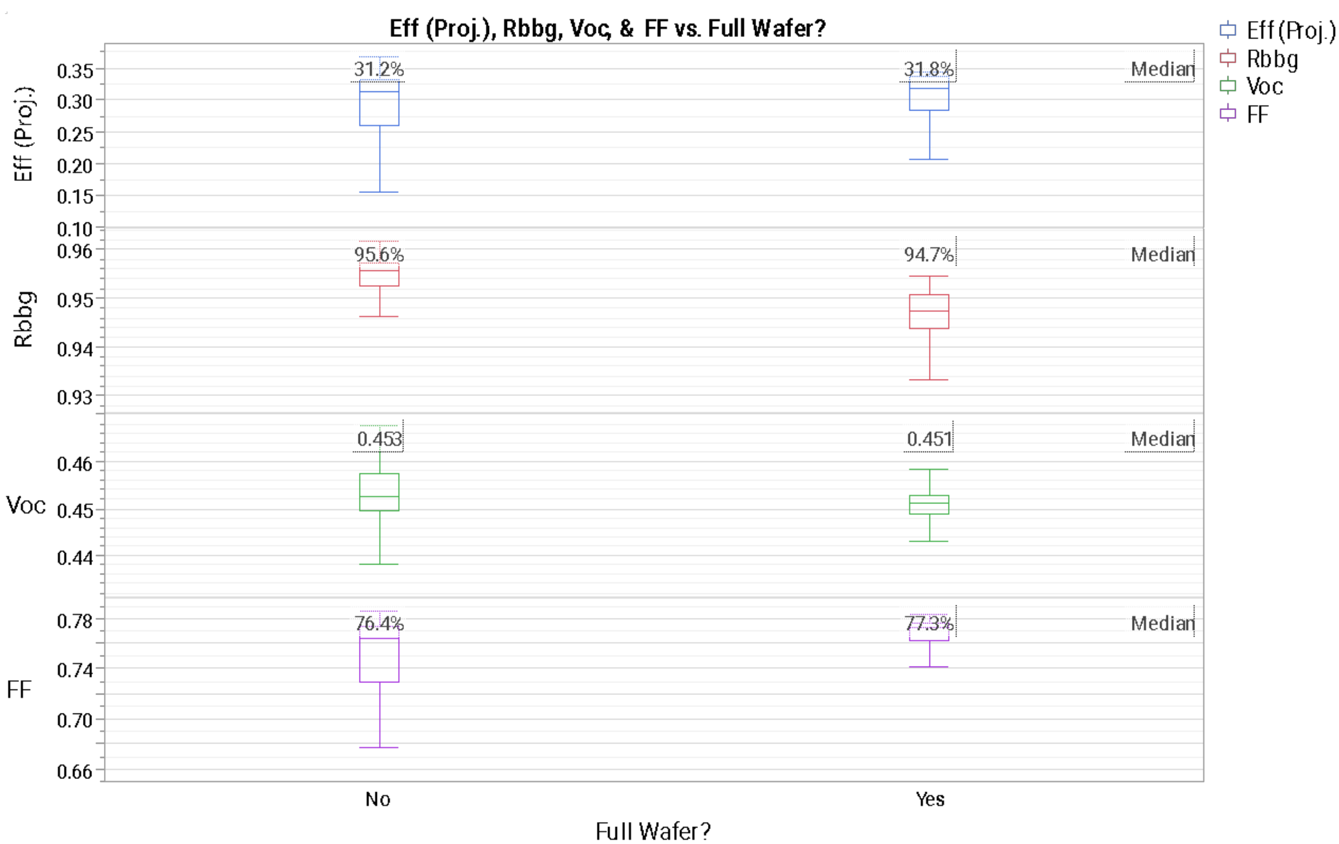
	Wafer fragment	Full wafer
Number of cells tested	101	341
Number (percentage) of yielding cells	69 (68.3 percent)	296 (86.8 percent)
Open-circuit voltage (V_{OC}) @ J_{SC} = 100 mA/cm^2, median (V)	0.453 +/- 0.007	0.451 +/- 0.004
Voltage at maximum power point (V_{MPP}) @ J_{SC} = 100 mA/cm^2, median (V)	0.343 +/- 0.019	0.348 +/- 0.029
Fill factor (FF) @ J_{SC} = 100 mA/cm^2, median	76.4 percent +/- 3.2 percent	77.3 percent +/- 1.8 percent
Series resistance (R_S), median (mΩ) (characterized @ J_{SC} = 100 mA/cm^2)	275	96

	Wafer fragment	Full wafer
Below-bandgap reflectivity, integrated against 1500°C (2732°F) blackbody spectrum, median (R_{BBG})	95.6 percent +/- 0.7 percent	94.7 percent +/- 0.3 percent
Projected TPV efficiency for a 1500°C (2732°F) blackbody, median	31.2 percent +/- 5.5 percent	31.8 percent +/- 4.4 percent

The summary in Table 3 is for cells with *FF* less than (<) 65 percent and/or V_{OC} < 0.4 Voltage (V) under 100 mA/cm^2 illumination were defined as non-yielding, as were cells with gross visual defects. Shunt resistance is sufficiently high on all yielding cells to not be a useful metric and is omitted here.

Figure 8 shows the statistics for several key performance parameters from the summary in Table 3.

Figure 8: Comparison of Figures of Merit for Wafer-fragment ("Full Wafer? = No") and Full-wafer TPV Cells



There are 69 wafer fragments and 296 full-wafer datapoints included in this analysis.

From these data, Antora's new full-wafer process can produce cells with high yield and high performance relative to the previous wafer-fragment process. R_S tends to be a strong function of illumination intensity, and the team typically sees lower values than shown here when it tests under stronger illumination.

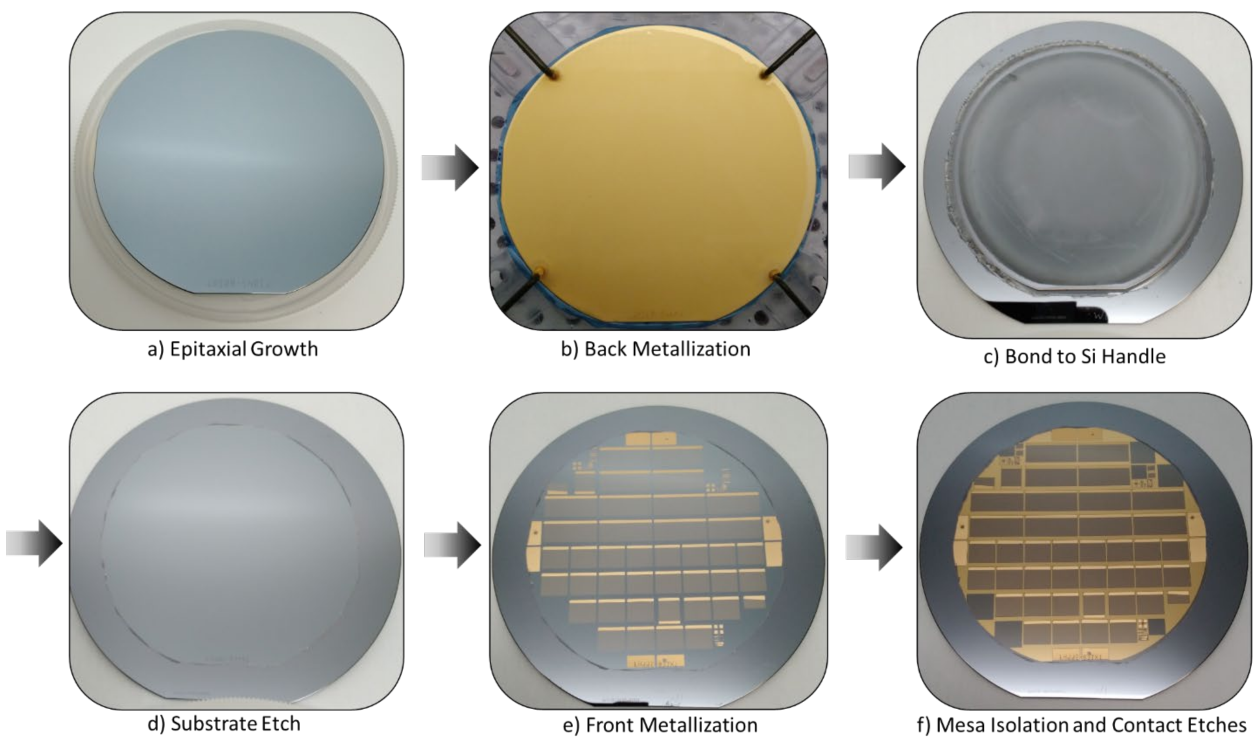
It was somewhat surprising to see a lower value of Below bandgap reflectivity (R_{BBG}) for the full-wafer process cells, but this could be a function of slightly evolving procedures in both the process flow and the characterization methods. It is not a cause for concern at this time, especially given that the full-wafer process showed higher yield and higher median TPV efficiency.

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 changes to the fixturing and labware for photoresist coating, photomasks, wet chemical etching, and metal deposition. 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.

The first notable challenge arose in back metal uniformity. For the cells described here, part of the back metallization process involves electroplating (see Figure 9b). For the full-wafer process, it was necessary to maintain uniform thickness of the electroplated metal over a larger area — the 4-inch diameter full wafer compared to approximately 1 inch for the wafer fragment. To achieve this, the team is increasing the number of point contacts being made to the wafer.

Figure 9: Process steps in full-wafer TPV cell processing



The bonding step (Figure 9c) also required some process improvements to achieve a high yield in the full-wafer process. The bonding of the wafer to the Si handle is a multi-step process: 1) droplets of Henkel EccoBond Tra-Bond 931-1 epoxy are dispensed on the silicon handle, 2) the metallized wafer is placed, metal side down, on the epoxy-coated silicon, 3) the wafer stack is placed on a hotplate (at 125°C [257°F]), 4) weights (108 g) are placed on top of the back of the wafer stack, and 6) the epoxy is baked for 20 minutes to cure it. In Antora's first attempt on full wafers, the substrate removal step (Figure 9 d) revealed bubbles in the epitaxial surface due to air bubbles trapped in the epoxy. The team took several steps to resolve this issue: 1) the Tra-Bond 931-1 epoxy was opened and left in a vacuum desiccator for at least 20 minutes prior to dispensing it onto the silicon handle, 2) the epoxy-coated silicon was placed in the desiccator for another 10 minutes prior to placing the wafer on top, 3) the wafer-silicon stack was placed in the vacuum desiccator prior to as well as after placing the weights. The degassed wafer stack was then placed on the hotplate to cure the epoxy. This modified process removed trapped air from the metal-silicon interface, resulting in bubble-free epi layer after substrate removal.

Task 3: TPV Cell Fabrication and Characterization Toolset

Fabrication Equipment Selection

The team engaged with two consultants, Jack Kelly (Kelly Equipment Management) and Dr. Al Renaldo (Arenaldo Consulting LLC), to help the team select a toolset and specific vendors, brands, and models that would fit Antora's throughput requirements and budget constraints. Jack Kelly has deep experience in equipment engineering, selection, installation, and maintenance, as well as cleanroom construction and management. Mr. Kelly's work experience includes time at Maxim Integrated, Soraa, and Apple. Dr. Renaldo is a photolithography specialist with deep experience in the equipment, processes, and chemicals required for photoresist coating, exposure, and development. Dr. Renaldo has worked at IBM, Cypress Semiconductor, Soraa, and Apple.

Antora's considerations for tool selection included:

- Minimum throughput/capacity requirements (per Table 1) — 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.

Under these considerations, Antora's consultants suggested:

- *Coating and developing* at these rates could be achieved with a linear coat/develop track using the following tools:
    - SVG86 or SVG88 series (used, refurbished by Rite Track)
    - TEL Mark Vz series (used, refurbished by Rite Track)
    - C&D Semiconductor P8000 series (new)

- *Mask exposure* could be achieved with a mask aligner with manual loading and unloading but automated layer-to-layer alignment using the following tools:
    - Suss MA6 (used, refurbished by ClassOne)
    - Suss MA150 (new)
    - OAI 6000 series (new)
    - Heidelberg MLA150 or MLA300 (new)
    - EVG 620NT (new)
    - NxQ 8000M (used, refurbished by NxQ)
- *Wet chemical etching* could be achieved in a fume hood/wet bench set up for cassette-level etching in recirculating baths with manual loading and unloading using the following vendors:
    - Modutek Corp. (new benches)
    - Labconco (new benches)
    - WaFab International/Kinetics (used, refurbished benches)
- *Metal deposition* could be achieved by electron beam evaporation using a refurbished CHA Mark 40 electron beam evaporator with a 9x6-inch wafer capacity by ClassOne Equipment, Inc. However, the team will continue to explore a Denton single-wafer sputtering option.
- *Solvent processing and metal liftoff* could be achieved in a wet bench set up for cassette processes with recirculating baths, and manual loading/unloading. The team focused the search on used equipment from WaFab International/Kinetics.
- *Spin rinse dryers* could be bought used. The team ended up finding one at auction from Equipment Dispositions, Inc.
- *Inspections* of in-process samples using:
    - Various traditional optical microscopes
    - Olympus OLS5100 series confocal microscope (new)
    - Keyence VK-X3000 series confocal microscope (new)

Given Antora's unique combination of budget, throughput, and California-based vendor constraints, the team arrived at the following main items for the fabrication toolset (details of exact methodology including price points are not revealed here, as generally the quotes the team received are confidential between Antora Energy and the vendor):

- *Coating and developing:* C&D Semiconductor P8000-series linear coat/develop track (new)
- *Mask exposure:* NxQ 8000M-series mask aligner (used, refurbished by NxQ)
- *Metal deposition:* CHA Mk40 electron beam evaporator (used, refurbished by ClassOne)
- *Wet chemical etching:* Various refurbished wet benches from WaFab International/Kinetics
- *Spin rinse dryer:* Used, bought at auction from Equipment Dispositions, Inc.
- *Inspection:* Keyence VK-X3000 series confocal microscope (new)

C&D Semiconductor, NxQ, WaFab International, and CHA are all local to the San Francisco Bay Area. Keyence has service support based in the San Francisco Bay Area.

Characterization Equipment Selection

To enable high throughput measurements of the cells, including light I-V under appropriately high illumination intensity, EQE, and FTIR, the team specified and ordered a custom high-throughput characterization tool from Tau Science. Tau Science is a specialized designer and builder of in-line and off-line characterization equipment for the photovoltaics (PV) industry, and the team has had successful engagements with the company on similar projects. This enabled the team to gather a more robust dataset at high throughput, and thereby increase Antora's confidence in the TPV efficiency projections.

Beyond specifying the required throughput of this tool, the team also specified that the tool should be capable of measuring external quantum efficiency (EQE), reflectivity, and high-intensity (hundreds of suns-equivalent) current-voltage (I-V) characteristics. These measurements yield parameters that contribute to the modeling and calculation of TPV efficiency (see "Project Approach, Task 3: TPV Cell Fabrication and Characterization Toolset"). The team provided Tau Science with a specification for the repeatability of the subset of parameters, including:

- Short-circuit current density (J_{SC}), calculated by combining and integrating the intended 1500°C blackbody illumination spectrum with the measured EQE.
- Below bandgap reflectivity (R_{BBG}), calculated by combining and integrating the intended 1500°C blackbody illumination spectrum with the measured reflectivity spectrum.
- Series resistivity (R_S), calculated by comparing light I-V curves at different illumination intensities.

To achieve better than a 5 percent reproducibility in Antora's TPV efficiency measurements, the team set the following "must have" and "nice to have" reproducibility specifications in Table 4 for the subset of key parameters:

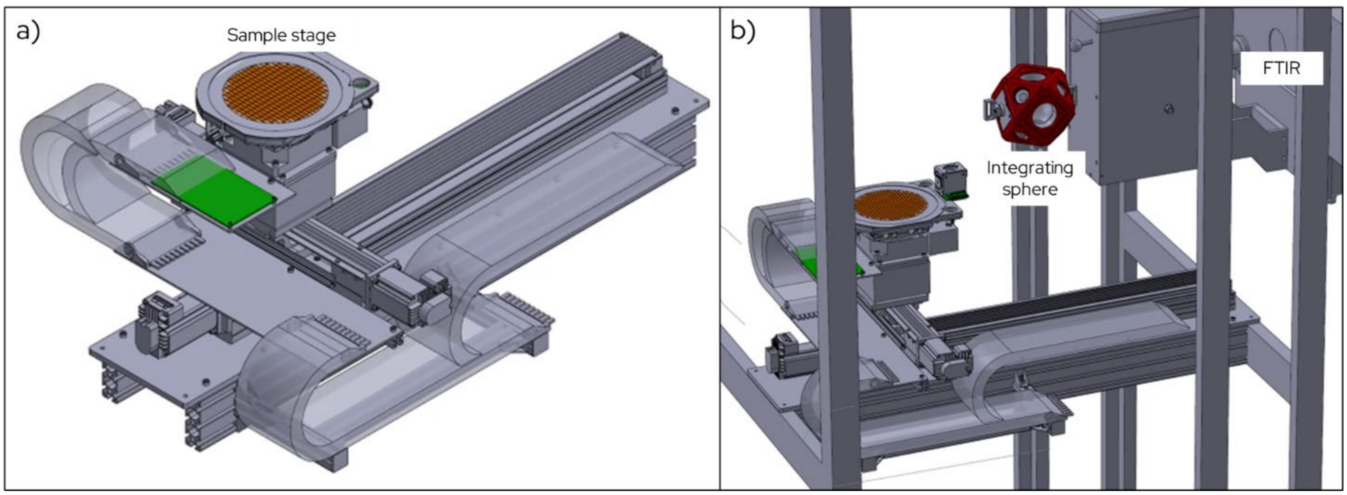
Table 4: 2-Sigma Reproducibility Specifications for Tau Science High-throughput Characterization Tool

Reproducibility specifications (2-sigma)	Must have	Nice to have/target
J_{SC}	< ±1.4 percent	< ±0.3 percent
R_{BBG}	< ±1.0 percent	< ±0.2 percent
R_S	< ±2 mΩ	< ±1 mΩ

Initial experiments at Tau Science determined that, to meet Antora's repeatability specification, it is preferred to use the current method of measuring reflectivity by FTIR spectroscopy — Bruker FTIR coupled to a Pike integrating sphere. The team originally planned to use a lower-cost solution from a Swiss FTIR supplier named ArcOptix. Unfortunately, the team was unable to reach an agreement on legal terms and it switched to a plan that integrates the

Bruker and Pike parts into the Tau Science tool. However, the higher cost of the Bruker tool and rising costs at Tau Science mean that the team no longer has the budget to include an FTIR system in the Tau Science tool from day one. Instead, the Tau Science design will allow for later integration of a Bruker FTIR and Pike integrating sphere (see Figure 10). In the near term, the team will continue to use the Bruker tool already in the lab to measure the reflectivity of samples of Antora's production runs. This interim approach is supported by results from other work that show R_{BBG} has the least variability overall and the least variability within each foil. These properties make it the most amenable to taking a single FTIR measurement per bonded foil or per batch (for additional details, see Task 2: TPV Cell Full-Wafer Process Report, Figure 9).

Figure 10: Computer Models of the High-throughput Characterization Tool Being Designed by Tau Science



a) shows the x-y motion of the mapping stage for the sample. b) shows how the integrating sphere and FTIR will fit into the tool. Not shown are the laser light source and probes for I-V measurements, as well as the EQE system.

Source: Tau Science.

Site Selection

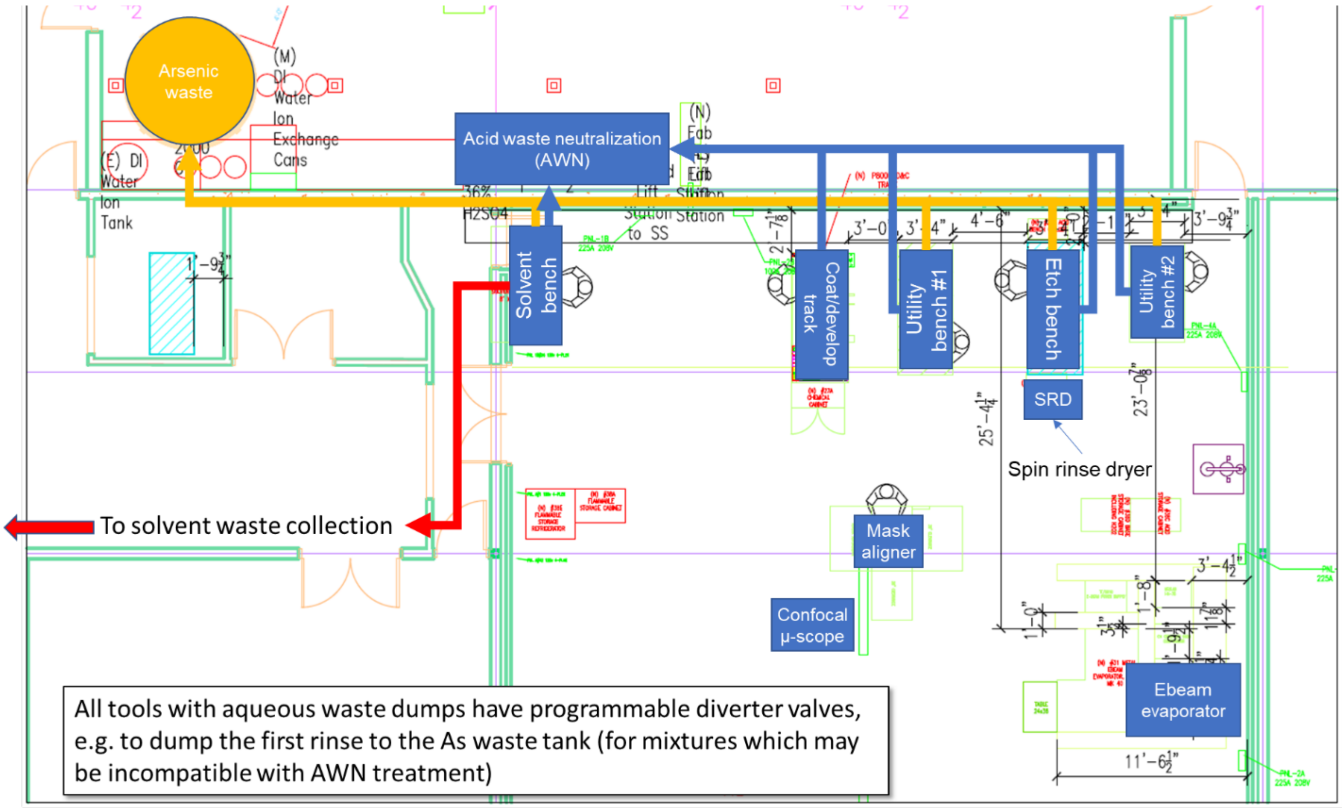
On April 19, 2021, the team executed a lease on Antora's current headquarters at 1244 Reamwood Avenue in Sunnyvale, California with a move-in date of June 1, 2021. The previous tenant of this location was Akamai Solar, and the cleanroom here has been used for prototyping copper indium gallium diselenide (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 Layout and Installation

Antora's equipment layout is shown in Figure 11. The location of the Tau Science characterization tool is to be determined but will likely be located in an adjacent lab not shown on the drawing below.

Figure 11: Antora Energy TPV Cell Fabrication Toolset Layout, Showing Liquid Waste Streams



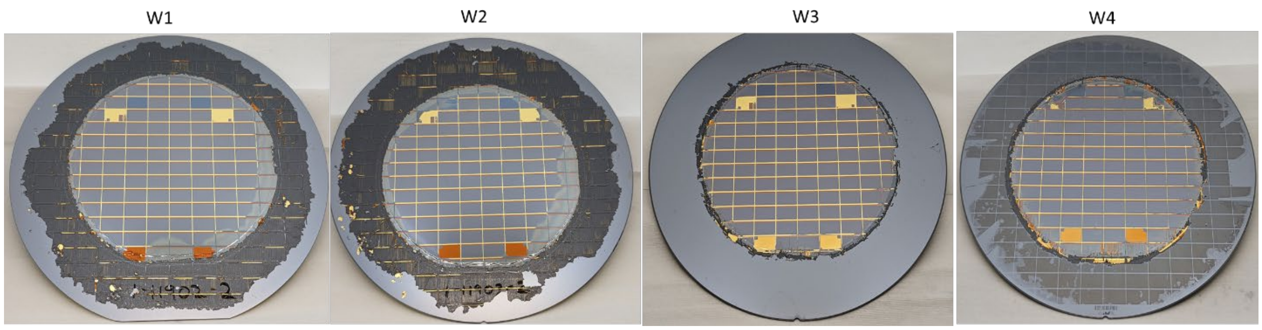
The team worked with consultants Troy Christensen (Otis Institute, Inc.) and Victor Navarro (Clean Tech LLC) on facility layout, facility upgrades, and Sunnyvale permit planning. The team also opened a new position for a Director of Facilities and Equipment, hiring John Perna for this role starting August 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 Antora's partner Microlink Devices (MLD) in Niles, Illinois. 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 MLD. In this test, the fabrication of the control TPV cells was fully done by MLD. For the Antora LRIP TPV cells, the back-side process steps (back metallization, bonding to a silicon handle wafer, and substrate etch back (SEB) were done by MLD, and the subsequent steps (etch stop removal, front metallization, contact and isolation etches) were executed at Antora's facility in Sunnyvale, California.

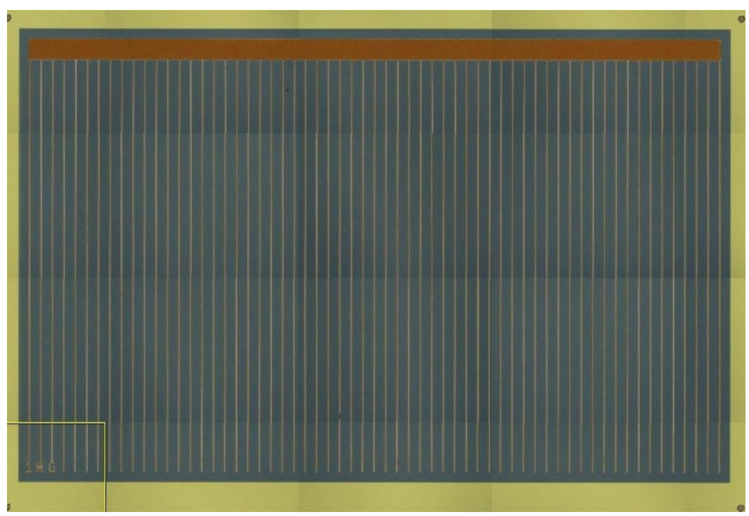
Figure 12 shows images of the four samples (where wafers 1 through 4 are labelled W1–W4) produced on Antora's LRIP toolset. Three equivalent control samples were processed at MLD but are not shown here. Figure 12 shows each wafer after the sequential steps of processing at Antora, that is, after removal of the etch stops, after front metallization and contact layer etch (aka "cap etch"), and the completed cells after the isolation etch.

Figure 12: Wafers After the Sequential Steps of Processing



(Top) Bonded Foils After Etch Stop Removal. (Middle) Bonded Foils After Front Metallization and Cap Etch. (Bottom) Completed Cells, After Isolation Etch.

Figure 13: Confocal Microscope Image of Finished TPV Cell



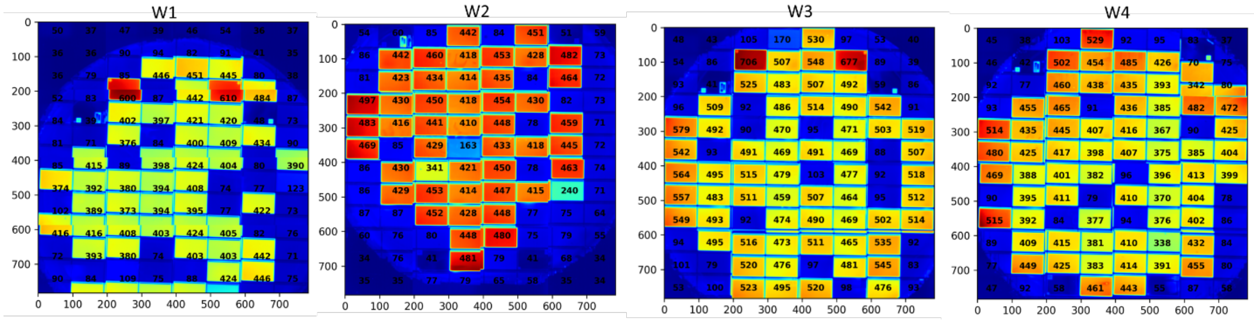
For reference, Figure 13 shows a stitched, high-resolution confocal microscope image of a single TPV cell from the samples in Figure 12.

Semi-Quantitative TPV Assessment via Photoluminescence

The team characterized the bandgap of the TPV cells W1-W4 using photoluminescence (PL) imaging. In PL imaging, a portion of the wafer sample (a few by a few TPV cells in extent) is illuminated with high-energy light that is absorbed by the TPV cell. The TPV cell re-emits light at its bandgap energy and wavelength. A higher intensity of this photoluminescence corresponds to a higher band gap voltage in the TPV cell and, therefore, higher TPV cell performance.

Figure 14 shows the intensity of the PL for the Antora-processed wafers in Figure 12, where the PL intensity has been converted using a false color scale. This spatial imaging of the PL intensity (and therefore bandgap) was made possible by recent work to improve Antora's PL mapping tool so that it correctly stitches together images and maintains a calibration so that different samples (potentially measured days or weeks apart) can be compared based on their PL values.

Figure 14: Stitched Photoluminescence (PL) Images Showing InGaAs Bandgap PL Intensity in Arbitrary Units

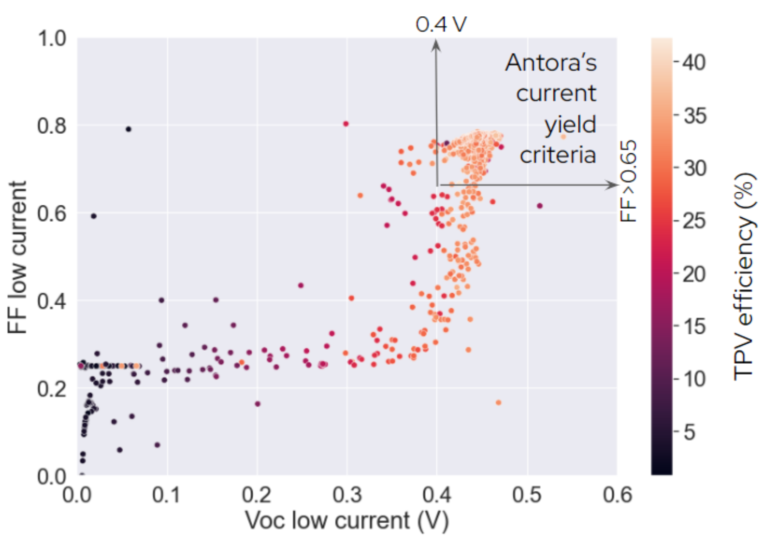


Higher values of PL indicate higher device voltage.

Quantitative TPV Assessment of TPV Cell Performance

Samples W1-W4 were quantitively assessed by MLD 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 MLD test with the Tau Science tool; in the short-term, the test will be performed by Antora using a Sinton flash tester with a mapping stage. The key advantage of these latter tools will be the ability to measure every cell on the wafer at the equivalent of hundreds of suns of illumination intensity, which approximates Antora's intended thermal battery conditions much more closely than the 1-sun illumination at MLD.

Figure 15: Correlation between 1-sun I-V metrics of FF and V_{OC}, and TPV Efficiency

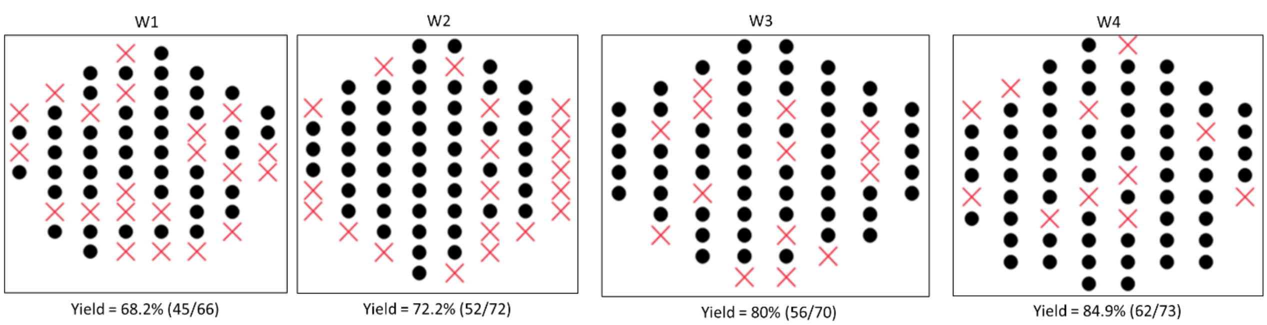


Despite the relatively low, 1-sun illumination intensity of the MLD instrument, the team can draw conclusions about the TPV cell yield.

The team has discussed previously how it can extract projected TPV efficiency from EQE-derived J_{SC}, FTIR-derived R_{BBG}, and I-V characterization (see Task 2: TPV Cell Full-Wafer Process Report or Figure 5 and surrounding discussion in this report). The color scale in Figure 15 shows the TPV cell efficiency for several TPV cells characterized using this method. These same TPV cells are also plotted on V_{OC} and FF axes, where these quantities are measured using the MLD 1-sun illumination and I-V mapping. Figure 15 shows a strong correlation between TPV efficiency and these 1-sun I-V characteristics, allowing the team to define yielding TPV cells as having an open-circuit voltage of $V_{OC} > 0.4$ V and a fill factor (FF) greater than 65 percent under 1-sun illumination.

Based on these criteria, the four sample wafers (W1-W4) in Figure 12 have the yield maps shown in Figure 16, where a black-filled circle is a yielding cell and a red X is a non-yielding cell. With an eye toward further simplifying the measurement of yield, the team notes the correlation between yielding cells in Figure 16 and cells with bright PL in Figure 14.

Figure 16: Yield Maps of the Sample Wafers W1-W4 in Figure 12



Using the correlation developed in Figure 15, a black-filled circle is a yielding cell and a red X is a non-yielding cell.

The average yield across the wafer samples W1-W4 was 76.5 percent, with individual yields of 68.2 percent (45/66 for W1), 72.2 percent (52/72 for W2), 80.0 percent (56/70 for W3), and 84.9 percent (62/73 for W4). The three MLD control samples (whose yield maps are not shown) had yields (defined the same way) of 75.6 percent (59/78), 72.4 percent (58/79), and 64.6 percent (51/79), for an average yield of 71.1 percent.[5]

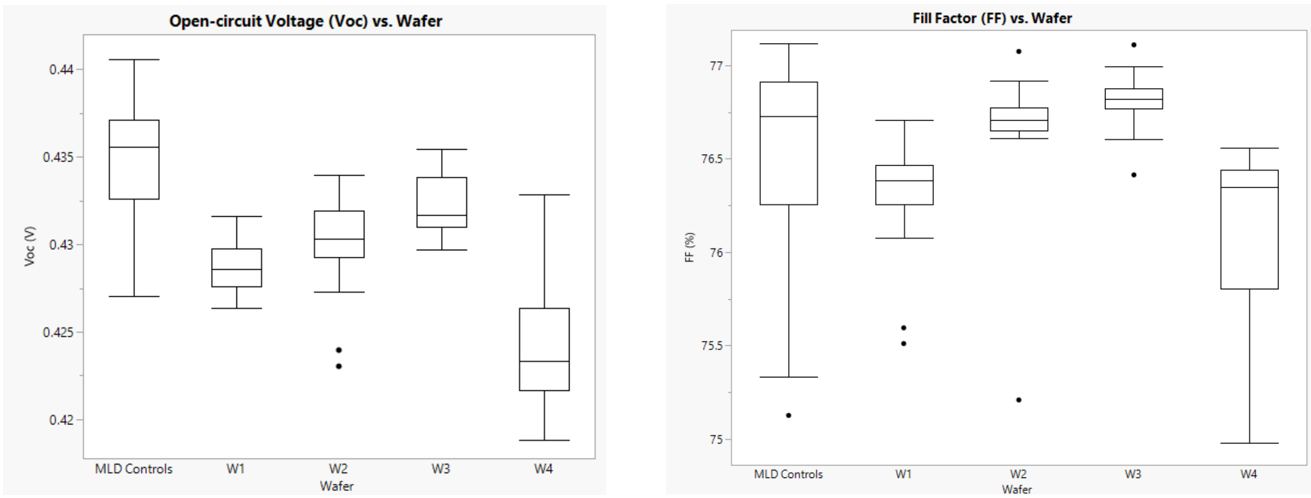
Figure 17 shows box plots comparing the 1-sun V_{OC} and FF of the MLD control wafers and wafer samples W1-W4. The Antora frontside process produces yielding cells with I-V parameters that are generally very similar to those produced by the MLD process, demonstrating the quality of the Antora process.[6] While there is still room for performance and yield improvement in Antora's Sunnyvale process, the fact that the team has achieved comparable

[5] To date the team has not been particular about aligning the cell mask to the foil, and therefore the denominator in the yield calculation changes between samples.

[6] 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.

performance (and a slightly better yield) at Sunnyvale than with the MLD controls gives the team confidence that the process is ready to ramp up.

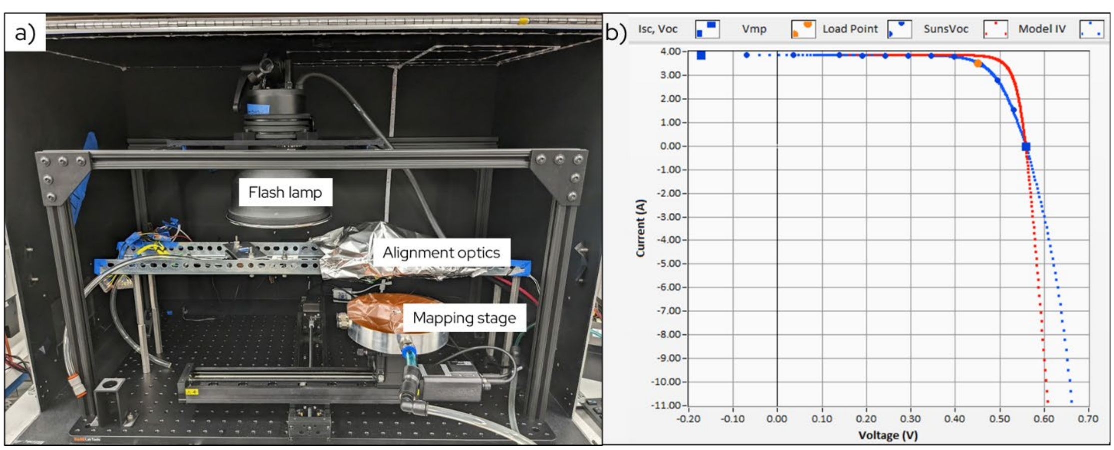
Figure 17: Comparison of Extracted Device Parameters of the MLD Control Samples Compared With the Samples Fabricated on the Antora Energy Toolset



(left) Open circuit voltage, V_{OC}. (right) Fill factor, FF.

When Antora's high-throughput test equipment from Tau Science is in operation, the team intends to modify Antora's definition of yield to correlate even more closely with high TPV efficiency. This advance will allow the team to gather more accurate information about JSC on a larger fraction of the cells, as well as to test the I-V performance under higher light intensities, which are more representative of the light intensities the cells will see in Antora's thermal storage systems. The Tau Science tool is currently expected to arrive at Antora's Sunnyvale location in July 2023. In the meantime, to measure the cells under high light intensities (the equivalent of hundreds of suns), the team has added a mapping stage capability to the Sinton flash I-V tester (see Figure 18). This work was completed and validated in June 2023.

Figure 18: a) Photograph of Antora's Sinton Flash Tester With Mapping Stage and Optics for Automated Cell Alignment. b) Example of Suns-VOC Curve (in Red) and Light I-V Curve With Load (in Blue), as Measured on an Antora TPV Cell



Discussion of Available Component Suppliers or Associated Partners

During this project the team has prioritized equipment suppliers local to the San Francisco Bay Area. Near the beginning of the project, the team connected with photolithography expert Al Renaldo for advice about coating tracks and cluster tools. In addition to providing a useful perspective on that set of tools and processes, Dr. Renaldo also made the invaluable contribution of introducing Antora to his former colleague Jack Kelly. Mr. Kelly is an expert at tool selection, cleanroom layout, and equipment engineering and maintenance, and he had a large impact on Antora's thinking when it came to selecting vendors. In addition to urging the team to work with vendors with local tool support, Mr. Kelly encouraged the team to consider purchasing used equipment that had been refurbished to "as new" condition with a warranty. He was then able to tap his network to identify a range of options for Antora's tool needs, thinking through the implications of the budget and providing recommendations for where the team could afford to spend less money and other areas where it should not.

Fortunately for Antora, the San Francisco Bay Area has no shortage of manufacturing expertise, particularly on the LRIP or prototyping scale. The Keyence and Tau Science characterization tools are the only examples of vendors where the team had to look beyond California, or even beyond the Bay Area.[7] As a result, the team enjoys rapid response service for all Antora's CEC RAMP equipment (the Keyence tool has not needed maintenance thus far, and there are many local reps), often from the OEMs themselves.

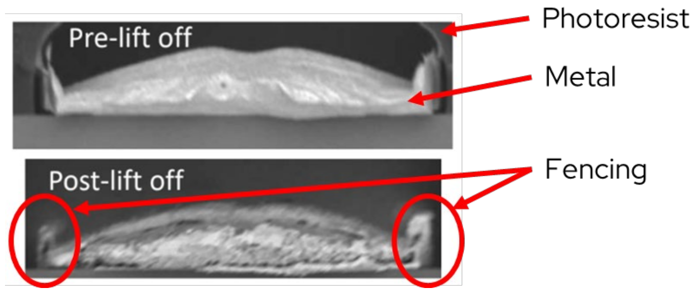
Discussion of Processing Improvements, Barriers, and Lessons Learned

Non-Technical: A key non-technical lesson learned is related to the interaction the team had with Tau Science, and later with ArcOptix, during the early stages of Antora's high-throughput characterization tool development. It took longer than expected to strike the right balance on legal terms related to this custom piece of equipment, which affected the project schedule.

Technical: The team overcame several challenges while developing Antora's in-house process for front-metal deposition and liftoff and isolation etching. Front-metal deposition and liftoff is challenging in Antora's TPV application because the front metal must carry electrical current densities of multiple amperes per square centimeter (A/cm^2). These current densities require multiple microns of front metal height, which pushes Antora's photolithography, electron beam evaporation, and liftoff steps to unusual processing parameter space compared with typical use cases.

[7] ClassOne is not a local company, but the refurbished tool the team bought from it was made by a local OEM named CHA, and the tool was refurbished by another local company named CPA Sputtering.

Figure 19: Example of "Fencing" in the Front Metal



The root cause is that there is insufficient space between the base of the photoresist pre-liftoff and the metal feature.

Source: Kayaku Advanced Materials

Figure 19 shows the "fencing" in the front metal that can result after liftoff where metal is left connected to the edges of the desired feature. This undesirable outcome is caused by insufficiently thick photoresist layers and/or inappropriate sidewall profiles in the photoresist patterns. Several learning cycles, as well as discussions with photoresist vendors, were required to down select Antora's photoresists and find appropriate process parameters.

Isolation etching is a wet-chemical etching process, typically using hydrochloric acid (HCl), that defines the individual devices on the bonded foil (see Figure 12, bottom row). HCl is known to be susceptible to process variability when there is variability in the water content in the samples or in the presence of certain metals, such as copper. A key lesson learned was how to design a robust isolation etch that was stable over time.

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

Table 5 shows Antora's measured takt times for all the steps in the process across eight lots, ranging in size from two to eight wafers per lot. Fields in Table 5 are shaded green for those lot+step combinations that were below the maximum allowable takt time estimated in Table 1.

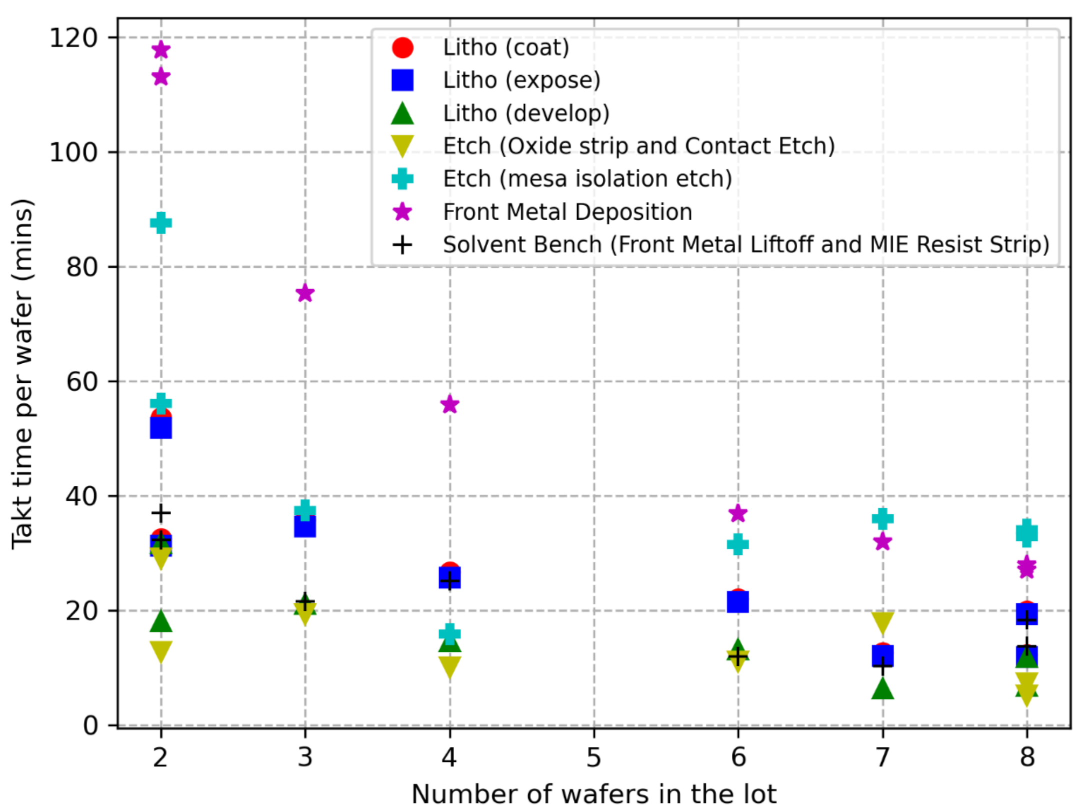
Table 5: Measured Takt Time for Process Steps

	Lot #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**					
	# of wafers in lot	**7**	**8**	**6**	**8**	**4**	**2**	**3**	**2**	**Average (all lots)**	**+/-**	**Average (lots w/6+ wafers)**	**+/-**	**Targets**
Mins/ wafer	Litho (coat)	12.6	12.3	22	19.9	26.7	53.6	35.7	32.5	26.9	13.7	16.7	5.0	**18**
	Litho (expose)	12	11.8	21.4	19.3	25.7	51.8	34.6	31.3	26.0	13.3	16.1	5.0	**18**
	Litho (develop)	6.3	6.8	13.2	11.8	14.6	31.7	21.1	18.1	15.5	8.3	9.5	3.5	**18**

	Lot #	1	2	3	4	5	6	7	8					
	# of wafers in lot	**7**	**8**	**6**	**8**	**4**	**2**	**3**	**2**	**Average (all lots)**	**+/-**	**Average (lots w/6+ wafers)**	**+/-**	**Targets**
	Etch (oxide strip and Contact etch)	17.7	7.2	11	5.1	10	29	19.3	12.7	14.0	7.7	10.3	5.5	**18**
	Etch (mesa isolation etch MIE)	36	34.1	31.5	32.8	15.8	56.1	37.4	87.6	41.4	21.6	33.6	1.9	**36**
	Front Metal Dep.	31.9	27.9	36.9	27	55.8	113	75.3	117.7	60.7	37.5	30.9	4.5	**36**
	Solvent Bench (front metal liftoff and MIE resist strip)	10.3	18.3	11.9	13.7	25.1	32.3	21.5	37	21.3	9.7	13.6	3.5	**18**

Light green shading indicates those steps where the takt time goal is met.

Figure 20: Takt Time/Wafer vs. Wafers/Lot, by Process Step



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 (such as Antora's front metal deposition step in the electron beam evaporator), 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 lot sizes of 15 wafers/lot (limited by the capacity of the electron beam evaporator), 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, the team asserts that **Antora's line has demonstrated > 2 MW/year theoretical nameplate 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 more than doubled when the team transitioned from 4-inch wafers to 6-inch wafers, as the team intends to do in the future.

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, if staffed to a level consistent with 24/7 manufacturing, 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). Antora's TPV cell supply chain includes the following categories of materials and services: indium phosphide (InP) substrates, custom epitaxy, and processing supplies including photoresists and chemicals.

The InP substrate market is a global commodity market and, during the project, the team sourced wafers from all major suppliers in this market. The team has two preferred suppliers based on price, business model, and production capacity, but it has qualified four suppliers whose substrates result in comparable TPV performance and yield.

There is a large number of custom epitaxy suppliers worldwide. The team has one preferred supplier based on business model and breadth of capabilities, and this supplier has the production capacity to supply more than 10MW/year of epitaxy. The team has qualified two other suppliers whose material results in comparable performance and yield and which have even greater production capacity.

Chemical supplies such as solvents, acids, and bases are used in Antora's process; these are commodity chemicals that are available from multiple suppliers, and there is no danger of a shortage. Antora processes are also qualified with common photoresist formulations, which can be exchanged with similar formulations if a preferred brand were to become unavailable.

Knowledge Transfer

The team already used the LRIP capability developed in this project to supply TPV customers such as Mesodyne and the Army Research Lab. 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 Thermo-photovoltaic 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 based on the semiconductor material InGaAs. 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 ClimateTech hardware ecosystem in this region.

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 a larger area and higher-power modules and products, more refined technoeconomic analysis, and customer outreach to better understand the pain points of the users of TPV devices.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
A/cm^2	Amperes per square centimeter
CE	Contact Etching
CIGS	copper indium gallium diselenide
EQE	External quantum efficiency
FTIR	Fourier transform infrared
InGaAs	indium gallium arsenide
InP	indium phosphide
I_{sc}	Cell's short-circuit electrical current
I-V	current-voltage
J_{SC}	short-circuit current density
FMD	Front Metal Deposition
FML	Front Metal Lithography
FMLO	Front Metal Liftoff
GW	gigawatts
HCl	hydrochloric acid
kt	kilotons
LRIP	low-rate initial production
MIE	Mesa Isolation Etching
MIL	Mesa Isolation Lithography
MLD	Microlink Devices
MRL	manufacturing readiness level
MW	megawatt
NIST	National Institute of Standards and Technology
NOx	Nitrogen oxide
PV	photovoltaics
PVSC	Photovoltaic Specialists Conference
R_{BBG}	below bandgap reflectivity
R_S	series resistivity
R&D	research and development
SEB	substrate etch back
Si	silicon
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.

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: How the TPV Cells Were Characterized

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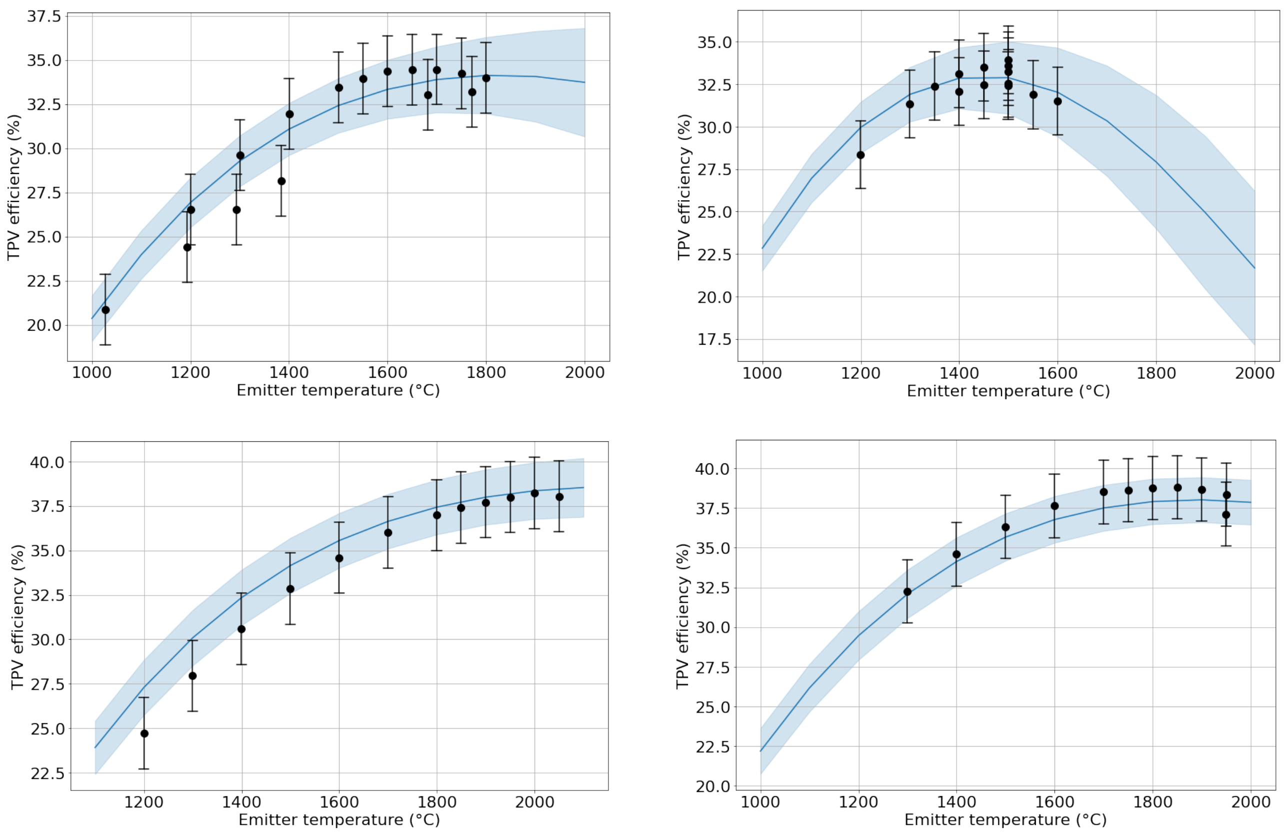
APPENDIX A: How the TPV Cells Were Characterized

Figure A-1: Some Examples of the Correspondence Between Antora's Model Prediction of TPV Efficiency as a Function of Temperature (Solid Blue Line), and Experimental Measurements in the Calorimetric Setup (Black Dots)



The cells were characterized by measuring light I-V, EQE, and reflectance in the way described in the previous section, with one difference. At the time the team developed Antora's full-wafer process, it did not yet own the Sinton flash tester. Rather, the team tested I-V on all cells under low-intensity light (1-10 suns equivalent) and extracted Antora's key metrics at a J_{SC} of 100 mA/cm^2. The team also sampled EQE and FTIR on a subset of cells on a given wafer, knowing from other work that EQE-derived J_{SC}, and FTIR-derived R_{BBG} are typically fairly consistent within a wafer (see figures 8 and 9). Because of the highly manual state of Antora's characterization equipment at the same time the team was developing the wafer fragment TPV cell process, it was not possible to measure 100 percent of cells through EQE and FTIR. In order to do this at high volume, the team needs something equivalent to the high-throughput characterization tool that the team is in the process of developing in collaboration with Tau Science as part of Task 3.

Figure A-2: Photographs of the Light I-V Test Station, FTIR setup, and EQE Setup Used to Characterize the TPV Cells

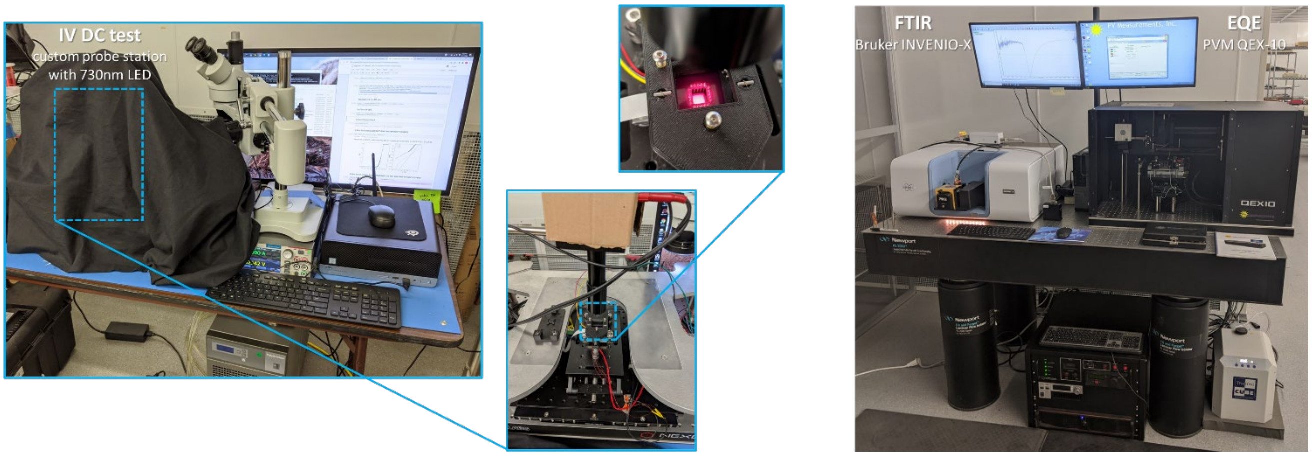
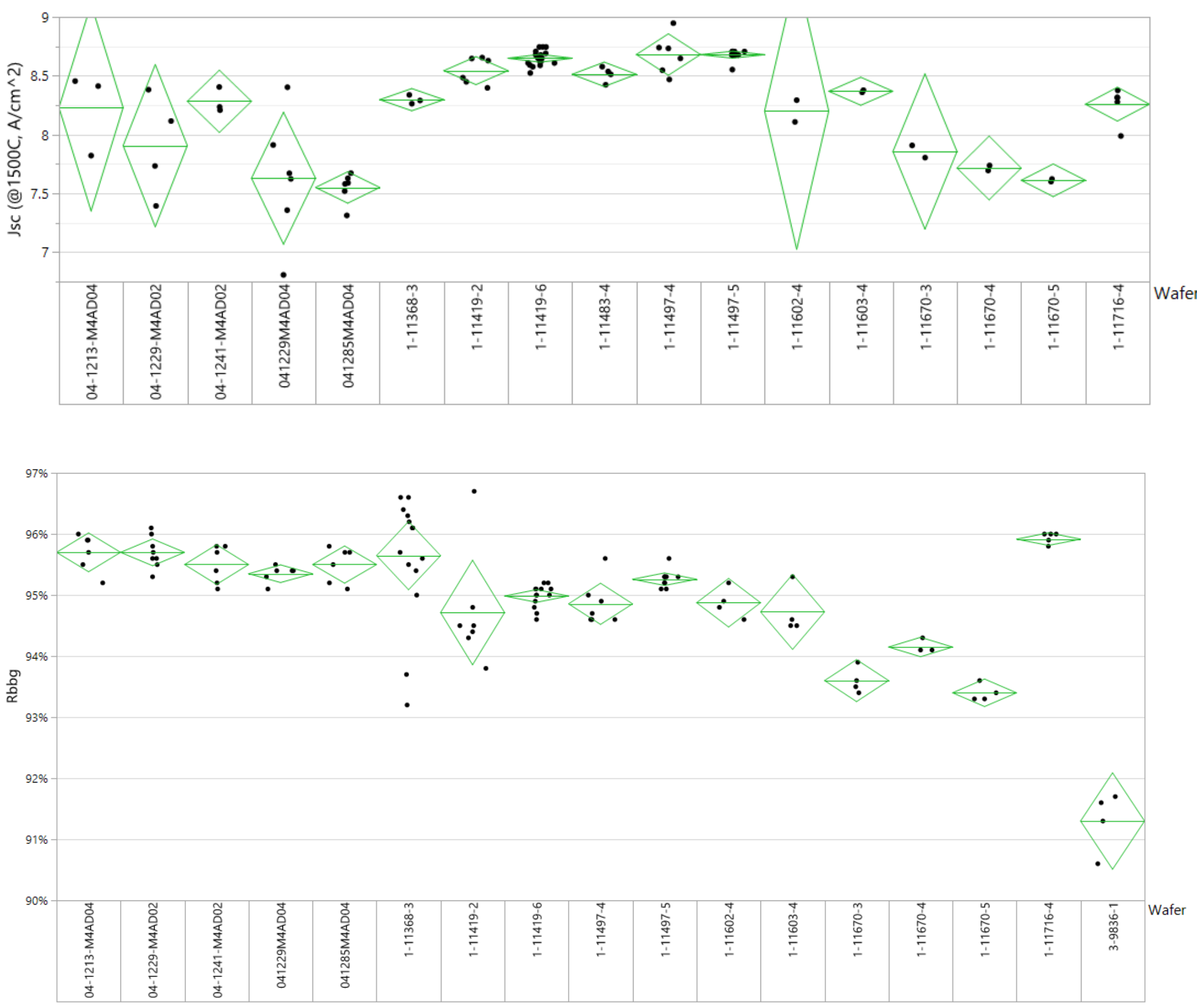


Figure A-3: Variability of EQE-derived J_{SC} and FTIR-derived R_{BBG} on Full-wafer Samples



This figure shows that between-wafer variation is typically larger than within-wafer variation, justifying a sampling approach to measuring these quantities, at least until the team has higher-capacity tools for measuring them.