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FINAL PROJECT REPORT

Processing and Architecture Design to Develop and Demonstrate Stable and Efficient Perovskite+Silicon Tandem Modules

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PREFACE

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

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas 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.

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ABSTRACT

This applied research project moved perovskite+silicon tandem photovoltaic technology, a thin-film approach to solar photovoltaics, using synthesized minerals of the formula ABX3 (e.g., calcium titanium oxide – CaTiO3), one step closer to commercial readiness. Perovskite+silicon tandem photovoltaic solar panels offer extremely high performance, with up to 25-percent to 30-percent efficiency. This would directly reduce the cost to install solar for California ratepayers by up to 40 percent and move the state closer to its ambitious climate and sustainability goals. This project demonstrates stable perovskite solar cells and panels and a shift from small-area, bench-scale academic processes for fabricating perovskite solar cells and panels to scalable, high-throughput, high-yield industrial processes and commercial-quality performance at product scale. This project developed a blade-coating process for an initial proof of scale up to 6 inches wide, demonstrated the three-month field durability of perovskite solar cells and over 10,000 hours of operational testing durability, demonstrated over 22-percent efficient tandem solar panels, and developed a recycling process for recovering materials at the tandem solar panels' end of life.

Keywords: perovskite, silicon, scalable processing, tandem modules.

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Executive Summary

This project took a critical first step toward commercial readiness of the emerging technology of perovskite+silicon tandem solar panels, which could significantly increase the power output of photovoltaic solar panels when compared with existing commercial technologies. Perovskite+silicon tandem solar panels are a thin-film photovoltaic technology that combines traditional crystal silicon with perovskite solar cells.

Background

California leads the nation in its clean energy goals and policies and has pledged to provide 100 percent of electricity retail sales and state loads from renewable and zero-carbon resources in California by 2045. This ambitious mandate shaped and continues to shape the generation, transmission, and distribution of electricity in California, and is codified in a broad spectrum of state law, summarized in the following paragraph.

California's clean-energy goals are incorporated into virtually every aspect of energy: reducing greenhouse gas emissions (Assembly Bill 32, Statutes of 2006 – also known as the Global Warming Solutions Act of 2006; Senate Bill 32, Statutes of 2016 – also known as the California Global Warming Solutions Act of 2016), building zero-emission buildings (Assembly Bill 32, Statutes of 2018 – also known as Zero-Emissions Buildings and Sources of Heat Energy, advancing cost-effective energy storage (Assembly Bill 2514, Statutes of 2010), and achieving 100-percent carbon-free electricity by 2045 (Senate Bill 100, Statutes of 2018 – also known as the 100 Percent Clean Energy Act of 2018). To fulfill these diverse and ambitious obligations, California supports the development and deployment of clean-energy technologies and further requires that new homes be both zero-net-energy and constructed with solar panels (Title 24). The state is also transitioning to electricity-ready heating, cooking, and electric-vehicle charging in homes (2022 Energy Code) and will require all new passenger vehicles to be zero-emission by 2035 (Executive Order N-79-20, California Air Resources Board regulations). The California Air Resources Board's 2022 Advanced Clean Cars II regulations further require that, beginning in 2023, strategies must be implemented to increase electric-vehicle penetration into low-income and disadvantaged communities.

These greenhouse gas-reducing initiatives will increase statewide electricity demand. Analyses of U.S. Energy Information Administration data indicate that achieving zero-net-electricity on typical homes after electrifying transport, heating, and cooking, will additionally require more efficient solar panels with sunlight-to-electricity efficiencies exceeding 25 percent, substantially higher than those of existing commercial solar photovoltaics.

Thin-film solar photovoltaics employ very thin layers, typically ~5 µm or thinner per layer, that are deposited on a supporting structure, such as the top cover sheet of glass common to almost all solar panels. Due to these thin layers, overall materials costs of thin-film solar panels can be substantially less than traditional silicon solar panels, which are wafer-based.

The metal-halide perovskite material can be integrated into a thin-film structure and take advantage of these lower material costs.

Tandem structures combining wide-bandgap metal-halide perovskite with narrow-bandgap silicon have the potential to increase solar-panel efficiency without increasing panel dollar-per-watt cost. More importantly, more-efficient solar panels reduce total system costs by amortizing non-panel costs over more watts of electricity. Some examples of non-panel costs include racking and wiring hardware, labor, design and engineering, and other costs associated with installing solar panels. These kinds of costs, known as balance-of-system costs, are much more expensive than the solar panels themselves, particularly on rooftop installations. With higher-efficiency solar panels that are 25 percent to 30 percent efficient, rooftop installations can also be 20 percent to 40 percent less expensive, which is extremely important for lowering electricity costs and encouraging rapid solar adoption, particularly in economically disadvantaged communities where pricing and upfront costs can be prohibitive. In the U.S., high-volume photovoltaic system installation companies report that 50 percent of residential rooftop customers want to install more photovoltaics than can fit on their roofs. They also estimate that a 30 percent efficient solar panel can reduce area-constrained residential total photovoltaic system costs by as much as $1/watt over standard solar panels (based on private conversations with residential solar installers, 2017).

A new technology called metal-halide perovskite can potentially increase both the efficiency and power output of existing silicon solar technologies through more effective use of sunlight's full spectrum. The perovskite technology is placed above the silicon to absorb visible light from the sun, sending infrared light to the silicon beneath. These are referred to as perovskite+silicon tandem solar panels. Perovskite+silicon tandem solar panels hold great promise in a line-of-sight future where current-technology solar panels are nearing their limits on cost and practical efficiency and the balance of system costs remains a dominant system-cost driver.

To advance perovskite technology to commercial production, two key challenges must be met: demonstrating stable perovskite solar cells and panels through field tests and standard accelerated tests, and shifting from small-area, bench-scale academic processes of fabricating perovskite solar cells and panels to scalable, high-throughput, high-yield industrial processes that demonstrate commercial-quality performance at product scale. This project tackled both of those key challenges.

Project Purpose and Approach

This project was managed by Tandem PV, Inc. It leveraged research and development (by its founders Colin Bailie and Chris Eberspacher) and the technology baseline developed by the company. The project's purpose was to identify and reduce technical risks at the research and development stage of this emerging technology to prepare it for commercial manufacture for the rooftop solar market.

The goal of this project was to fabricate and stress-test durable perovskite+silicon tandem solar panels using scalable materials and processes as a precursor technology-readiness step to commercializing full-sized solar panels. The project achieved the scalable and robust processing of perovskite layers through blade coating and rapid-thermal annealing processing methods, which were applied to Tandem PV's proprietary perovskite formulations. Durability was achieved through incorporation of innovative barrier materials that increased both perovskite solar PV-panel efficiency and its inherent cell stability, demonstrated through long-term field and accelerated-lifetime tests.

Several metrics demonstrate project success at this stage of research and development, such as > 3 outdoor field testing, passing standard accelerated tests, and >25 percent efficiency. The metrics for success in commercialization will be >25 year anticipated outdoor field life, passing standard accelerated tests, >25 percent efficiency, and scale to product size.

Key Results

Scalable Perovskite Processing

New perovskite ink and blade coating, rapid air drying, and high-temperature anneal processes were developed during this project to deposit thin films of metal halide perovskite on the cover glass of silicon-solar panels. The blade coating and rapid air-drying processes successfully produced 6 inches by 3 inch and 6 inch by 6 inch coatings of metal halide perovskite within both the targeted thickness homogeneity and the roughness specifications of the project. The thickness homogeneity can be further tightened by transitioning to slot-die coating, an easily scaled process like blade coating. Blade coating and rapid air drying were used to make greater than 20 percent efficient perovskite solar cells and approximately 18 percent efficient perovskite solar modules.

Barrier Layers

A halide barrier layer was developed during this project that exhibited both resistance to electrode corrosion and degradation by water penetration. The halide barrier layer was demonstrated and found to be compatible with high-efficiency solar cells. To further improve the barrier layer, a method was developed to remove defective perovskite material from the top surface of the perovskite thin film.

Certified Performance

Multiple cells and modules were sent to the National Renewable Energy Laboratory (NREL) for performance certification. A 1 cm2 perovskite+silicon tandem panel was certified at 19.3 percent efficiency. Later in the project, a 25 cm2 perovskite+silicon tandem panel was certified at 20.3 percent efficiency. The best 25 cm2 perovskite+silicon tandem panel was measured in-house at 22.4 percent efficiency but was not certified by NREL.

Accelerated and Operational Durability

Perovskite solar cells were tested using custom tools for simulating field-equivalent conditions for over 4,000 hours; they maintained 95 percent of peak efficiency, representing many years of field-equivalent operation. Perovskite solar cells were also tested in a rooftop installation, and there was no observed loss in performance over a **three-month** period, which affirmed that the perovskite solar cells were stable in field operation. Packaged perovskite modules maintained >92 percent efficiency after a standardized accelerated test involving 200 cycles at temperatures between 185°F and -40°F (85°C and -40°C). Package failure was still observed in the damp-heat and temperature-cycling tests, suggesting further packaging refinement is needed.

Recycling and End-of-Life, Supply Chain, and Life-Cycle Analyses

In life-cycle analyses, the energy-payback time was lower for perovskite+silicon tandems when compared with silicon-only panels. In the supply-chain analysis, no fundamental materials or tool constraints were identified that would prevent the cost-effective mass production of this technology. For recycling, Tandem PV developed a method to recycle and recover the glass and metal components of perovskite solar panels, a method that is compatible with some current commercial recycling methods.

Knowledge Transfer and Next Steps

As a direct result of this project, two academic papers were published on perovskite+silicon life-cycle analyses, one academic paper is currently being written on perovskite solar panel recycling, two patent applications were filed, and a third patent application is being prepared.

With the technical results achieved in this project, Tandem PV raised $9 million in Series A financing and was awarded a grant from the United States Department of Energy to continue developing the technology. Tandem PV is continuing research and development after the end of this project focused on combining target performance metrics into a single panel to achieve the certified performance anticipated in this project. Tandem PV is also assembling a pilot manufacturing line in San Jose, California, and has applied to the California Energy Commission’s Realizing Accelerated Manufacturing and Production for Clean Energy Technologies program with the goal of delivering its first high-efficiency solar panels within the next two years.

Results from this project demonstrated key milestones and metrics on the path to commercialization of a novel technology and identified further areas for continued research and development to bring this technology to higher technology and manufacturing readiness levels.

This work benefits ratepayers, the public, and the environment by bringing closer to commercial reality a technology that will substantially reduce the cost of solar panels, the cost of solar installations, and therefore the total levelized cost of electricity at all scales of solar installations, further reducing reliance on fossil fuels and associated air pollution and greenhouse gas emissions.

This work, together with other academic works by researchers at California universities, informs policy and planning by demonstrating the promise of perovskite technology and underscoring the need for further support at the state level for research and development, demonstration, and initial commercial production to accelerate the commercial readiness and adoption of this technology.

CHAPTER 1: Introduction

As an applied research, development, and demonstration project, this project moved perovskite tandem photovoltaic (PV) technology, a thin-film technology, one step closer to commercial readiness. Perovskite is a class of metal-halide minerals with optical and electronic properties uniquely suitable for use in PV solar panels due to the ability of perovskite to absorb different portions of the sunlight spectrum to generate very high voltage. Perovskite+silicon tandem PV solar panels have the potential to significantly increase the power output of solar PV panels when compared with existing technologies on the market today. The increase in power output is due to the more effective use of the full spectrum of light available from the sun, which utilizes the unique properties of perovskite minerals. The perovskite technology is placed on top of traditional silicon to absorb visible sunlight, sending only infrared light to the silicon below; the combination of the perovskite and the traditional silicon layers gives the technology its label: perovskite+silicon tandem PV solar panels.

Perovskite+silicon tandem solar PV panels can significantly improve both solar-panel performance and its cost. However, remaining multiple technological hurdles must be overcome to ultimately transition perovskite+silicon tandem PV solar panels into commercial products. These hurdles include: development of manufacturable processing for the metal-halide perovskite layers and other layers in the perovskite solar cell architecture; development of additional materials and methods to improve the long-term durability of perovskite solar panels; ensuring such novel solar panels have sufficiently large and diverse upstream supply chains to manufacture perovskite solar panels in large quantities; and ensuring that perovskite+silicon tandem solar panels are recyclable.

Addressing these technological hurdles readies perovskite technology for commercial availability, enabling this new class of high-performance solar panels to be manufactured and sold in California to support the state’s ambitious environmental and climate-change mandates (see appendix A).

Table 1. Competitive Matrix

Attribute	Tandem PV	Existing Technology
Description	Mechanical-stack perovskite+Si tandem	Crystalline wafer Si, thin-film CdTe
Sunlight-to-electricity conversion efficiency	25% market entry, >30% mature	20-21% typical Si module, 18% typical CdTe module
Fabrication cost $/m^2	<$15/m^2 added cost	~$30-40/m^2
Power product $/W	< Si $/W	Commodity Si sets market $/W, net margins very low
Market focus	High-BOS for max efficiency impact, e.g., rooftops	Si residential & commercial roofs; CdTe ground mount
Capital Intensity	Low	Medium

Source: Tandem PV

Development of manufacturable processing for perovskite solar cells is a critical technological hurdle for commercialization of perovskite+silicon tandem solar panels. Most laboratory perovskite solar panels are made with a method called *spin-coating*, which is a non-scalable process with high waste. To compete in the commoditized solar marketplace, perovskite solar panel manufacturing methods must meet or exceed the manufacturing efficiency of existing silicon (Si) and cadmium telluride (CdTe) solar technologies, including high throughputs, high materials usage efficiency, nearly 100 percent manufacturing yield, and manufacturing methods compatible with commercial solar panels measuring approximately 1 meter (m) by 2 meters in dimension.

A perovskite solar cell is a set of coatings on a substrate that has a photovoltaic effect. The solar cell is typically evaluated by its power conversion efficiency (PCE or η) with units in percentages, the short circuit current density (JSC), with units of mA/cm2, the open-circuit voltage (VOC) with units of V, and the fill factor (FF) with units in percent. The JSC describes how well the solar cell converts photons from the sun into current. The VOC describes how well the solar cell maintains the energy of those photons as they are converted into electrical current. The FF describes how well the solar cell converts that maximum electrical current and voltage (JSC and VOC) into actual electricity. A perovskite solar module consists of multiple solar cells. Those modules are typically constructed through a series of cuts in the perovskite layers that turn a single large perovskite solar cell into several smaller perovskite solar cells, which are electrically connected in series. A perovskite solar module is typically evaluated with these metrics, with an additional metric called the geometric fill factor (GFF), expressed in percentages. The GFF describes how much performance is expected to be maintained in the JSC when making the series of cuts to turn a large perovskite solar cell into a module.

Development of additional materials and methods for the long-term durability of perovskite solar panels is required to achieve the "bankability" of this new technology. Bankability is loosely defined as the threshold at which banks will finance solar projects, which generally requires components of the solar project to have little or no technical risk. In particular, for solar projects, the profitability calculations of these projects require that solar panels last for years to decades, and that the solar panels be backed by, at minimum, 25-year warranties. Development of additional innovations to advance perovskite technologies that pass accelerated tests would increase confidence in a 25-plus year field life, so are therefore critical to the future commercial success of the technology. Demonstrations of accelerated and outdoor field tests are also critical for marketing perovskite+silicon tandem solar panels to the public.

Ensuring an available supply chain for manufacturing perovskite+silicon tandem solar panels is the third essential component for achieving the commercial viability of those panels. Ensuring recyclability is also critical for long-term sustainability. Existing commercial solar panel technologies have well-established supply chains. Perovskite technology has similar supply chains, but also requires materials and tools uncommon in the solar industry. These unique materials and tools will be key in determining who can manufacture these materials and tools, and at what costs and quantities. Existing commercial silicon solar panels are technically recyclable, though at high cost, and recycling typically occurs at high rates only in Europe, where it is legally mandated. Ensuring the recyclability of perovskite+silicon tandem PV solar panels is required to sell panels in Europe, and potentially could become necessary in the United States as recycling laws evolve.

The goals of this project were to fabricate and stress-test durable perovskite+silicon tandem solar panels, using scalable materials and processes as a technology-readiness step in commercializing full-sized perovskite tandem PV solar panels. Those goals were achieved through the following tasks to:

1. Develop scalable perovskite processing, for which the team evaluated both spray-coating and blade-coating techniques.
2. Develop barrier layers, which improved the operational durability of perovskite solar cells and panels; the team evaluated nanoparticles, surface-conversion, and defect-removal techniques.
3. Certify the performance of perovskite+silicon tandem PV solar panels through independent third parties.
4. Measure the accelerated and operational durability of perovskite+silicon tandem PV solar cells and panels through both standardized accelerated tests and outdoor field tests.
5. Develop recycling methods for product end-of-life, evaluate the upstream supply chain, and compare the life-cycle analysis of this new technology against existing commercial solar PV technologies.

The intended audience of this report and its results includes potential investors, customers, and commercialization partners of Tandem PV. Bankability and manufacturing costs are two critical factors considered by this audience as it evaluates the acceptance of perovskite technologies in commercial products.

CHAPTER 2: Project Approach

This project was approached through experimental research and design by building on the technical expertise and experience of the project participants. Tandem PV identified major technical risks to commercialization of perovskite technology, including scalable deposition of perovskite thin-films, barrier layers to improve durability of perovskite cells and modules, proof points for accelerated and operational durability of this new technology, and recyclability of the technology. Through internal resources and with collaborating organizations, Tandem PV worked to address these risks through fabrication and testing of thin-films, solar cells, and solar panels and advanced measurement techniques to understand failure modes, material properties, and device characteristics.

Scalable Perovskite Processing

Commercialization of perovskite solar PV technology requires scalable, inexpensive, and rapid techniques for making high-quality perovskite films. This project tested improved methods of depositing and crystallizing perovskite films.

Perovskite films can be deposited by simple liquid processing. Perovskite precursor reactants such as lead iodide and methylammonium iodide are dissolved in organic solvents, and the resulting precursor ink is then deposited as a thin layer onto a substrate, which is a few micrometers thick of wet film deposited by spin coating. A perovskite film can then form at room temperature as the solvent evaporates and the reactants interact. Perovskite crystal nucleation begins with the supersaturation of the wet film during drying; in order to grow large high-quality grains, it is important to crystallize rapidly from a low density of nucleation sites, which generally necessitates rapid solvent removal, such as by displacing the ink solvent with *anti-solvents* (solvents that are miscible with the ink solvent but immiscible with the perovskite precursor components). In order to better control nucleation, complexing agents (molecules that temporarily bind to perovskite precursor components to prevent crystal formation until the agents are removed) can be added to the precursor ink. As part of the project, Tandem PV developed patent-pending inks with unique complexing agents that facilitate simple evaporative drying in air (as opposed to the use of hazardous anti-solvents). This enables the use of cheaper, more easily scaled layer deposition tools and techniques.

Tandem PV has previous experience with depositing PV thin films with spin-coating, ink-jet printing, blade coating, slot-die coating, and spray coating. This project built upon Tandem PV's prior experience to implement high-efficiency, conformal ultrasonic spray coating to deposit perovskite precursor layers. Ink-jet and slot-die coating techniques are hampered by precursor ink viscosity and concentration requirements, rates of liquid deposition, and long drying times of wet films. Ultrasonic spray coating is more compatible with typical viscosities of perovskite precursor inks. With fine droplet spraying, the drying process can be accelerated by removing some fraction of the solvent from high surface area droplets in milliseconds in flight from the nozzle to the substrate, compared with drying times of approximately one minute for printed wet films. Reduced drying time is critical to process reproducibility since standard ink drying and nucleation rates vary with temperature, solvent vapor concentration, humidity, and forced convection gas flows. A more rapid drying process limits the effect of these environmental variables on the vulnerable pre-annealed perovskite precursor layer.

Scalable spray coating was tested on a commercial ultrasonic spray coater optimized for fluid flow rate, ultrasonic frequency, nozzle shape, distance from nozzle to substrate, substrate movement speed, and raster overlap. Spraying was completed in a custom enclosure in which air velocity, solvent vapor, air temperature, and humidity were individually controllable so that drying, and nucleation processes could be modulated. Films were evaluated for thickness homogeneity, grain size, carrier mobility and lifetime, surface roughness, density of pinholes or positive defects, and solar cell performance. Spray-coated films were compared against spin-coated and blade-coated films.

Key Milestone:

- Film Quality Report

- Perovskite Layer Thickness and Homogeneity
- Perovskite Layer Surface Roughness
- Perovskite Layer Grain Size
- Perovskite Solar Cell Performance Using Spray-Coating and Rapid Thermal Processing
- CPR Report #1

Barrier Layers

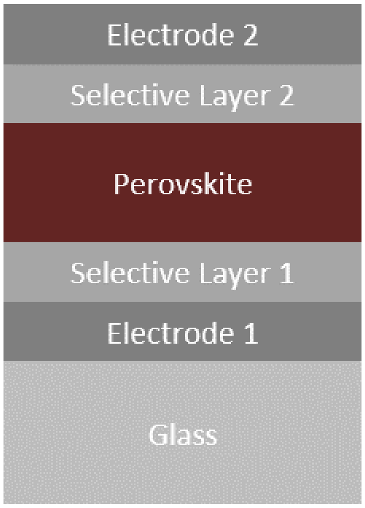
Perovskites are relatively new, pre-commercial materials that offer significant promise for solar PV module efficiency gains and PV-system cost savings even though early-generation small-area perovskite cells exhibited poor inherent environmental stability. Interviews with PV manufacturing companies and major PV installers indicated that perovskite commercial readiness will require passing accelerated tests such as International Electrotechnical Commission (IEC) 61215 or 61646 (California Energy Commission [Energy Commission] 2021), conducted three times, and multi-season field tests (tandem PV interviews with solar manufacturing CTOs, n.d.). Existing commercial technologies are regularly subjected to and pass such tests. Thus far, perovskite solar cells have only passed some standard-duration International Electrotechnical Commission-type durability tests.

Scientific understanding of the stability of perovskite solar cells identified humidity (J. Yang et al., 2015), ultraviolet (UV) light (Melvin et al., 2018) and temperature (Bush et al., 2016; Conings et al., 2015) as environmental stressors that can induce chemical degradation in perovskite cells. Data suggests that defects (Kim et al., 2018), grain size (Wang et al., 2017), morphology (Shallcross et al., 2017), chemical makeup (Saliba et al., 2016), choice of heterojunction (Guo et al., 2018), and electrode (Domanski et al., 2016) layers also affect the longevity of perovskite solar cells. The root causes of perovskite solar cell degradation are likely multifaceted including electrochemical reactions at interfaces (Kato et al., 2015; Zhou et al., 2016), bulk diffusion of perovskite component species through ionic conductivity (Kim et al., 2018), and by vacancy concentration and bulk vapor evolution (Conings et al., 2015) of perovskite component species. These root causes are often generated by operational and environmental stressors, and were improved through breakthroughs in interface materials (Lira-Cantú, 2017), perovskite composition and processing (Saliba et al., 2016), and barriers and packaging (Bush et al., 2017). While progress was made, the technology required for assuring perovskite cell stability and perovskite module durability was not established.

Adding barrier properties to functional layers on top of the perovskites was shown to substantially improve the durability of perovskite solar cells (Bush et al., 2016, 2017). Bailie et al. (2016) demonstrated that by first using an inorganic nanoparticle selective layer, followed by an indium tin oxide (ITO) transparent conductive oxide (TCO) layer (a known gas barrier), (Henry et al., 2001), as the second electrode on a perovskite solar cell, devices were much more stable to temperature while operating (Bush et al., 2016). A key limitation to the device stability was the presence of pinholes in the ITO layer caused by defects in underlying layers. Degradation was observed to proceed from those pinholes. In a subsequent study, atomic layer deposition (ALD) was used to deposit a low pinhole-density selective layer on top of the perovskite (Bush et al., 2017). The combination of low pinhole density, a TCO layer, and standard PV packaging together passed temperature and humidity tests consistent with IEC 61215, along with 1,000-hour light-soaking. This combination is one of the few perovskite solar cells in the research community to pass critical tests consistent with IEC 61215. This suggests that commercial-grade product durability will be more easily reached by thin conformal continuous carrier selective layers and a protective-barrier transparent electrode.

The successful demonstration of an inorganic selective layer, which can be manufactured with fewer pinholes by solution processing, will significantly increase the commercial readiness of perovskite solar technology by combining industry-standard durability with low-cost manufacturing. This project generally focused on Selective Layer 2 (as seen in Figure 2), and its interfaces, developing either an inorganic or partially inorganic Selective Layer 2 or adding inorganic barrier-layer properties to the interface between the perovskite layer and Selective Layer 2.

Figure 1. Typical Perovskite Solar Cell Stack



Source: Tandem PV, 2022

Certified Performance

Working with independent certified testing laboratories was important for conveying high confidence in the measurements reported during this project. The National Renewable Energy Laboratory (NREL) in Golden, Colorado, was chosen as the independent certified testing laboratory to which perovskite+silicon tandem PV solar cells and panels were submitted for performance certification.

To meet the milestones in this project, four samples were submitted to NREL. (More were not submitted as planned due to the throughput limitations of NREL's laboratory.)

Key Milestones:

- Efficiency Certification Report

- The Tandem PV Baseline Performance
- The Certified Tandem PV Cell Performance
- Panel Efficiency Certification Report

- The Certified Tandem PV Module Performance

Accelerated and Operational Durability

The specific objective of this task was to advance perovskite solar PV panels from the presumption of an inherent durability deficit to a practical demonstration of production-worthy panel durability by passing the basic threshold needed for solar PV panel manufacturers to pursue perovskite product commercialization, specifically IEC 61215 or 61646 and outdoor field testing. This task applied the results gained from Task 3 in developing more robust and durable perovskite solar cells and fabricating and testing more durable perovskite modules. Panel-sized solution-based processes occurred with tools and processes developed throughout this process, as well as tools and processes previously developed by Tandem PV. Cell-to-module integration was performed using tools and processes previously developed by Tandem PV. Lamination services and silicon cells were provided by Tandem PV's collaborators.

Accelerated testing occurred at the independent laboratory D2 Solar. Prototype modules were additionally monitored for failure mechanisms not present in laboratory-scale perovskite solar cells. Field testing occurred in-house on the rooftop of Tandem PV's laboratory.

Key Milestones:

- Durability Report

- Results of IEC 61215 Tests for Cell Performance Under Damp Heat and Temperature Cycling
- Results of 3-Month Outdoor Field Testing
- Panel Durability Report

- Results of In-House Accelerated Testing of Perovskite on Silicon Tandem PV Solar Panels
- Results of Independent Accelerated Testing of Perovskite on Silicon Tandem PV Solar Panels
- Results of Field Testing of Perovskite on Silicon Tandem PV Solar Panels

Recycling and End-of-Life, Supply Chain, and Life-Cycle Analyses

Supply Chain

Perovskite solar PV products will for the most part utilize materials, tools, and services that already exist in the supply chains of traditional silicon and thin-film PV manufacturing. Notable exceptions are specialty materials such as perovskite precursor reactants and charge-selective-layer raw materials, and wet-film deposition and annealing tools for spray-coating and printing perovskite precursor inks and charge-selective-layer colloidal suspensions. Some of these materials were evaluated in the supply chain by published technoeconomic analyses (L. Chang et al., 2017; Song et al., 2017; X. Yang et al., 2016; Li et al., 2018) with widely varying conclusions. Tandem PV created its own supply chain and technoeconomic analysis and expanded upon its existing analysis during this project with the materials and methods developed over the course of the project. Tandem PV interviewed vendors and received specifications and quotes to estimate costs and throughputs, and used the data generated during this project to estimate yield and performance.

During this project, Tandem PV defined materials and tools needed for commercial-scale manufacturing and strengthened relationships with key prospective suppliers to accelerate readiness of the technologies and materials and the availability of materials, tools, and expertise.

Life-Cycle Analysis

The life cycle of perovskite PV solar panels is an area of concern due to the novel nature of this technology, the use of potentially toxic chemicals and materials (such as the lead present in the perovskite crystalline structures), and the energy involved in producing solar PV modules. To enable sustainable power generation, the solar panels must produce significantly more power than the input energy used to manufacture them, typically defined as energy payback time. Numerous life-cycle analyses (LCAs) for perovskite PV solar technology (Celik et al., 2016; Kadro and Hagfeldt, 2017; Vidal et al., 2017; Alberola-Borràs et al., 2018; Billen et al., 2019; Alberola-Borràs, Vidal, and Mora-Seró, 2018; Bae et al., 2019) have generally concluded that the energy payback time is short, the lead content is not a significant toxicity factor, and recycling can further reduce the energy payback time. Tandem PV worked with experts from Columbia University and Brookhaven National Laboratory to determine the unique LCA contributions to the components of the perovskite technology, specific to Tandem PV.

Recycling

Multiple efforts have also been made to address the recyclability of perovskite technology (Kadro and Hagfeldt, 2017), which have yielded methods to recycle the lead content as well as the precious metals and even the TCO-coated glass, the most expensive and most concerning material from a perception-of-toxicity standpoint. Tandem PV tested these recycling methods on its perovskite panels and evaluated the potential cost of the impacts, both positive and negative, of these recycling methods.

Key Milestones:

- Supply Chain Analysis Report
  - The Status of Upstream Suppliers of Input Materials, Costs, and Current and Anticipated Production Volumes
  - The Status of Manufacturers of Suitable Processing Equipment, Costs, Throughputs, and Yields
  - The Difference Between the Baseline Materials and Processes and Those Developed During This Project
- Life-Cycle Analysis Report
  - The Life Cycle of Baseline Materials and Processes
  - The Life Cycle of the Materials and Processes Developed During This Project
- Recycling Report
  - The Efficacy of Methods for Recycling Components of Perovskite Solar Cells

- The Efficacy of Such Recycling Methods When Applied to a Product-Style Perovskite on Silicon Tandem Solar Panels

CHAPTER 3:
Results

New perovskite ink and blade coating, rapid air drying, and high-temperature annealing processes were developed during this project to deposit thin films of metal halide perovskite on the cover glass of silicon-solar panels. Blade coating and rapid air drying were used to make greater than 20 percent efficient perovskite solar cells and approximately 18 percent efficient perovskite solar modules. Perovskite solar cells were tested in a rooftop installation, and there was no observed loss in performance over a three-month period, which affirmed that the perovskite solar cells were stable in field operation. To advance perovskite solar panel recycling, Tandem PV developed a method to recycle and recover the glass and metal components of perovskite solar panels, a method that is compatible with some current commercial recycling methods.

Film Quality Report

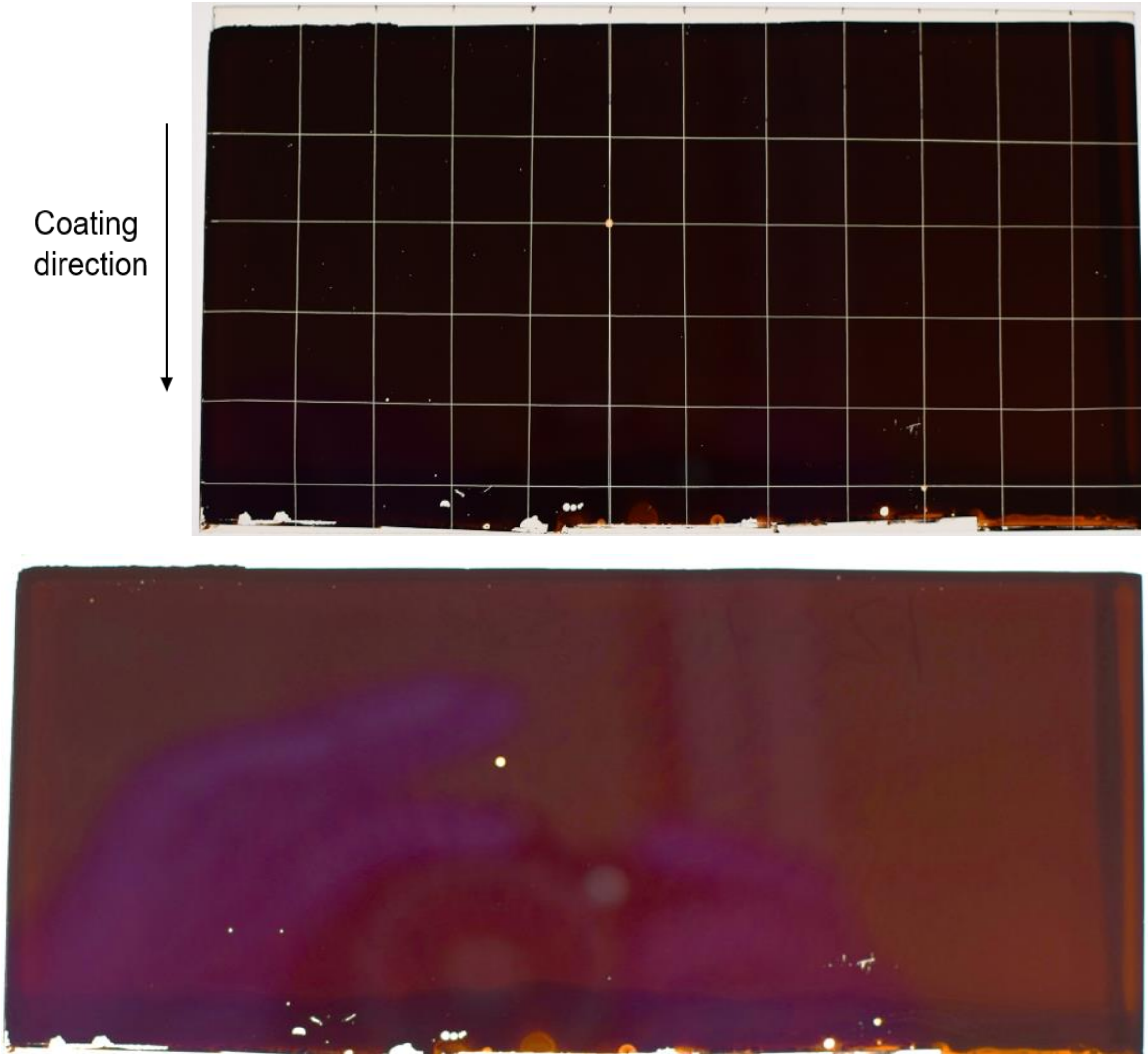
Key metrics were:

- Perovskite Layer Thickness and Homogeneity.
- Perovskite Layer Surface Roughness.
- Perovskite Layer Grain Size.
- Perovskite Solar Cell Performance, Using Spray-Coating and Rapid Thermal Processing.

Perovskite Layer Thickness, Homogeneity, and Surface Roughness

The target perovskite layer thickness was between 600 and 1,000 nanometers (nm), and was achieved using a blade coating process, which is a benchtop analog to the more common slot-die coating industrial process. Perovskite films were coated on 3" x 6" inch glass substrates and evaluated by optical profilometry (a technique which uses light to measure the thickness of films down to nanometer resolution) at regular intervals to measure the thickness and roughness of the sample. The target roughness was 0 to 25 nm. An example appears in Figure 2.

Figure 2. 6-Inch by 3-Inch Perovskite Film. Top picture shows the profilometry grid. The bottom picture was taken with a backlight to show good film uniformity. Gloves and camera are reflected in the bottom picture.



Source: Tandem PV

The results of the optical profilometry data are shown in Table 2 and Table 3. The coating was within thickness and roughness target ranges.

Table 2. Perovskite-layer thickness measurements were taken with an optical profilometer in a 2D grid on a 6-inch-wide by 3-inch-long sample.

		Position of Scribe in Width Direction (in)											
		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	Average
		Thickness (nm)											
Position of scribe in length direction (in)	*0.5*	1082	1118	1080	1095	1036	1008	992	952	977	922	903	1015
	1	1036	1032	1033	995	983	964	955	932	895	882	873	962
	1.5	1004	983	987	966	915	876	866	844	832	811	810	899
	2	910	884	885	886	844	830	801	794	785	775	748	831
	Average	1008	1004	996	986	945	920	904	881	872	848	834	927
	Start to end Δ	172	234	195	209	192	178	191	158	192	147	155	184

Source: Tandem PV

Table 3. Perovskite layer root mean square (RMS) roughness measurements were taken with an optical profilometer in a 2D grid on a 6-inch-wide by 3-inch-long sample.

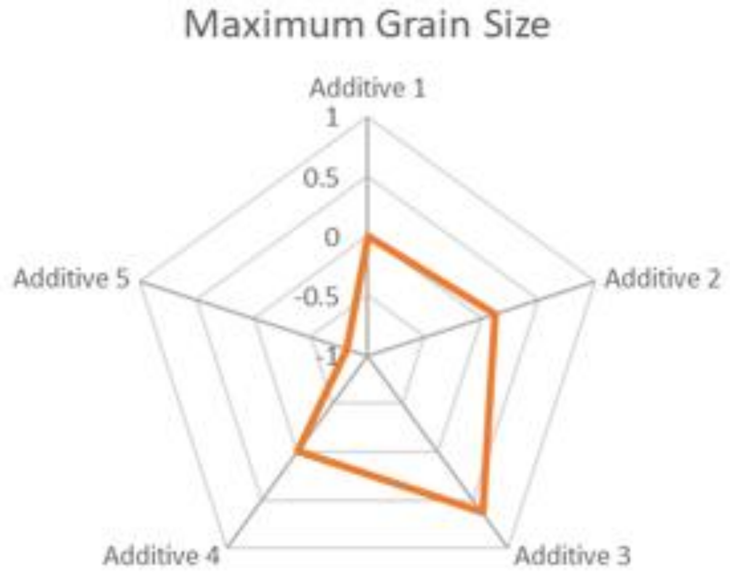
		Position of Scribe in Width Direction (in)											
		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	Average
		RMS Roughness (nm)											
Position of scribe in length direction (in)	*0.5*	7	8	7	8	5	6	7	9	5	7	10	7
	1	6	7	7	6	4	9	5	7	8	7	11	7
	1.5	5	10	6	8	8	8	6	5	4	5	15	7
	2	6	6	6	7	7	7	4	4	5	4	6	7
	Average	6	8	7	7	6	8	6	6	6	6	11	6

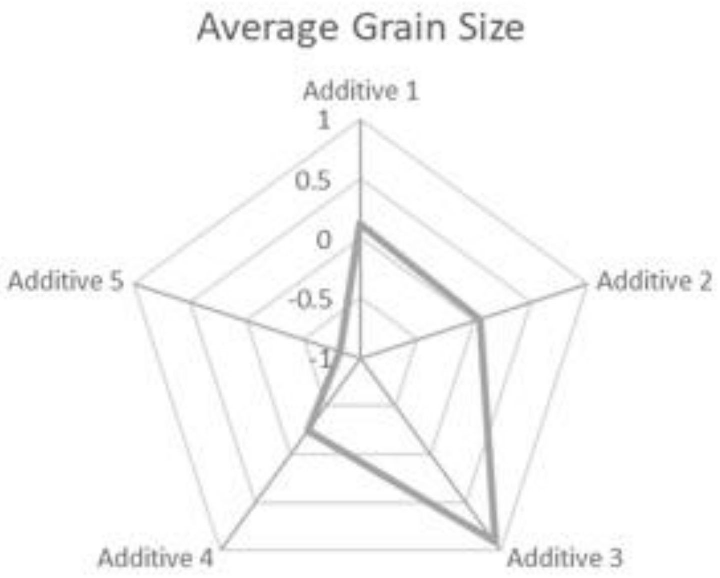
Source: Tandem PV

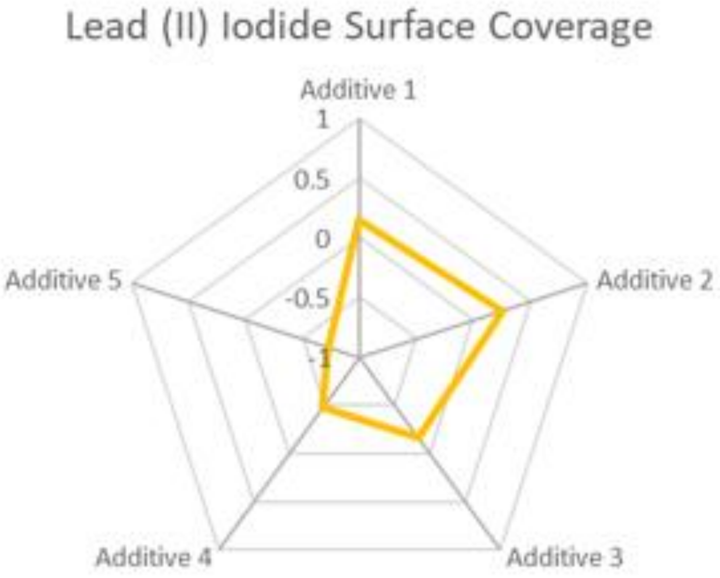
Perovskite Layer Grain Size

Over 500 perovskite films were evaluated using scanning electron microscopy (SEM) to correlate minimum grain size, average grain size, maximum grain size, and lead iodide (PbI_2) surface coverage against a wide variety of ink and processing variables including drying conditions, annealing time and temperature, and inclusion of various additives. Over 20 additives were tested and 5 were found to affect film quality at the grain level. The radar plots for the effect of these 5 additives on grain size and PbI_2 percent surface coverage are shown in Figure 3; SEM images for Additive 3 are shown in Figure 4, which also shows that increasing amounts of this additive significantly increases grain size beyond the 500 nm. target.

Figure 3. Correlation Coefficients of Five Additives to a Variety of Film Qualities

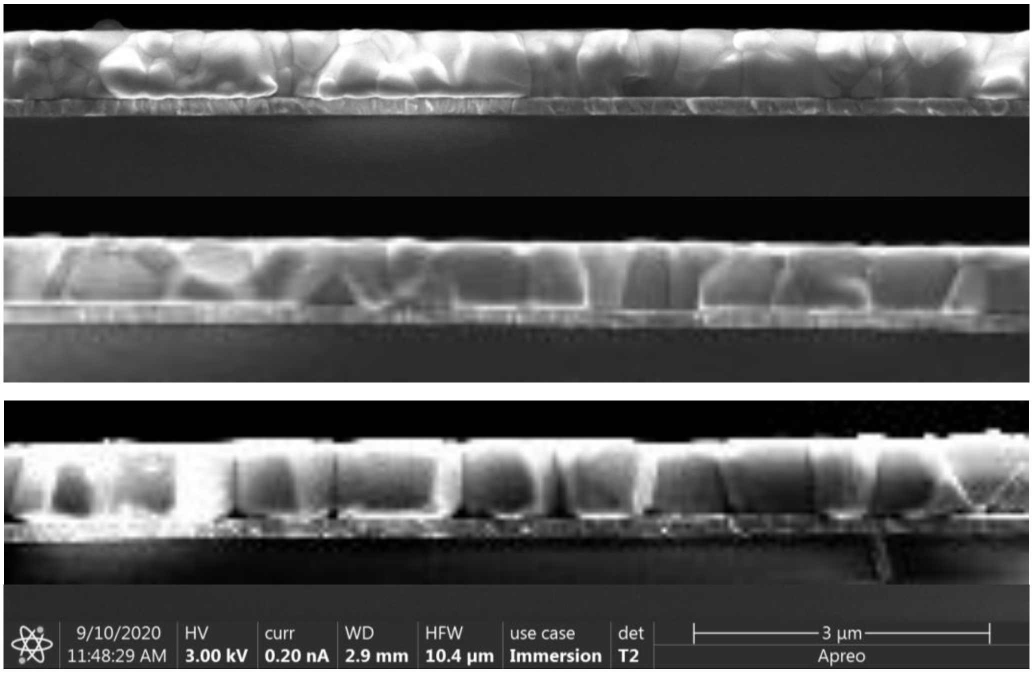






Source: Tandem PV

Figure 4. Top to Bottom, Cross Section SEMs of Increasing Additive 3. (Note the increase in grain size with greater amount of Additive 3.)

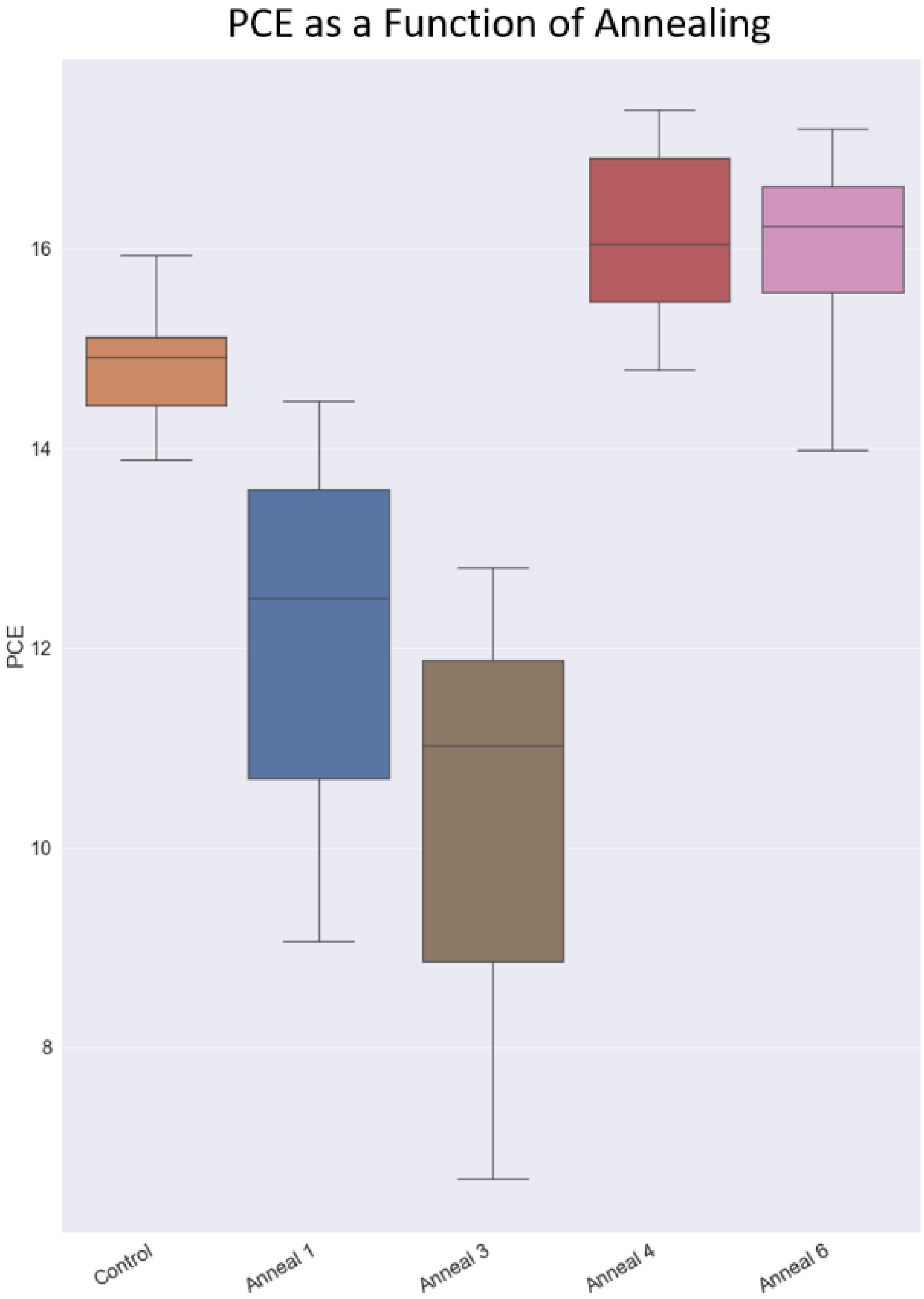


Source: Tandem PV

Perovskite Solar Cell Performance

Processing moved away from spray coating early in the project due to processing difficulties, in particular controlling drying of the deposited film. Solar cells were instead primarily fabricated with blade-coated perovskite films. Trials were performed with rapid thermal processing (RTP), as shown in Figure 5, which also demonstrates the viability of rapid wet-film coating, immediately followed by RTP.

Figure 5. Efficiency of blade-coated perovskite solar cells with the perovskite film annealing, performed by hotplate (Control, Anneal 1), combination hotplate then RTP (Anneal 3), or RTP-only (Anneal 4, Anneal 6)

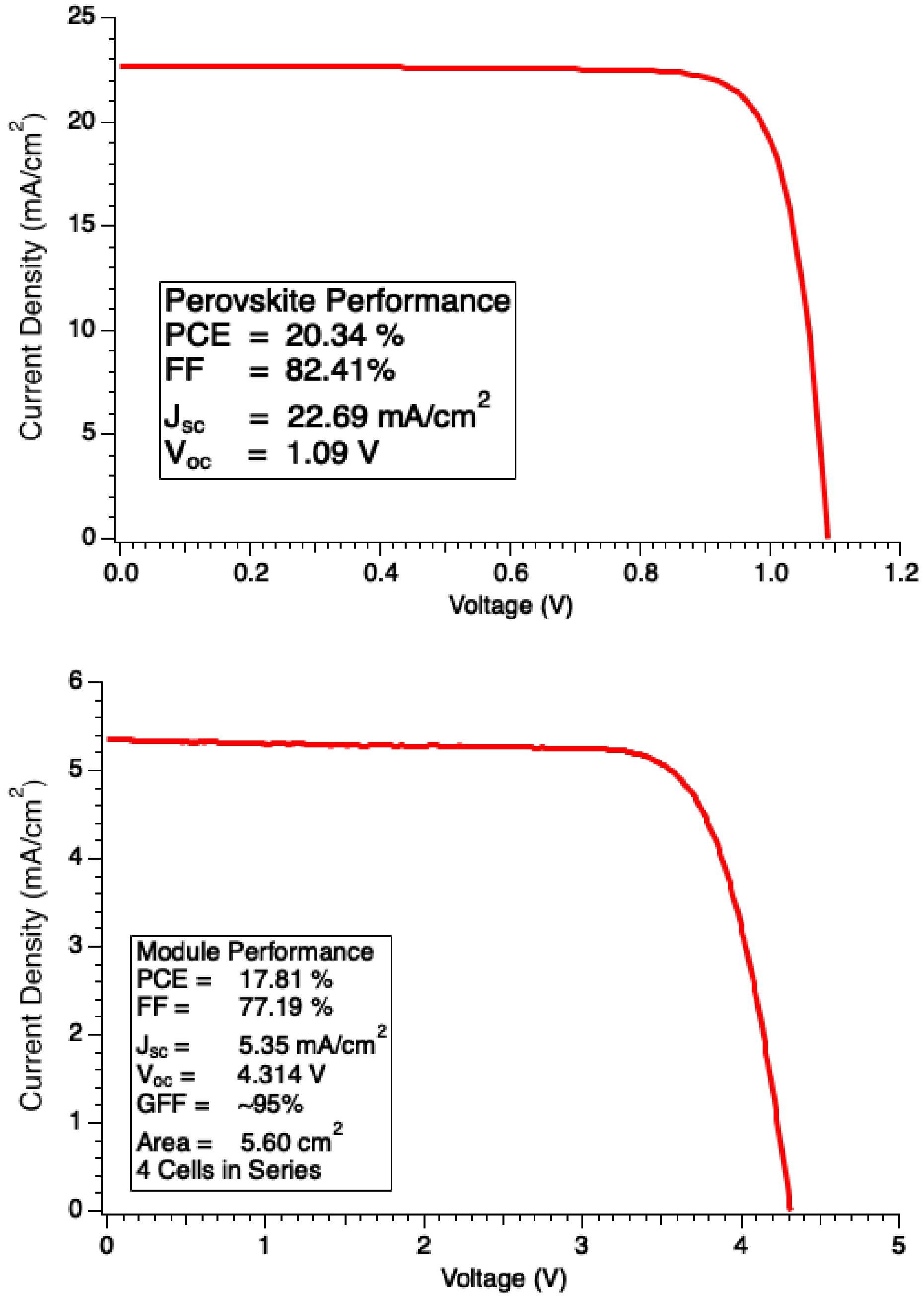


Source: Tandem PV

The control and optimization of ink formulation, printing, drying, and annealing of the perovskite layer led to the fabrication of fully scalable perovskite solar cells and modules (shown in Figure 6), achieving more than 20-percent efficiency on the cell level and 17.8

percent efficiency on the module level, as well as the fabrication of perovskite+silicon tandem modules in the following section.

Figure 6. (Top) Champion perovskite solar cell fabricated with fully scalable processes. (Bottom) Champion perovskite solar module fabricated with fully scalable processes.



Source: Tandem PV.

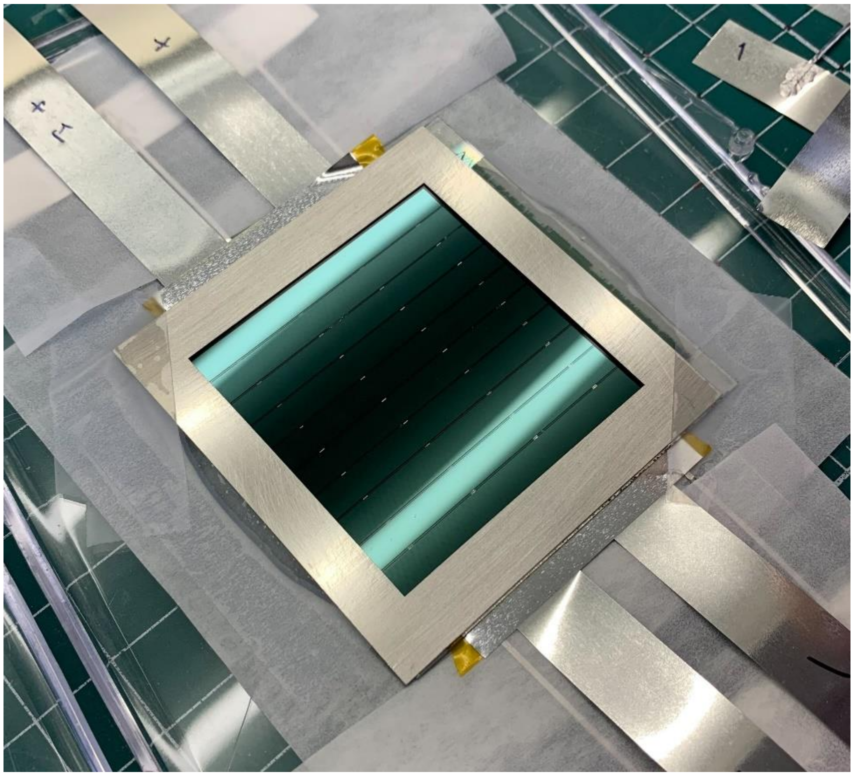
Efficiency Certification and Panel Efficiency Certification Reports

In the *Efficiency Certification and Panel Efficiency Certification* reports provided to the Energy Commission as part of this grant agreement, Tandem PV went through significant learning curves to combine perovskite modules with silicon cells to form full tandem panels.

The *Efficiency Certification Report* used a 1 square centimeter (cm^2) perovskite module, stacked on top of a 1 cm^2 silicon cell provided by a partner silicon manufacturer. The perovskite tandem solar cell was tested at the NREL in Golden, Colorado, an independent certified testing laboratory. The perovskite module had an efficiency of 13.0 percent, and the silicon cell had an efficiency of 6.3 percent, resulting in a tandem efficiency of 19.3 percent. This first test resulted in significant lessons learned for the development team, but efficiency was far below performance targets.

A follow-on *Panel Efficiency Certification Report* scaled up to a 25 cm^2 perovskite module stacked on top of a 25 cm^2 silicon cell (provided by a partner silicon manufacturer) significantly increased process homogeneity and maturity. The perovskite tandem solar panel was certified by NREL with a perovskite module performance of 13.5 percent and a silicon cell performance of 6.8 percent, resulting in a tandem performance of 20.3 percent. The certified module is shown in Figure 7. Table 4 and Table 5 describe the performance achievable with further improvements. On the silicon cell (Table 4), significant losses were observed in cutting the 25 cm^2 silicon cell from a full wafer. If those losses were avoided, the silicon cell could contribute nearly 10 percent in total efficiency to the tandem performance rather than the current 7 percent. On the perovskite module (Table 5), avoiding the electrical failure that caused the performance loss between pre-certification and the certified performance is a first step. The remainder of the table describes the individual metric performance – short-circuit current density (J_{SC}), open-circuit voltage (V_{OC}), and fill factor (FF) – which was individually demonstrated by perovskite modules fabricated during the course of this project; this in turn resulted in an achievable contribution of nearly 20 percent in total efficiency to the perovskite tandem solar cell, and a resulting tandem efficiency with silicon improvements of 29.5 percent. Tandem PV is continuing research and development after the end of this project focused on combining these metrics into a single panel to achieve the certified performance anticipated in this project.

Figure 7. Photo is of the perovskite/silicon 4-terminal tandem panel submitted to the National Renewable Energy Laboratory for certification.



Source: Tandem PV

Table 4. Pareto Table for Silicon Panel Efficiency due to Cell Cutting

Silicon Cell	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	Efficiency (%)
Full 6″ silicon cell	40	710	82	23.2
Cut 25 cm^2 cell	37.7	664	78	19.5
Cut 25 cm^2 cell in tandem	13.1	659	79	6.8
Expectation in tandem for full 6″ cell	17.4	680	84	**9.9%**

Table 5. Pareto Table for Perovskite Sub-Module due to Non-Optical Perovskite and Module Processing

Perovskite sub-module	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	Efficiency (%)
TPV3	17.54	1.18	65	13.5
TVP3 pre-certification	17.87	1.18	74	15.6
Improve J_{SC} through GFF optimization	**20.4**	1.18	71	17.1
Improve VOC through shunt and interface management	20.4	**1.2**	71	17.4

Improve FF through scribe and contacting management	20.4	1.2	**80**	19.6
Ideal TPV1				**19.6**

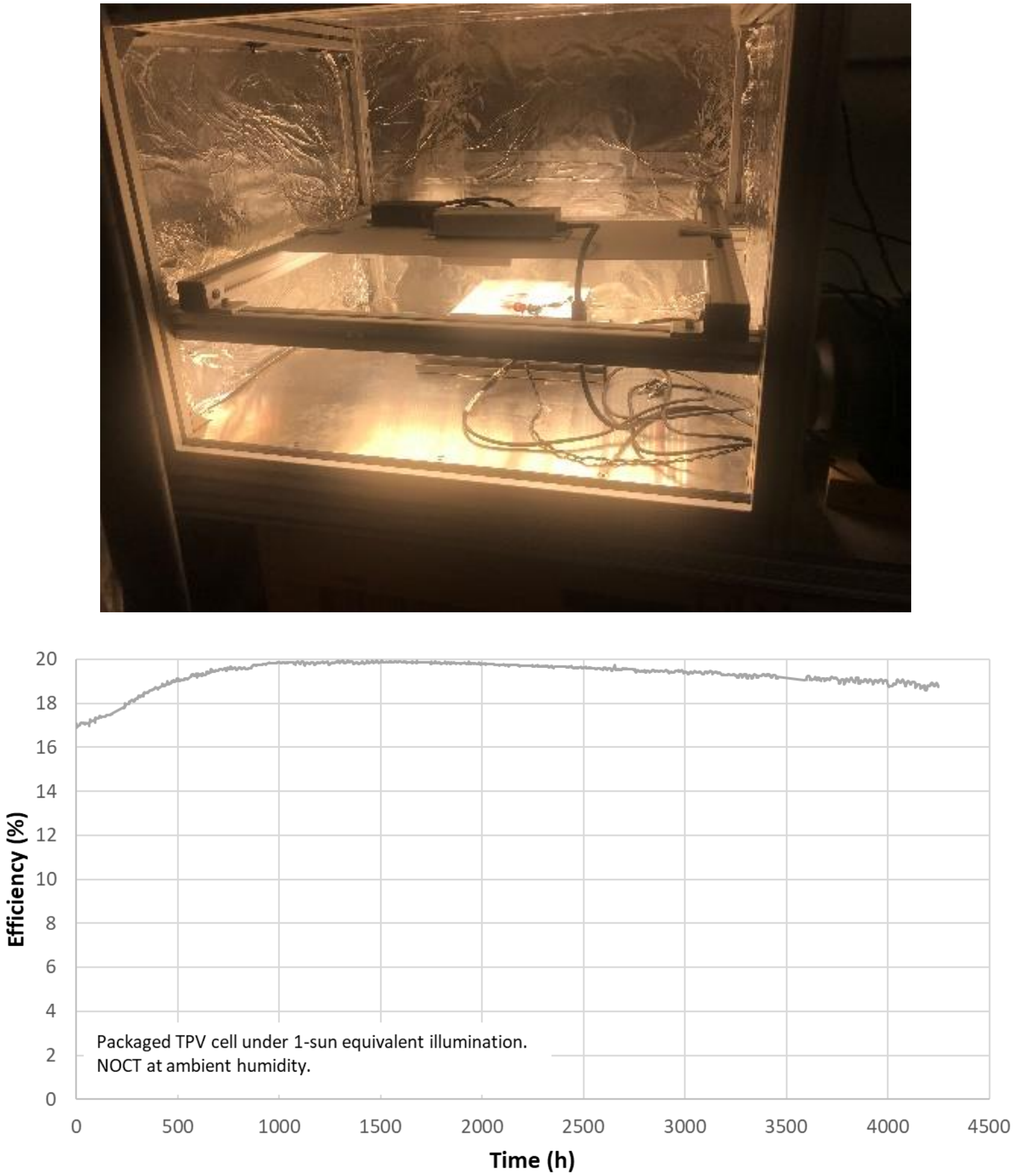
Durability and Panel Durability Reports

In the *Durability and Panel Durability* reports, Tandem PV subjected perovskite solar cells and panels to accelerated, field-equivalent, and outdoor tests over long periods of time.

In the durability report, Tandem PV focused on small perovskite solar cells approximately 0.1 cm^2 in size. These perovskite solar cells were tested in: 1) field-equivalent conditions under constant illumination, equilibrated temperature and humidity, and operational electrical conditions; 2) glass/glass encapsulated packages on the rooftop of Tandem PV's laboratory; and 3) packages in special ovens for running standard accelerated tests for solar panels.

Field-equivalent conditions were simulated in a custom-built chamber, shown in Figure 8. The best perovskite cells tested demonstrated a projected time to 80 percent of initial efficiency (T80) of 18,000 hours, equivalent to between 9 and 18 years of field deployment.

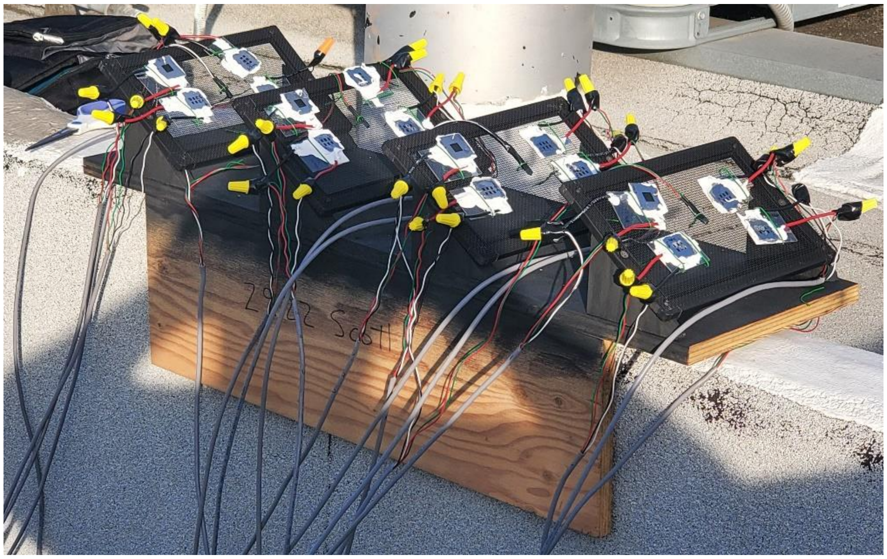
Figure 8. (Top) Custom-Built Constant-Illumination Durability Chamber. Bottom: Operational Curve of a Perovskite Solar Cell Over Thousands of Hours of Continuous Operation



Source: Tandem PV

Outdoor testing on the rooftop of Tandem PV’s laboratory was enabled with a mounting rack, and the solar cells were connected to the same custom electrical tracking software used for the constant-illumination chambers. The mounting rack is shown in Figure 9. Fifteen cells were tested. Of the eight cells that survived initial failure due to manual packaging or wiring issues, seven cells showed no observable degradation in power output over the course of the three-month test run between December 2020 and February 2021, during California's rainy season.

Figure 9. Rooftop Testing Frame



Source: Tandem PV

Accelerated testing, a method of placing solar cells and modules under high stress levels for short durations (which can predict long-term solar cell performance in the field), was performed by the independent engineering services firm D2 Solar, located in San Jose. The three accelerated tests were performed according to protocols defined by IEC 61215 for solar panels (Energy Commission 2021). The three individual tests performed were: 1) a damp heat test, subjecting the solar cells to XX°F (85°C) and 85 percent relative humidity for 1,000 hours; 2) a temperature-cycling test, subjecting the solar cell to 200 cycles between XX°F (85°C) and XX°F (-40°C), also taking approximately 1,000 hours; and 3) a humidity freeze test, subjecting the solar cell to 10 cycles between XX°F (85°C) with 85-percent relative humidity and XX°F (-40°C) with uncontrolled humidity. A target performance after the accelerated test is 90 percent of the performance of the solar panel, as measured before the test.

The solar cells retained the highest performance when subjected to the temperature cycling test, retaining between 50 percent and 70 percent of the original performance, far lower than the 90-percent target. The solar cells subjected to the damp heat and humidity freeze tests experienced catastrophic package failure, retaining 0 percent of the original performance. An example of the package failure is shown in Figure 10.

Figure 10. Tandem solar cell subjected to a damp heat test, which completely separated during testing. Lifting the device was enough to separate the two pieces of glass. The actual device is on the left, while the cover glass with epoxy is on the right.

Source: Tandem PV

This experience demonstrated the need to improve the packaging of the perovskite solar cells.

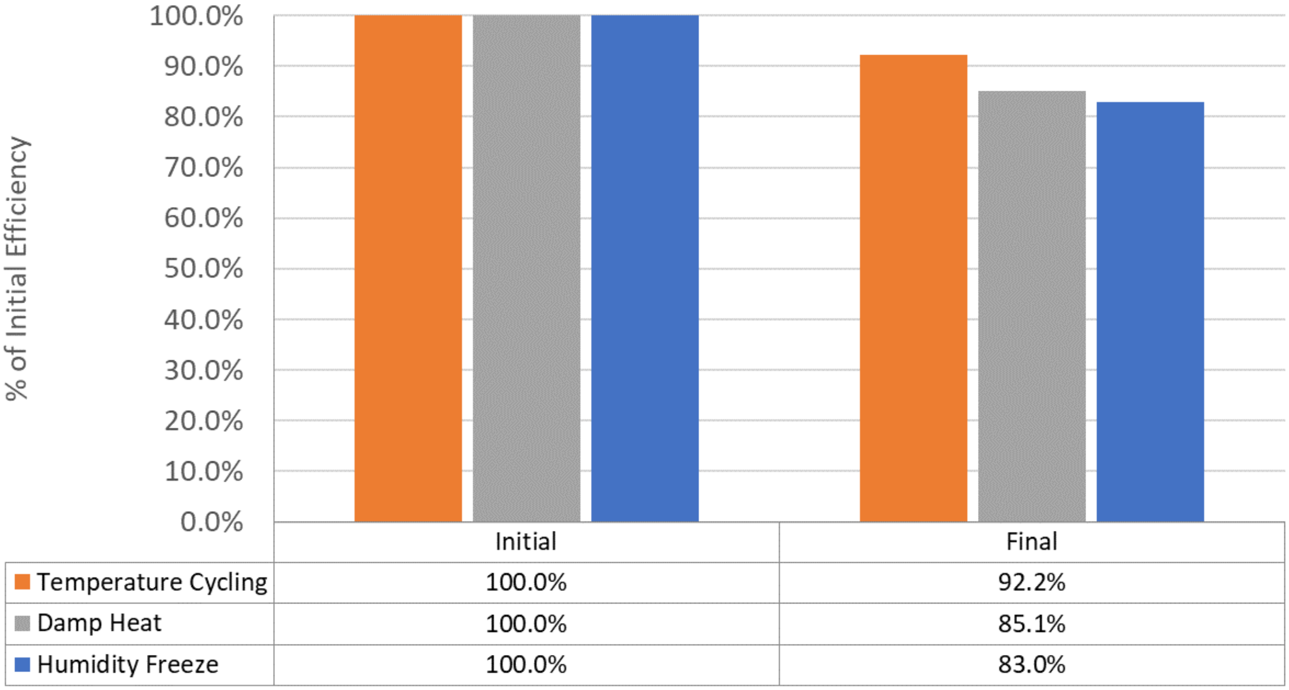
In the *Panel Durability Report*, Tandem PV focused on perovskite panels between 1 cm^2 and 25 cm^2 in size. This report was prepared in 2022 and further improvements to the packaging were made. New failure modes were observed in panel outdoor testing compared with solar cell outdoor testing. Rather than no observable degradation, the 11 panels tested had a typical T80 of approximately 50 days. The new failure mode was observed in the scribe lines needed to turn solar cells into solar panels. Tandem PV is focused on solutions to address this new failure mode.

Accelerated testing was again performed by D2 Solar and focused once again on the IEC 61215 tests: damp heat, temperature cycling, and humidity freeze. Further packaging improvements were made with the introduction of an edge seal (Figure 11). In this round of accelerated tests, the modules maintained significantly more performance after the test, with the best panel retaining more than 92 percent of initial efficiency after temperature cycling. In the damp heat test, the best panel retained 85 percent of initial efficiency and in the humidity freeze test, the best panel retained 83 percent of initial efficiency, a significant improvement over critical failure in the first set of tests, shown in Figure 12. Package failure was still observed in the damp-heat and temperature-cycling tests, suggesting further packaging refinement is needed.

Figure 11. (Left) Perovskite+silicon tandem module viewed from the top, perovskite-facing. (Right) Perovskite+silicon tandem module viewed from the back, silicon-facing.

Source: Tandem PV

Figure 12. Results of Perovskite Modules Subjected to IEC 61215 Tests



	Initial	Final
🟧 Temperature Cycling	100.0%	92.2%
◼ Damp Heat	100.0%	85.1%
🟦 Humidity Freeze	100.0%	83.0%

Source: Tandem PV

Recycling and End-of-Life, Supply Chain, and Life Cycle Analyses

Supply Chain Analysis Report

The supply chain analysis was based on Tandem PV's most current established process and is limited to the sourcing of materials and equipment required to manufacture an infrared-transparent perovskite module. Tandem PV worked with materials suppliers to determine costs, production volumes, and purity specifications. Tandem PV also worked with tool vendors to understand tool design, cost, throughput, downtime, cost of ownership, and footprint. Where direct answers were unobtainable within the desired timeframe, Tandem PV used established methodologies to extrapolate from known quantities.

Tandem PV identified several supply chain challenges in scaling perovskite+silicon tandem solar technology, in particular for certain materials available today in laboratory experimentation volumes but for which industrial demand has not yet catalyzed large-volume materials availability. This supply chain analysis did not reveal any fundamental materials or tool constraints, such as where Tandem PV requirements would approach known materials resource capacity – approaching a materials resource capacity would be if most or all of the available material (for example, silver) in the world was needed to manufacture the planned volume of solar panels. Tandem PV is working with present and prospective suppliers to address these potential constraints on timelines, consistent with Tandem PV's commercialization targets.

Life-Cycle Analysis Report

Tandem PV worked to define a bill of materials (the full set of components in a perovskite+silicon tandem solar panel product) and manufacturing processes for a mechanically stacked perovskite+silicon tandem solar panel. These materials and processes were modeled by Columbia University's Center for Life Cycle Analysis. This collaborative work directly yielded two academic publications: *Life Cycle Energy Demand and Carbon Emissions of Scalable Single-Junction and Tandem Perovskite PV*, by Enrica Leccisi and Vasilis Fthenakis, published in *Progress in Photovoltaics* in May 2021; and *Life-Cycle Analysis of Tandem PV Perovskite-Modules and Systems*, by Vasilis Fthenakis and Enrica Leccisi, presented at the Institute of Electrical and Electronics Engineers Photovoltaic Specialists Conference (IEEE PVSC) conference in June 2021 and published in IEEE PVSC 2021 conference proceedings in August 2021. These life cycle analyses were performed using a cradle-to-grave analysis.

In terms of life-cycle toxicity impacts, a 750-nm thick lead-based absorber layer did not represent a major contribution when compared with toxic compound emissions associated with the life cycles of other metals used in PVs, especially when PbI_2 is encapsulated in glass architectures.

It was found that the perovskite+silicon tandem systems would require less energy and have less global-warming potential (GWP) and human- and eco-toxicity potentials (HTP and ETP, respectively) than crystalline-silicon (c-Si) and copper-indium-gallium-selenide (CIGS) systems if they reach the same 30-year life span as conventional PV systems. Sensitivity analysis on lifetimes shows that even when the solar panels last 20 years, their energy and environmental performances are comparable to those of c-Si and CIGS systems. The energy pay-back times (EPBT) of perovskite+silicon tandem systems were estimated to range from 7 months (installations at 1,800 kWh/m^2/yr) to 5 months (installations at 2,300 kWh/m^2/yr). Their EPBTs would therefore be lower than those of c-Si systems, which range from 9 to 7 months, and CIGS systems, which range from 8 to 6 months.

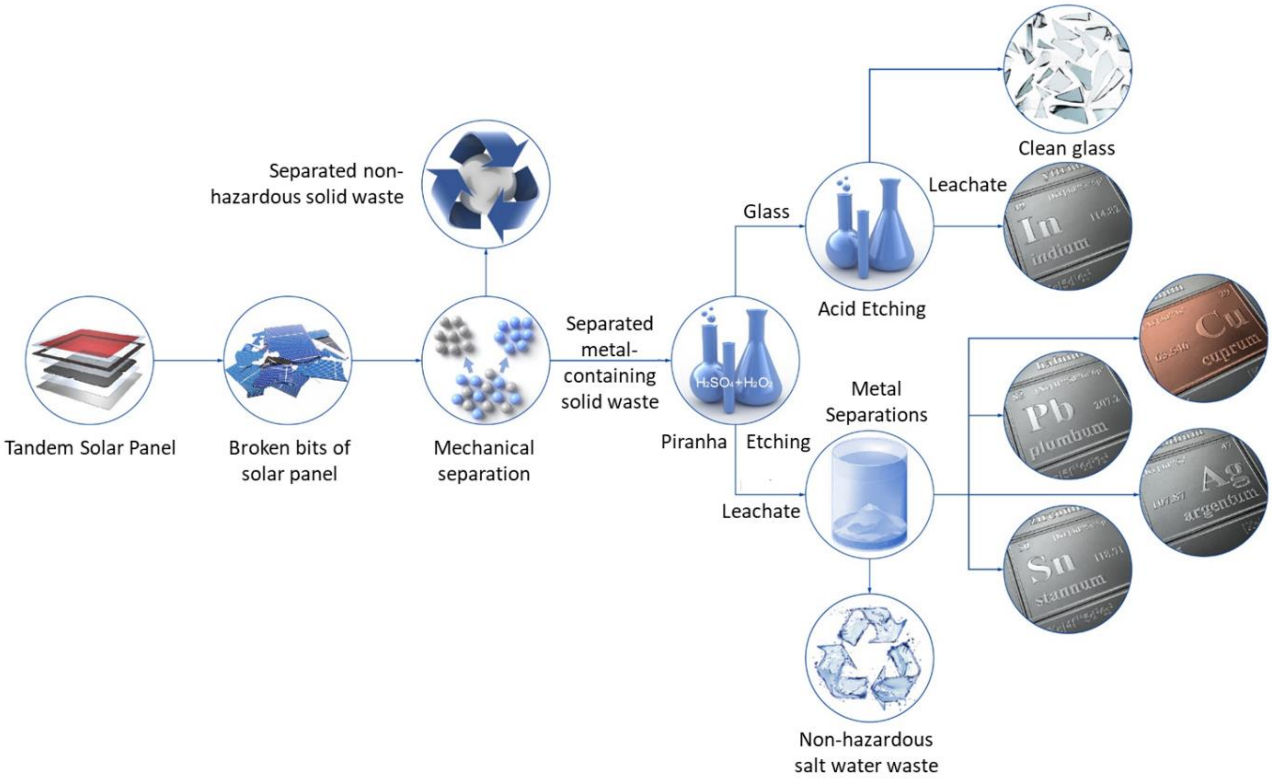
Recycling and End-of-Life Report

Existing solar PV panel recycling programs focus largely on crystalline silicon, particularly their panel components – most notably lead (Pb) in tin-lead (Sn-Pb) solder – which can require that PV panels to be handled as hazardous waste at end-of-life. The addition of Pb-containing perovskite cells to silicon PV panels only marginally increases the total Pb content for typical silicon panels, so would not affect material-handling requirements for solar PV panels.

Perovskite+silicon PV panels can also be recycled using techniques similar to those developed for silicon and cadmium telluride PV panels. A major difficulty with recycling the metals in solar panels is the encapsulation processes used to ensure that those products are operational for >25 years; they are intentionally durable and would be difficult to undo. Special methods that are often ignored in the academic literature are required to undo the encapsulation process for any recycling method employed to access the desired metals.

In this project, Tandem PV developed a method to mechanically crush the glass encapsulating the tandem PV solar modules, followed by *piranha etching* (a reactive solution made by combining sulfuric acid with hydrogen peroxide) and precipitation to fully recycle both the toxic and precious metals in a perovskite+silicon tandem PV solar panel (Figure 13). The developed method is a process that readily adapts existing methods for commercial recycling of thin-film solar panels to recycling of perovskite+silicon tandem solar PV panels. Tandem PV anticipates no technical, policy, or regulatory barriers to the implementation of this method as similar commercial-scale recycling methods are already in widespread use.

Figure 13. Recycling Method for Perovskite+Silicon Tandem PV Solar Panels Developed by Tandem PV



Source: Tandem PV

CHAPTER 4: Conclusion

This project, *Processing and Architecture Design to Develop and Demonstrate Stable and Efficient Perovskite+Silicon Tandem Modules*, focused on reducing technical risks for a new solar-panel technology prior to its commercialization including its scalability, durability, efficiency, supply-chain and life-cycle analysis, and recyclability at end-of-product life.

Perovskite+silicon tandem solar panels hold significant promise as a step-function improvement to silicon solar PV panel performance and cost. In 2022, laboratory technology demonstrations of perovskite+silicon tandem PV solar panels across the industry exceeded 30-percent efficiency, well above the laboratory performance achievements of commercial silicon solar PV panel technologies alone.

Tandem structures combining wide-bandgap metal-halide perovskite and narrow-bandgap silicon increase solar-panel efficiency without increasing panel $/watt cost. More importantly, more-efficient solar panels reduce total system costs by amortizing non-panel costs over more watts of electricity. In the U.S., high-volume PV-system installation companies report that 50 percent of residential rooftop customers desire more PV than can fit on their roofs. They estimate that a 30 percent efficient solar panel can reduce area-constrained total residential PV system costs by as much as $1/watt over standard solar panels (private conversations with residential solar installers, 2017). With higher efficiency solar panels (25 percent to 30 percent efficient), rooftop installations can also be 20 percent to 40 percent less expensive, which is extremely important for lowering electricity costs and encouraging rapid solar adoption in economically disadvantaged communities where pricing and upfront costs can be prohibitive.

The technical results of this project show significantly reduced technology risks of perovskite+silicon tandem PV solar panels. As a result of this project, Tandem PV is preparing to transition to initial manufacturing to produce a first product for initial pilot installations with residential, commercial, and utility customers in California, across the United States, and internationally. Tandem PV has lined up pilot-installation commitments for these first products. These products may become either directly available to ratepayers as options to install low-cost solar on their households, or indirectly through lower electricity bills from low-cost utility-scale solar installations.

Across the United States and the world, many areas have not adopted solar, in part because the local regulatory infrastructure favors fossil fuels over renewable electricity. A significant barrier is the free market cost of renewable electricity over subsidized fossil fuels. Tandem PV’s modeling and industry interviews suggest that the lower costs of solar energy enabled by perovskite+silicon tandem technology will break solar into new markets.

In the solar industry, differentiation is difficult among major manufacturers. The efficiency potential of perovskite+silicon tandem PV solar cells represents an advance in the performance and cost of solar panels and the opportunity to become the standard solar technology for the coming decades owning a majority market share of an industry that is growing toward a 1 terawatt-per-year manufacturing target.

California has an opportunity to be a leader in manufacturing solar panels of the future and bring diverse manufacturing opportunities to California communities. A robust homegrown domestic supply of solar-panel manufacturing would also reduce California's dependence on other geopolitical entities to meet its ambitious climate mandates.

The next step to enable increased production and adoption is to support the low-rate initial production of perovskite+silicon tandem PV solar panels by companies operating in California. Tandem PV is one such company, though there are at least two other startup companies in California working toward initial production. Since this project significantly reduces technical risk, reducing manufacturing risks through support for low-rate initial production through a program such as the California Energy Commission's Realizing Accelerated Manufacturing and Production for Clean Energy Technologies program is key to bridging the commercialization gap and promoting private investments in high-volume manufacturing.

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Project Deliverables

- Film Quality Report
- Efficiency Certification Report
- Panel Efficiency Certification Report
- Durability Report
- Panel Durability Report
- Supply Chain Analysis Report
- Life Cycle Analysis Report
- Recycling and End-of-Life Report

Appendix A – Relevant Legislative Statutes

- Assembly Bill 32, Statutes of 2006
- Senate Bill 32, Statutes of 2016
- Assembly Bill 3232, Statutes of 2018
- Assembly Bill 2514, Statutes of 2010
- Senate Bill 100, Statutes of 2018
- 2022 Energy Code
- Executive Order N-79-20
- The California Air Resources Board Advanced Clean Cars II Regulations (2022