CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Rapid Innovation Development of Energy-Generating Windows for Zero- and Negative-Carbon Emission Buildings

July 2024 | CEC-500-2024-080

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Agreement Number: EPC-20-014

ACKNOWLEDGEMENTS

NEXT would like to thank our Project Managers from the California Energy Commission – Rachel Salazar and Jemar Roble Tan; the TAC Committee Members – Robert Tenent, Stan Pipkin, Christopher Fenton, Audrey Wu, Craig Lewis, and Payam Bozorgchami; the NEXT Project Team; and commercial partners and subrecipients – Viracon, Walters & Wolf, and Robert Born.

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

The purpose of this agreement was to fund the development and demonstration of pilot-size energy-generating windows using all pilot production manufacturing methods. In this project, the project team fabricated and demonstrated energy-generating windows using all manufacturing methods and processes necessary for pilot production. Specifically, techniques required for pilot production that are not currently employed at a bench scale were demonstrated. This included glass handling and transportation techniques during the coating processes that are fully applicable to large-area, full-scale glass. In addition, techniques that will allow easier fit and less disruption when introducing this technology into the window manufacturing industry and market were also demonstrated. The results of this project significantly reduced remaining scale-up risk and enables pilot production and then full production.

Keywords: Energy, solar, organic photovoltaics, windows, glass, buildings, coating, pilot-size energy-generating windows, building-integrated photovoltaic

Please use the following citation for this report:

Hoven, Corey and Bruno Caputo. 2024. *Rapid Innovation Development of Energy-Generating Windows for Zero- and Negative-Carbon Emission Buildings*. California Energy Commission. Publication Number: CEC-500-2024-080.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

NEXT Energy Technologies (NEXT) has developed breakthrough transparent solar cells that allow solar panels to look like normal windows. NEXT's building-integrated photovoltaic windows absorb light in the infrared and ultraviolet spectrum while allowing significant visible light transmission with colors that are desirable to the window market, while also achieving high efficiency and long lifetime. This is a radical breakthrough that will have significant impact on the pursuit of California's statutory energy goals, which include promoting greater energy reliability, lower costs, and the mitigation of climate change effects.

Greater energy reliability will be achieved by enabling buildings to generate energy onsite, which will also help achieve net-zero energy developments. NEXT's unique approach will also allow for much lower module and balance of system costs compared to other photovoltaic technologies. NEXT's significant innovation is projected to have a levelized cost of energy of $0.03 per kilowatt-hour by 2030, which will profoundly impact the pursuit of Electric Program Investment Charge goals for lowering costs as a barrier of entry for clean energy technologies. NEXT's energy-generating window product will help mitigate climate change effects and thereby promote the health and safety of California ratepayers by significantly reducing greenhouse gas emissions compared to traditional windows.

Project Purpose and Approach

The purpose of California Energy Commission Agreement EPC-20-014 was to fund the development and demonstration of pilot-size energy-generating windows using all pilot production manufacturing methods.

In this associated project called "Bringing Rapid Innovation Development to Green Energy," agreement recipient NEXT successfully demonstrated pilot-size energy-generating windows using all pilot production manufacturing methods and developed techniques that will allow easier fit and less disruption when introducing this technology into the window manufacturing industry and market. For example, rather than printing on display glass and laminating to the outboard lite (pane) of a window, NEXT fabricated solution-processed coatings directly onto large sheets of architectural glass. This processing method used by NEXT allows for commercial glass to be suitable for precision coatings. Being able to coat directly on the window glass allows NEXT's technology to seamlessly integrate into insulated glass unit fabrication lines, leading to much higher margins with low capital costs for equipment. In addition to building a large-area coating tool, NEXT specified other equipment that will be required to soon fabricate pilot-size energy-generating windows at a low-rate initial production scale. With its innovative manufacturing solutions, NEXT's approach to scaling up this solution processing method allows for throughput equal to that of a conventional integrated glass unit fabrication line while adding significant value potential via precision manufacturing and production efficiency.

Key Results

The goals achieved in this project included the following:

- Building a coating tool for the fabrication of organic photovoltaic modules capable of handling commercially fabricated window glass,
- Using the coating tool to fabricate films with high aesthetic quality suitable for commercial window applications,
- Building necessary equipment to complete a large-area coating line,
- Building and installing a demonstration wall using modules fabricated on the large-area coating line, and
- Building and testing a module with commercially relevant techniques at commercially relevant sizes.

All these goals were completed within the scope of this Bringing Rapid Innovation Development to Green Energy project, with in-depth detail found in the project deliverables (see List of Project Deliverables at the end of this report). Critical measurables within this project include industry-accepted aesthetic requirements that are based upon color uniformity as well as defect reduction. These stringent requirements are imperative to attain for the product to be a viable option for the window industry. Within the scope of this project, the NEXT team achieved all of the proposed project performance metrics, with most achieving the high targets. In addition, all the aesthetic-based milestones and metrics were achieved and had surpassed industry requirements. The project team constructed two demonstration walls, each with four 27” x 35” units meeting or exceeding all of the proposed specifications as well as one 40” x 60” standalone demonstration unit showing the commercial feasibility of the technology and toolsets built within the scope of this project. The project team was also successful in expanding on business development efforts as part of Task 9 of the agreement, which involved validating and updating costs, market, and benefits information. These results provided successful updates to the cost model as well as ratepayer benefits. These findings and deliverables will be used to further the technology as described in the Knowledge Transfer and Next Steps section below.

Knowledge Transfer and Next Steps

The agreement recipient NEXT continues to engage in multiple activities to accelerate the commercial adoption of their building-integrated photovoltaic window technology, including the following:

- Scale-up analysis including manufacturing analysis, independent design verification, and process improvement efforts;
- Technology verification testing or application to a test bed program located in California; and
- Market research, business plan development, and cost-performance modeling.

These achievements also coincided with the agreement goals of assembling tools that previously did not exist and qualifying those tools in a commercially relevant way to produce modules with high aesthetic quality suitable for commercial window applications.

CHAPTER 1: Introduction

NEXT Energy Technologies (NEXT) has developed breakthrough transparent solar modules that allow solar panels to look like normal windows. NEXT's building-integrated photovoltaic windows absorb light in the infrared and ultraviolet spectrum while allowing significant visible light transmission with colors and transmission levels that are desirable to the window market, while also achieving high efficiency and a long product lifetime. This is a radical breakthrough that will have significant impact on the pursuit of California's statutory energy goals, which include promoting greater energy reliability, lower costs, and the mitigation of climate change effects. Buildings account for 40 percent of U.S. energy use,[1] and energy represents the single largest variable operating expense for commercial buildings.[2] A growing number of developers are building to green/sustainability standards, and regulatory regimes are increasingly driving toward net zero energy buildings. Under the California Efficiency Strategic Plan, all new commercial buildings in California are to be designed to zero-net energy standards by 2030.[3] In light of these drivers, substantial progress has been made toward making buildings more energy efficient, but the missing link to meeting the zero-net energy goals remains the lack of options for onsite clean energy generation. There are currently few viable solutions for onsite generation of renewable energy for commercial buildings. Compounding this issue is the problem posed by large commercial buildings often not having enough or any free rooftop space for conventional photovoltaic solar panels.

NEXT has solved this problem by developing first-of-its-kind windows that generate energy and also exhibit the thermal performance of energy-efficient low-emissivity (low-e) windows. The façade of a building has considerable surface area. For widespread adoption of building-integrated photovoltaic windows, the market demands the exceptional aesthetics of a standard window and a good return on investment. Current technologies on the market do not meet the critical requirements of aesthetics, high transparency, good power conversion efficiency, long product lifetimes, and low cost. In contrast to all other technologies, NEXT's photovoltaic windows fully meet these requirements (see Figure 1 Left). NEXT's technology is based on solution processable organic semiconductors that have the unique ability to absorb infrared light while still allowing the transmission of light in the visible spectra (see Figure 1 Middle), which is not possible with conventional photovoltaics. In addition, NEXT's technology allows significant energy generation with little to no aesthetic impact to the window. A functioning demonstration façade with NEXT windows is shown in Figure 1 Right.

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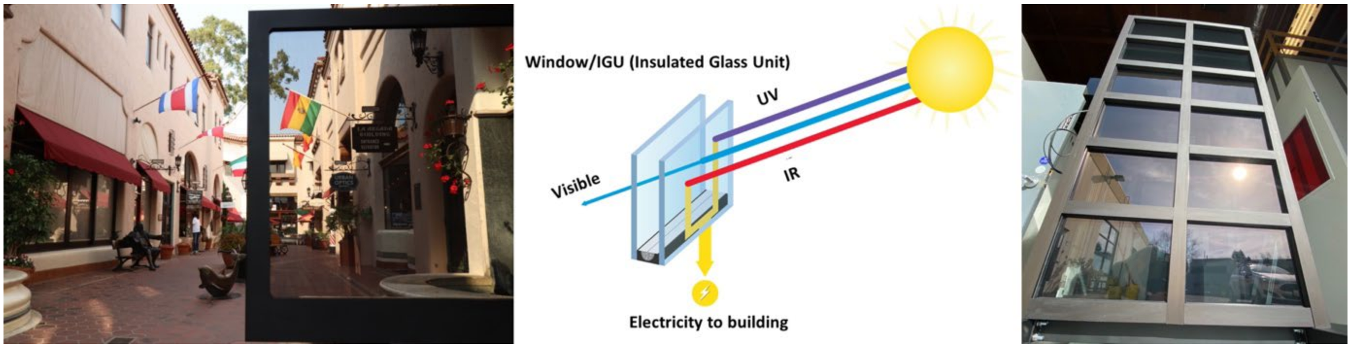
1 IEA. December 2019. *Global Status Report for Buildings and Construction 2019*. Available at https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019.

2 Energy Star. n.d. "Commercial Real Estate: An Overview of Energy Use and Energy Efficiency Opportunities." Available at https://www.energystar.gov/sites/default/files/buildings/tools/CommercialRealEstate.pdf.

3 California Public Utilities Commission. 2017. *Zero Net Energy*. Available at https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/energy-efficiency/zero-net-energy.

Figure 1: Transparent NEXT Soluble Small Molecule-Organic Photovoltaics (SSM-OPV) Module (Left), NEXT SSM-OPV Insulated Glass Unit (IGU) Removing Encapsulation Costs Through Window Integration (Middle), and Functioning Demo Wall Using NEXT modules (Right)



Source: NEXT Energy Technologies, Inc.

This unique approach also allows for much lower module and balance of system costs compared to other photovoltaic (PV) technologies, considering that the majority of the products costs are sunk costs related to building the conventional window base. NEXT's approach is a significant innovation that will have a profound impact toward the pursuit of the Electric Program Investment Charge (EPIC) goals of providing lower production costs for clean energy technologies; the projected levelized cost of energy (LCOE) for NEXT's building-integrated photovoltaic is only $0.03 per kilowatt-hour (kWh) by 2030 when taking into account currently known tax incentives for 2030.

Very low module costs are achieved by integrating the photovoltaics into the insulated glass units (IGUs). NEXT's soluble small molecule-organic photovoltaics (SSM-OPVs) have the potential to be exceptionally low-cost relative to other solar technologies due to their: (1) inexpensive and abundant raw materials and (2) extremely low production and capital costs enabled by wet coating. Organic PVs are based on raw materials that are low-cost, Earth-abundant, non-toxic, and environmentally friendly. The simple printing/coating technique of NEXT's SSM-OPVs enables substantial production at low manufacturing and capital costs and the ability to quickly scale production. Most importantly, by integrating SSM-OPVs into windows, encapsulation costs (including the cost of the glass) are effectively eliminated as they are already paid for in the window, which would otherwise represent a majority of the cost of SSM-OPVs. This is significant as most of the material in thin-film solar modules is glass.

The balance of systems costs for building-integrated photovoltaic windows are also significantly reduced relative to conventional solar technologies. In conventional PV, the mounting structure/foundation and the labor costs for installation (not including the labor costs for the installation of electrical components) comprise the two largest components of balance of systems and represent almost 50 percent of the balance of systems costs when combined. In PV-integrated windows, these costs are essentially removed as they are already being paid for in the installation of the window.

In addition to providing energy generation, NEXT's technology also offers improvements in energy efficiency for commercial buildings. NEXT's energy-generating windows convert near-infrared light, which would otherwise contribute to building heat load, into electricity. Modeling done by NEXT and the National Renewable Energy Laboratory of NEXT's windows integrated with low-e glass showed an improved solar heat gain coefficient over high-performance low-e windows that otherwise had the same specifications including color and visible light transmission. Importantly, this also reduces light reflected to other buildings compared to conventional low-e windows.

Thus, NEXT's technology is a significant boon for the construction of zero and negative-carbon emission generation buildings through energy generation, cost efficiency, and insulation/ energy efficiency.

CHAPTER 2: Project Approach

The purpose of California Energy Commission (CEC) Agreement EPC-20-014 was to fund the development and demonstration of pilot-size energy-generating windows using all pilot production manufacturing methods.

In this associated project called "Bringing Rapid Innovation Development to Green Energy," the agreement recipient NEXT demonstrated developed techniques that will allow easier fit and less disruption when introducing this technology into the window manufacturing industry and market. For example, rather than printing on display glass and laminating to the outboard lite (section) of a window, NEXT fabricated solution-processed coatings directly onto large sheets of architectural glass. This processing method used by NEXT allows for commercial glass to be suitable for precision coatings. Being able to coat directly on the window glass allows NEXT's technology to seamlessly integrate into insulated glass unit fabrication lines, leading to much higher margins with low capital costs for equipment. In addition to building a large-area coating tool, NEXT specified other equipment that will be required to soon fabricate pilot-size energy-generating windows at a low-rate initial production scale. With its innovative manufacturing solutions, NEXT's approach to scaling up this solution processing method allows for throughput equal to that of a conventional integrated glass unit fabrication line while adding significant value potential via precision manufacturing and production efficiency.

The project achieved the objectives of this agreement, which were to:

- Transfer the Recipient's optimized, demonstrated benchtop-scale processes to a large-scale process compatible with commercial deployment. Quantitative milestones for this objective included the following:
    - Building a glass coating tool that can transport industrial glass for coating at adjustable width levels;
    - Evaluating aesthetics, uniformity, and performance of coated layers from the new large-area coater with a spectrophotometer to ensure that devices exhibit the necessary levels for commercial viability within American Society for Testing and Materials (ASTM) Standard C1376;
    - Demonstrating fabrication of the device stack on glass with varying widths to prove the ability to provide devices with comparable quality at different sizes;
    - Producing functional window–PV lites within aesthetic and performance targets; and
    - Manufacturing IGUs using window-PV lites with high level of uniformity, consistent with ASTM C1376.

- Integrate modules fabricated using the large-scale processing into IGUs and a demonstration wall. Quantitative milestones for this objective included the following:
    - Consultations with building window system manufacturers to fabricate IGUs that pass applicable safety and durability tests,
    - Collaborations with a building window system integrator to fabricate and install a glazing system integrating large-area modules with an interactive element, and
    - Completed work with a PV module manufacturer to demonstrate larger area (pilot line size) 40” x 60” modules.
- Validate and update the cost, market, and benefits projections and results. Quantitative milestones for this objective included the following:
    - Validating the projected LCOE of $0.03/kWh by 2030 that accounts for currently known tax incentives for 2030.
- Plan for upcoming pilot production line to provide a competitive advantage.

Commercial partners were instrumental in guiding direction of progress throughout the project. The main commercial partners that contributed help included Viracon[4] and Walters & Wolf.[5]

The overall approach to this project includes equipment buildout and upgrades to enable the project team to fabricate larger transparent PV modules than previously demonstrated. These large-area tools included, but were not limited to, the following:

- Coater
- Laser
- Laminator
- Curing oven

Upon completion of this buildout, modules that demonstrably achieved the key project performance metrics were fabricated.

[4] A leading global glass fabricator, Viracon offers the most complete range of high-performance architectural glass products available worldwide. With over 60 percent market share of the U.S. tall buildings segment, Viracon can perform virtually any glass fabrication process needed for a commercial building project. Viracon’s complete product line includes insulating, laminated, silk- screened, spandrel (windows between floors of a building), hurricane-resistant, acoustical, blast-mitigating, heat-treated, and high- performance coated glass. Viracon is headquartered in Owatonna, Minnesota, and has facilities in Statesboro, Georgia and Nazaré Paulista, Brazil. The facilities are strategically located to provide optimum service and support to Viracon’s worldwide customers.

[5] Walters & Wolf was founded in 1977 and is based in Fremont, California. Walters & Wolf currently has five production facilities serving the western United States with high-quality concept to completion cladding services for commercial buildings. Walters & Wolf is the largest glazing subcontractor in the West and the fourth largest in the United States. Walters & Wolf engages in design, engineering, fabricating, and installing custom precast and glass fiber reinforced concrete facade panels in addition to glass and aluminum curtain walls. As a result, Walters & Wolf is well placed to understand the potential of new glazing technologies.

CHAPTER 3: Results

All the technical goals and milestones proposed at agreement execution within the scope of this project were achieved and delivered as expected. Each proposed project performance metric was successfully met, with most exceeding the high target. Challenges encountered and lessons learned within this project are detailed below, along with specific technology and research outcomes and their significance.

Task 2: Large-Area Coating Equipment

The goal of this task was to build or purchase the tools and equipment needed to fabricate large-area solution-processed films that meet appropriate project performance metrics for coatings for fenestration and building envelopes. These tools and equipment were used in all the subsequent technical tasks to fabricate large area modules.

The tools that were built included the large-area coater and its subcomponents. When using a precision coating technique such as slot die coating, it is imperative to have precise control of the transport of the glass under the coating head. The large-area coater provided this precise control. In the **Test Plan Report**, NEXT detailed the initial studies critical to specifying the functionality of the large-area coating equipment. To ensure adequate precautions were taken, commercial glass was sourced for these studies. As tools were being built and assembled, data was obtained from commercial partners detailing glass imperfections such as glass shape, roller wave, and edge kink. All of these industrially known distortions are a product of the glass manufacturing process. Other experiments were detailed and planned to compare commercial partner results to data that will be obtained in house once the tools are completed. The details of glass imperfections acquired from commercial partners were imperative to the final tool specification. For example, a substrate characterization table was built to include precision sensors integrated into the large-area coating station to provide feedback concerning the profile of the glass, allowing the tool to compensate for fluctuating input variables while maintaining a stable process.

Implementation of the Test Plan Report came upon the completion of the tools being integrated. These results were successful, and a **Large-Area Tools Integration Report** was subsequently submitted, which outlined the build or purchase of the tools and equipment needed to fabricate large-area solution-processed films that would meet appropriate project performance metrics for fenestration coatings and building envelopes. The tools that were completed included the following:

- Substrate Transport System
- Large-Area Coating Station
- Substrate Characterization Table
- Large-Area Dryer

- Buffer Stations
- Large-Area Oven and Curing Station
- Enclosure and Environmental Control

These tools were critical additions to be able to fabricate large-area modules within the scope of the proposed project performance metrics.

Also, the project performance metric of being able to "implement controls on the Large-Area Coating Station to effectively improve [the] uniformity of heat-strengthened glass" is significant to successful coating production. The NEXT team achieved the high target for this project performance metric, which confirmed the coating tool performed better than the current uniformity standards require. These uniformity standards were determined internally on benchtop research and development (R&D) tools. The method of validation was confirming that the uniform coatings on the large-area coating tool were within ASTM C1376 standards. The details for this validation process are elaborated upon in Section 3.2. In summary, the tools and equipment needed to fabricate large-area solution-processed films that meet appropriate project performance metrics for coatings for fenestration and building envelopes were installed and integrated. The large-area R&D coater has been shown to address and successfully mitigate critical scalability issues of the benchtop R&D coaters. Results achieved were as anticipated due to successful execution of the test plan and strategic planning, which allowed the project team to overcome supplier lead time challenges.

Products:

- Test Plan Report
- Large-Area Tools Integration Report

Task 3: Large-Area Coatings

The goal of this task was to fabricate high-quality films acceptable for window applications, using the large-area R&D coating tools. In this task, films were coated onto glass substrates and measured for uniformity using a third-party-calibrated Konica Minolta 3700a or an Ocean Optics USB2000 spectrophotometer to characterize transmission and color uniformity. The most critical feature to quality in building-integrated photovoltaics is film uniformity, as this directly impacts the aesthetics of the final product as well as the functionality of the device. Color uniformity can be quantified using the DeltaE2000 metric (Equation 1) to compare the difference in color between two points on a surface, as per ASTM C1376—the uniformity standard for window products. A lower DeltaE2000 value corresponds to greater uniformity, and this value must be below 4.5 to be deemed acceptable by the standard.

Equation 1: CIE DeltaE2000 Color Difference Between Two Points

$$\Delta E_{00}^{12} = \Delta E_{00}(L_1^*, a_1^*, b_1^*; L_2^*, a_2^*, b_2^*)$$

For measurements on large-area 27" x 35" modules, color information was measured at four predefined locations and compared to the average value to quantify uniformity within a sample and between samples (Figure 2). As described in the **Coating Process Report**, these results were determined to demonstrate high-quality uniform coated active layers and full stacks by measuring DeltaE2000 within and between samples to be less than 4.5 as per ASTM C1376 for each permutation using the spectrophotometer.

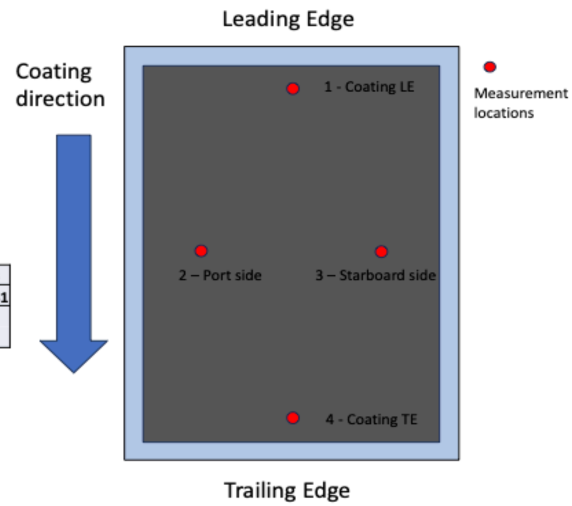
Figure 2: Summary of Aesthetic Performance of 27″ x 35″ Modules

27x35 Color Uniformity

- Delta E 2000 between individual points on a module and the average color of the module is less than 1 for both samples
- Delta E 2000 between samples is also less than 1

LAB color	Avg color of NEXT Sample A	Avg color of NEXT Sample B	deltaE2000 between samples
L*	66.59	67.46	**0.81**
a*	-1.68	-1.46	
b*	-2.21	-1.89	

deltaE2000 within samples		
Location	deltaE2000 of NEXT Sample A	deltaE2000 of NEXT Sample B
LE - Avg	0.79	0.39
PORT - Avg	0.10	0.53
SBD - Avg	0.44	0.43
TE - Avg	0.43	0.30

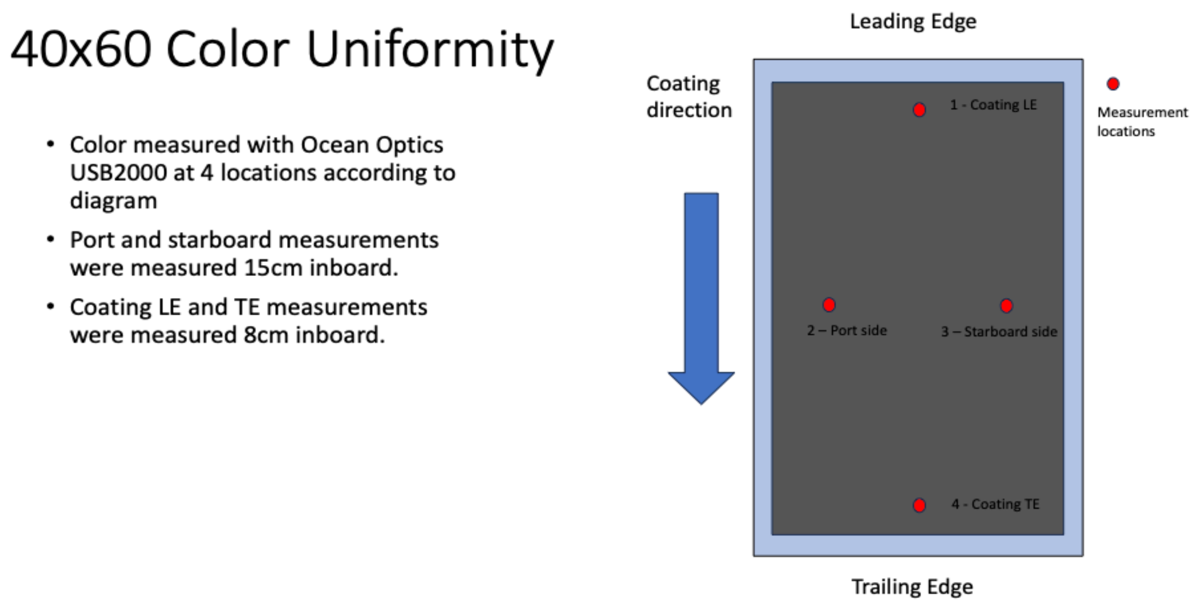


Source: NEXT Energy Technologies, Inc.

With further optimization, it was shown in the **Coating Progress Report** that DeltaE2000 between samples was 0.81 whereas DeltaE2000 within a sample was 0.80 or less (Figure 2). This metric surpasses the High Target of DeltaE2000 less than 2 in the project performance metrics describing repeatability and uniformity of larger slot-coated films and modules on large-area coater both at lab-scale and at the larger pilot-scale. Aesthetic uniformity is critical to achieving a successful window-integrated product as well as an excellent indicator of good module performance and reproducibility.

Also, as seen in Figure 3, the sample uniformities of the largest size substrate (40″ x 60″) were determined to be high-quality uniform coated modules, as demonstrated by the DeltaE2000 within and between samples being less than 4.5 as per ASTM C1376 standards for each permutation using the spectrophotometer. All packaged modules also show acceptable metrics for defect reduction according to the project performance metrics describing optical viewing from a distance of 10 feet (3 meters) in transmission, at a viewing angle of 90 degrees to the specimen and against a bright, uniform background as per industry standards.

Figure 3: Summary of Aesthetic Performance of 40″ x 60″ Modules



Source: NEXT Energy Technologies, Inc.

Products:

- Coating Process Report
- Coating Progress Report

Task 4: Adjustable Width Coatings on Large Areas

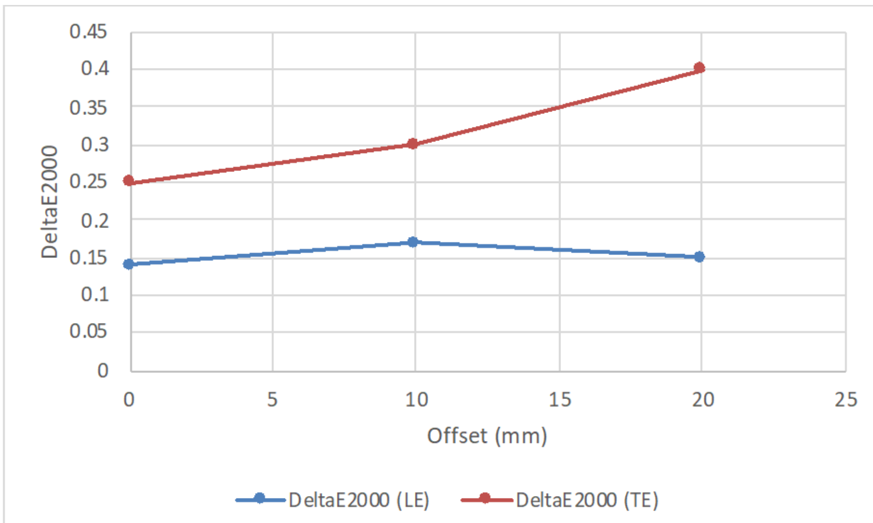
The goal of this task was to prove the capability of NEXT's technology to adapt to the very custom nature of the window industry—specifically, the requirement of fabricating custom-width coatings with minimal interruption to the production process. To accomplish this, the fixed width coating process was modified by adding an adjustable width mechanism to the standard slot die in the fabrication process. Test criteria were defined in an Adjustable Width Coating Test Plan, which was then executed for the adjustable width coating process on a benchtop R&D coater. This Adjustable Width Coating Test Plan included the following:

- Fabrication
  - Install adjustable width mechanism on benchtop R&D coater
  - Use 14″ substrates and alcohol/water mixture for ink
  - Coat at least three substrates with coating widths varying between 8″ and 14″
- Characterization/Testing
  - Measure actual coating width and compare with target width
    - Variance from target width ±¼″

The results of the **Adjustable Width Coating Summary Report** prove that the adjustable width mechanism facilitated successful coating at various target widths within the specified tolerance without opening the slot die or otherwise interrupting the production process.

Figure 4 shows that as long as the adjustable width mechanism is mounted somewhat accurately, the coating uniformity is maintained within the prescribed target width ±¼" throughout the entirety of the coating. The red curve in Figure 4 shows that the end of the coating (trailing edge, labeled TE) begins to increase over the length of the substrate as the offset increases. These DeltaE2000 values are still very low, so it was concluded that this is a minimal risk for defects in larger area coatings, especially with higher precision being readily achievable.

Figure 4: DeltaE2000 Results from Preliminary Experiments to Determine Test Criteria for Adjustable Width Coating Test Plan



Increasing offset displayed increasing DeltaE2000, which is undesirable.

Source: NEXT Energy Technologies, Inc.

Because the adjustable width mechanism is size-agnostic with respect to the slot die, it can be installed on any future system, including a 27", 40", or even larger slot die for production scenarios. This adjustable width mechanism is a modular upgrade to the coating system, permitting modification to any fixed width slot die process, making NEXT's technology a scalable solution to future manufacturing needs for custom widths in the window industry.

Products:

- Adjustable Width Coating Summary Report

Task 5: Large-Area Energy-Generating Lite Fabrication Equipment

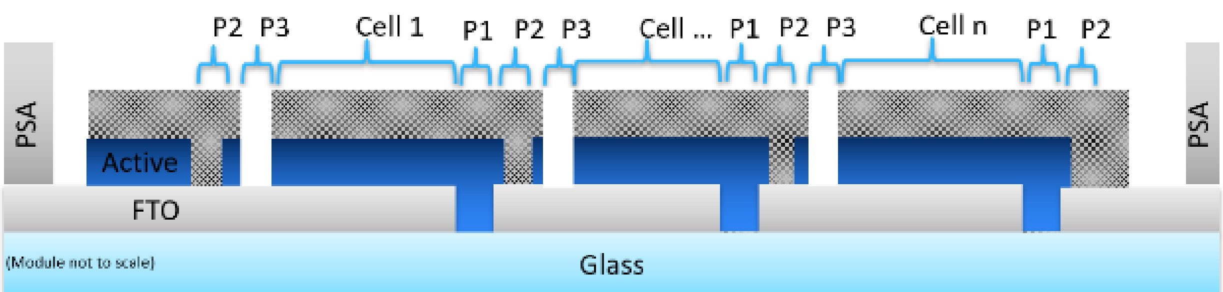
The goal of this task was to add further appropriate equipment beyond the large-area R&D coater to create a pilot line that is technically relevant to a production line. Installing a larger heating element to a laminator already in use allowed for larger modules to be made. Building and integrating a larger laser ablation patterning tool similar to a system already in-house was also completed. An additional feature of laser edge deletion was added to the tool, which mimicked an already established process on R&D scales. These laser upgrades and modifications were detailed in the **Laser Build Report**. The biggest accomplishment of this task was maintaining the precision of this laser tool over much larger areas. The R&D based tool only needs to maintain precision in areas over 20” length, whereas this large-area laser tool is able to maintain similar precision in areas over 60” in length. This 300-percent increase in size was critical to maintaining good aesthetics and performance despite the relatively longer lead times associated with using the precision optics and equipment.

The geometric fill factor (GFF) was computed and compared for lites generated on the large-area laser tool and the R&D laser tool using Equation 2, where ($P1_2 - P3_1$) is the distance from the first P3 scribe (laser cut) to the second P1 scribe, and ($P3_2 - P3_1$) is the distance from the first P3 scribe to the second P3 scribe, as depicted by the diagram in Figure 5.

Equation 2: Computation of Geometrical Fill Factor (GFF) for an Active Cell

$$GFF = \frac{(P1_2 - P3_1)}{(P3_2 - P3_1)}$$

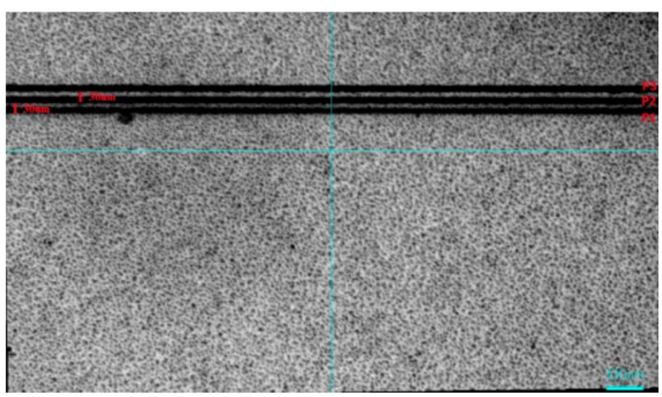
Figure 5: Representative Diagram of P-cut Pattern Placement and Active Cell Area



FTO: Fluorine-doped Tin Oxide; PSA: Pressure Sensitive Adhesive

Source: NEXT Energy Technologies, Inc.

Figure 6: P1/P2/P3 Scribes with 30-micron Spacing Generated on the Large-Area Laser Tool



Scale bar in the bottom right is equivalent to 100 microns. GFF of about 99 percent achieved.

Source: NEXT Energy Technologies, Inc.

The large-area laser tool produced a geometric fill factor of 99 percent (Figure 6), which meets the low target in the project performance metrics and was similar to the performance using the current in-house R&D laser tool (98-99 percent). Upgrades to existing tools were also implemented for the busbar application, edge seal application, and precision interlayer cutting. The expanded functionality of these backend fabrication tools allowed for successful fabrication of large-area energy-generating lites.

Additional processes which required equipment upgrades (including busbar application, edge seal application, and precision interlayer cutting) were summarized in the **Backend Fabrication Tool Report**. All these tools required a simple scale-up in footprint to permit processing of larger maximum lite sizes for the pilot line. Future work outside the scope of this project is planned for automating these processes, as will be required in a full production line. The new and upgraded equipment functionalized in this task allowed for the fabrication of large-area energy-generating lites, validating a pilot line that is technically relevant to a full-scale production line. These upgrades resulted in achieving the high target in the "defect reduction in large-area lamination" project performance metric aimed at eliminating all defects observable from a distance of 10 feet.

Products:

- Laser Build Report
- Backend Fabrication Tool Report

Task 6: Large-Area Energy-Generating Lite Fabrication

The goal of this task was to fabricate functional modules within aesthetic targets. Utilizing the tools built in Task 2 and Task 5, along with the film fabrication process used in Task 3, NEXT produced fully functional large-area modules to achieve performances similar to the R&D scale tools.

Small and large format module performances were compared in the **Transition from Benchtop R&D to Large-Area Coating Report**, with results demonstrating achievement of the high targets for the project performance metrics. Because of this, comparisons could be made between substrate size and coating tool simultaneously.

When using similar processing parameters for the complete fabrication process of small-format modules and large-area modules, the performances were equal within processing error, achieving high target performance for the "Modules have equal or better power output performance when fabricated on R&D benchtop coater and large-area coater" project performance metric.

Within the scope of this project, multiple fabrication runs of modules were completed. Large-area modules demonstrated excellent aesthetics, far surpassing the high expectations of the project performance metrics. These results were documented in the **Commercially Scalable Module Report** and had been anticipated due to the precision of the tools as well as the specifications of the previously designed ink formulations.

Products:

- Transition from Benchtop R&D to Large-Area Coating Report
- Commercially Scalable Module Summary Report

Task 7: Fabrication of Insulated Glass Units and Demo Wall

The goal of this task was to build a demonstration wall that holds IGUs with the recipient's energy-generating windows capable of powering an interactive element.

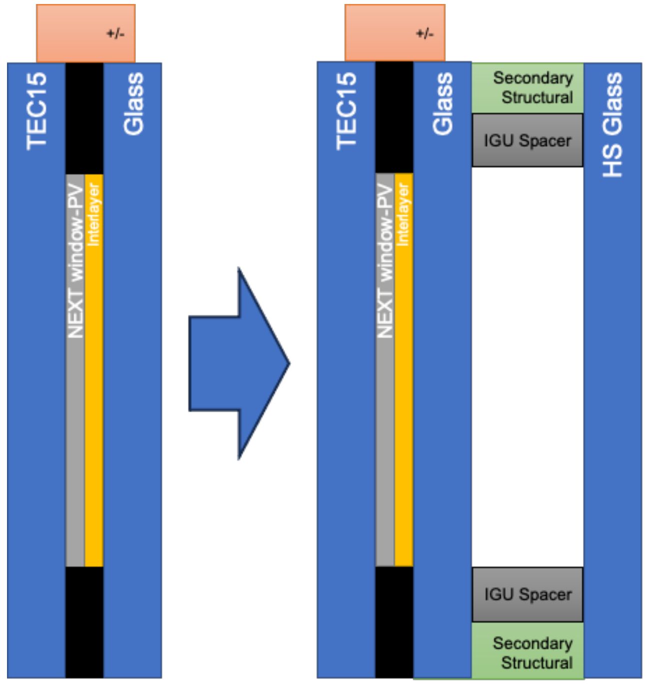
As described in the **Demo Wall Report**, functional modules with excellent aesthetic quality were fabricated to exhibit the capability of all the fabrication tools assembled within the scope of this project. These 27" x 35" sized modules were fabricated in partnership with a commercial window manufacturer, Viracon. The substrate was sourced from Viracon prior to coating steps. Laser patterns were optimized in-house to yield high geometric fill factors as well as patterns that are barely visible by eye.

Aesthetic and color information was collected at predefined locations and compared to the average value to quantify uniformity within a sample and between samples, as per guidelines from commercial partners or industry standards. The samples selected were determined to demonstrate high-quality uniform coated active layers and full stacks by measuring DeltaE2000 within and between samples to be less than 4.5 as per ASTM C1376 standards for each permutation using the spectrophotometer. It was determined that DeltaE2000 between samples was 0.81 whereas DeltaE2000 within a sample was 0.80 or less. This metric surpasses the high target of DeltaE2000 less than 2 in the project performance metrics describing repeatability and uniformity of larger slot-coated modules on large-area coater. Aesthetic uniformity is critical to achieving a successful window-integrated product as well as an excellent indicator of good module performance and reproducibility.

Representative samples were also used to take wet leakage current tests, all of which passed as expected (all based on IEC 61215-1, which is a solar module safety standard that dictates that any device over 0.1 m^2 should have an insulative resistance multiplied by the area of the module not less than 40 M□/m^2 under applied voltage more than 500 V). This confirms adequate safety packaging and laser edge cleaning of any conductive material. This passes the high target in the project performance metrics ensuring the passing requirement for IEC 61215-1. This is critical for the sale of energy-generating windows or any solar module.

After fabrication and packaging, the demo modules were shipped to Viracon to be converted into insulated glass units. This process included using Viracon's automated insulated glass unit line to apply a soft edge spacer as well as a mating glass to create the insulated glass unit (Figure 7). Next, the samples were then shipped to commercial glazing partner, Walters and Wolf for junction box application and installation into the preassembled glazing system. The modules were then wired in parallel and connected to a predesigned maximum power point tracker and interactive element that has the capability to display current output.

Figure 7: Diagram of NEXT Window-Photovoltaic Module Before (Left) and After (Right) Fabrication of the Insulated Glass Unit



HS: Heat-strengthened; TEC15: Pilkington TEC15 Glass Product

Source: NEXT Energy Technologies, Inc.

Figure 8: Image of Final Demo Wall with Interactive Element Connected and Functional

Source: NEXT Energy Technologies, Inc.

The creation of these very high-quality films, deemed viable by the team to be sufficient for an externally facing demo wall (Figure 8), was a critical milestone for the team to bring together the accomplishments of each project-supported step. Defect reduction in larger area lamination was also a key step that was previously established to produce no defects observed from a distance of 10 ft. This high target from the project performance metrics was the additional metric needed to deliver a demo wall with excellent aesthetics. The combination of acceptable defects as well as uniform film produced functional modules ready for exhibition.

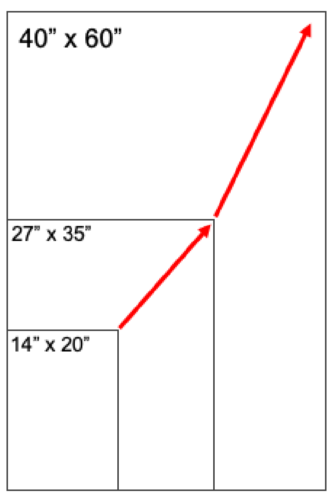
Products:

- Demo Wall Report

Task 8: Fabrication Of Larger Modules With Commercial Partners

The goal of this task was to create larger modules at a size that proves to be commercially relevant for pilot production needs. Final tool modifications were made to accommodate the largest-sized modules to be fabricated on the tools built within the scope of this project. These modifications included adding additional sensors to maintain the precision required to achieve proper coating gaps. These pilot-size modules demonstrate a successful increase in the module dimensions from 27" x 35" to 40" x 60" (that is, more than a 250-percent increase in area) in this iteration. The pilot-size modules also demonstrate a total increase from the initial substrate size of 14" x 20" to 40" x 60", which equates to more than an 850-percent increase in area (shown in Figure 9).

Figure 9: Incremental Size Increases From 14" x 20" to 40" x 60" within the Scope of This Project



Source: NEXT Energy Technologies, Inc.

Figure 10 shows a picture of a completed functional module from the fabrication. As described in the **Pilot-size Module Report**, it was determined that DeltaE2000 between samples was on average 0.70 whereas DeltaE2000 within a sample was 1.25. This metric surpasses the high target of DeltaE2000 less than 2 in the project performance metrics describing "repeatability and uniformity of largest slot-coated modules on Large-Area Coater." This value compares to the previous size of modules and can be seen compared in the Table 1 below.

These color measurements demonstrate the feasibility of the coating process to be able to produce products suitable for the window industry.

Figure 10: Representative Sample of 40" x 60" Modules

Source: NEXT Energy Technologies, Inc.

Table 1: Comparison of the Aesthetic Metrics

Module Size	DeltaE2000 within	DeltaE2000 between
27" x 35"	0.80	0.81
40" x 60"	1.25	0.70

Source: NEXT Energy Technologies, Inc.

Initial plans included shipping modules to be packaged with established processes with a commercial partner. Instead of this, NEXT decided to package these fabricated modules using manual in-house methods to expedite the process with expected results. The quality of the packaging is sufficient to meet the aesthetic performance of "defect reduction for larger area" requirements outlined in the project performance metrics. The high target was met with no defects observed from a distance of 10 ft. These results were anticipated and no critical challenges to the successful completion of this target arose.

Products:

- Pilot-size Module Report

Task 9: Validation And Updating Cost, Market And Benefits

The goal of this task was to validate and update customer and market analysis, cost models, energy and non-energy benefits, other benefits for California investor-owned utility ratepayers, and benefits to disadvantaged and low-income communities. This work demonstrated and built on the recipient's existing stakeholder engagement efforts, which include outreach to external partners and collaborators. The summaries of these findings can also be found in the project products.

The Unit Level Cost Model was updated by the project team as described in the **Updated Unit Level Cost Model Report**. This model aimed to assess the manufacturing costs of insulated glass units incorporating the project team's technology on a per-square-foot basis. Notably, the breakdown of costs focuses on the additional expenses associated with a NEXT IGU compared to a standard commercial window. A comprehensive buildup of the costs involved in producing both standard and NEXT IGUs was included. Following our collaboration with Viracon, the project team has integrated a wealth of valuable insights into the updated model.

A thorough examination of the bill of materials was conducted. To enhance the reliability of the calculations, sourcing of cost components by obtaining quotations from vendors, suppliers, and supply chain partners was expanded. In the case of proprietary materials, quotations from contract manufacturers were acquired, with possibilities for long-term improvements explored. The model also provided a detailed overview of production yields at each stage of the fabrication process, encompassing PV lite coating, PV lite assembly, and IGU fabrication. This cost model underwent rigorous review by the team's project partner, Viracon, and has received the endorsement of glass industry experts who have contributed valuable insights without reservations.

As detailed in the **System Level Cost Model Report**, an enhanced Return to Building Owner Model was developed and aligned with the updated Unit Level Cost Model and incorporating system-level costs and a downstream selling price. The model showcased the value proposition of NEXT's building-integrated photovoltaic (BIPV) windows to end users. The Return to Building Owner Model offered a net present value analysis from the perspective of building owners, helping them to identify potential long-term cost savings and revenue generation opportunities associated with NEXT's window-PV product.

This Return to Building Owner Model extended the unit level costs to project the complete balance of system (BOS) costs and supply chain markups for fully installed NEXT BIPV windows. Similar to the unit level cost model, the spotlight was placed on incremental costs over a baseline conventional window. The model incorporated a straightforward payback calculation and took into consideration various factors, including but not limited to weather, insolation, electricity prices, tax treatment, and location-based assumptions. The model calculated the total benefits to the building owner as the sum of the net present value over 30 years of the power generated, the impact of accelerated depreciation for solar assets, and the solar investment tax credit. Under current taxation policies, the cumulative benefit of installing NEXT windows is greater than the incremental fully installed cost of NEXT windows, indicating a strong return and one-year payback on the building owner's investment.

The work demonstrated that this product would provide a compelling return to owners of commercial buildings: a result that the team had anticipated due to the majority of the benefits being realized in year one of the building owner's investment horizon.

A range of stakeholders, including licensees, supply chain partners, and end-customers, were actively engaged to validate the developed solution, market viability, and cost model with details provided in the **Stakeholder Engagement Summary** submitted to the CEC. Fourteen letters of commitment or support from supply chain partners indicating interest in development, adoption, purchase, or use of the technology were delivered to the CEC, meeting the low target and almost hitting the high target of the "15 letters of commitment or support from supply chain partners indicating interest in development, adoption, purchase or use of our technology" project performance metric.

As described in the **Ratepayer Benefits Report**, a sophisticated greenhouse gas (GHG) reduction model was developed to project how adoption of NEXT's technology would impact global GHG emissions. The GHG model serves as a comprehensive assessment of NEXT's technology and its potential to deliver tangible energy and non-energy benefits to California ratepayers.

The model was put together with the help of industry experts and used numerous reports for quantifying existing building stock floor space, predicting growth in building stock floor space, and determining vision area from floor space in markets around the world independently for residential and commercial building stock. NEXT applied predicted adoption rates for different regions, for residential and commercial buildings, and for retrofits versus new construction projects independently for all markets. Overall, the predicted adoption rate in the model was very similar to the historical adoption of low-E windows. The energy savings from the energy generation of the windows and projected future product improvement was taken into account in the model. The model also independently included energy savings via improvement in solar heat gain coefficient, which improves the energy efficiency of windows. In addition, the model included the energy savings of manufacturing PV panels without the additional carbon cost of glass manufacturing since the glass is already intrinsic to the construction of conventional windows. It was found that 0.9 Giga Tons of CO_2 savings could potentially be realized by 2050 with the implementation of this technology.

As highlighted in the reports, NEXT placed the spotlight on the additional costs incurred by building owners for installing NEXT's BIPV windows compared to their installing standard commercial windows. NEXT's incremental cost of a fully installed PV-IGU is added to the standard commercial IGU selling price and BOS costs to calculate a total installed cost for a NEXT window on a square-foot basis.

The additional costs include:

- NEXT materials (ink)
- NEXT labor (coating and assembly)
- Incremental window framing (labor)
- Incremental glazing labor
- BOS (inverter, hardware, electrical labor, permitting, other soft costs)

By running the updated Return to Building Owner Model, NEXT was able to verify that NEXT's technology will offer an internal rate of return of 22 percent and a simple payback period of one to two years for an average California commercial building in San Francisco, Sacramento, and Santa Barbara, demonstrating the economic feasibility of adoption in cities across the state with varying weather and electricity prices. This meets the high target for the project performance metric / goal of projecting a "Simple payback of two (2) years or less is achievable for an average California commercial building." NEXT also included non-California U.S. cities in its model (Honolulu, Phoenix, Denver, Omaha, Chicago, Dallas, Miami, New York, Atlanta) and determined that the payback on the incremental cost of NEXT's technology is less than 10 years in all locations.

Based on the updated models, NEXT expects to achieve an LCOE below $0.03 kWh in 2030 when taking into account currently known tax incentives for 2030. This meets or surpasses the low target for the project performance metric / goal of a "Projected LCOE of $0.03/kWh by 2030." NEXT's calculations also show that an LCOE of $0.04 kWh in 2030 could be possible without including the investment tax credit, though this does not appear to represent a realistic situation based on current law. In addition, based on extensive conversation with potential customers, the LCOE does not appear to be the driving force for adoption of this technology in the United States by 2030 because the product is a window, and the bigger driving force for increasing the demand for a window product such as NEXT's is improving the energy impact of windows. Architects, building owners, and building occupants currently prefer windows over wall area; this is advantageous because current window technologies often have a negative energy impact to a building compared to wall areas whereas a NEXT window has a positive energy impact.

Products:

- Updated Unit Level Cost Model Report
- System Level Cost Model Report
- Stakeholder Engagement Summary
- Ratepayer Benefits Report

Task 10: Pilot Production Line

The goal of this task was to show that a pilot production line based on technological merits from the previous tasks is acceptable and feasible. The front-end process has been detailed specifically based on the findings of the CEC Bringing Rapid Innovation Development to Green Energy (BRIDGE) grant. The pilot production back-end process is specifically out of the scope of the BRIDGE award, but the development for this will be separately funded and supported by the CEC Realizing Accelerated Manufacturing and Production for Clean Energy Technologies (RAMP) grant already awarded to NEXT under CEC Agreement EPC-22-011. The plan for an integrated production line consists of a series of tools replicating the accomplished large-area coating tools that were purchased, built, or assembled within the scope of the BRIDGE agreement. The resulting projected pricing, throughput, and yield estimates were considered acceptable, as described in the Updated Unit Level Cost Model Report. These findings are also detailed in the **Integrated Production Line Report**.

The initial production plan continues to utilize commercial window glass and is designed to be located in about 48,000 ft^2 of floor space. The initial production plan was planned with the aim of producing 1,500,000 ft^2 of BIPV product per year. Based on incremental assembly requirements, the production line can be modular and installed in phases.

With these plans in place, the projected pricing, throughput, and yield estimates were also considered acceptable in the **Updated Unit Level Cost Model Report**. The associated assumptions included the aforementioned production capacity of 1,500,000 ft^2 of building-integrated photovoltaic product per year. Yield estimates were considered and validated with similar processing types that are commercially available. As described in **Section 3.8 and Task 9 reports**, the updated pricing revisited materials costs, labor costs, and processing costs and was still considered acceptable.

The team worked closely with external partners to review the integrated production line. It was determined that a larger footprint than the current facility would be needed to be able to achieve production capacity at 1,500,000 ft^2 of building-integrated photovoltaic product per year. These results were anticipated. Fortunately, the ramp-up to this full production is to take place over the course of a few years and Low-Rate Initial Production, to be supported by CEC Agreement EPC-22-011 under the RAMP CEC grant, is expected to be more than sufficiently achieved within the floor space of the current production facility. The lessons learned from completing the pilot production line-related task included realizing the criticality of: (1) efficient tool placement to allow for serviceability and reduced down time, and (2) proper production line design and partner selection to reduce unnecessary long lead times.

Products:

- Integrated Production Line Report

CHAPTER 4: Conclusion

Within the scope of this project, the project team NEXT was successful in:

- building coating tools,
- optimizing coatings,
- building backend tools,
- fabricating devices,
- completing a demo wall, and
- scaling up substrate size to be commercially relevant

These tasks have clearly de-risked the fabrication efforts outlined in this report. Multiple fabrication runs of modules were completed with successful outcomes. Large-area modules showed excellent aesthetics, far surpassing the high expectations of the project performance metrics. These successful results were anticipated due to the precision of the tools built into the IGU production line as well as the suitability of the previously designed ink formulations. The lessons learned from the overall project included the identification of details crucial to the equipment set-up that contribute to the precision needed to achieve coatings of sufficient quality. For example, if there are inaccuracies in the coating gap (that is, the distance between the substrate and the coating die), then non-uniformities would be observed. The same need for accuracy applies to the precision alignment of the laser in achieving adequate cut distances. For example, if the laser is not focused correctly or the distance between the focal point and substrate is insufficient, the laser might be out of focus or not registered correctly to the previous cuts. Fortunately, the laser tool used by NEXT was appropriately designed to allow for process optimization, which would result in the required performances. All the predetermined goals, objectives, and project performance metrics were met or exceeded within the duration of the BRIDGE project. Future work was also outlined and will be continued as planned in the RAMP project. To showcase these technical accomplishments, two demonstration walls of four 27″ x 35″ units each were constructed as well as a freestanding 40″ x 60″ unit to demonstrate the scalability of the technology. All these units represent the great progress made in accelerating the core technology to its full market potential.

Alongside the technical accomplishments, the market potential, value proposition, and business plan for NEXT transparent building-integrated photovoltaic technology have been further validated throughout the industry. This was done via furthering engagement with commercial partners such as Viracon and Walters & Wolf. As previously reported, according to statements made by these industry leaders, a functional, attractive, transparent solar window product has been an unmet objective of the commercial glass industry. In all instances, these companies have indicated an interest in building-integrated photovoltaic window solutions. These companies also said the aesthetics, performance, lifetime, and cost of NEXT's technology in particular were extremely compelling and far superior to others' previous attempts or other technologies on the market. The results of this BRIDGE project further instilled this confidence in NEXT's technology, especially through the GHG reduction model, which reassessed ratepayer benefits to be similar or better than previously anticipated and the comprehensive system level cost model, which considered the balance of systems costs, materials and labor costs, incremental window framing labor costs, and incremental glazing labor costs.

From the standpoint of infrastructure requirements, the integration of NEXT's energy-generating module production step as an additional feature and capability on existing fabrication lines is even more attractive because the low-cost capital expenditure coating machinery can be seamlessly integrated into current supply chains and manufacturing footprints. The seamlessness of this integration is even greater than was anticipated by NEXT at the outset of this project. Based on discussions with window fabrication industry leaders, this successful BRIDGE project for the production of pilot-size energy-generating windows using all pilot production manufacturing methods has been a critical milestone for establishing the path-to-market for NEXT's technology, commercialization, and the future growth of NEXT.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ASTM	American Society for Testing and Materials
BIPV	building-integrated photovoltaic
BOS	balance of system
BRIDGE	Bringing Rapid Innovation Development to Green Energy
GFF	geometric fill factor
GHG	greenhouse gas
IGU	insulated glass units
LCOE	levelized cost of energy
low-e	low-emissivity
NEXT	NEXT Energy Technologies
RAMP	Realizing Accelerated Manufacturing and Production for Clean Energy Technologies

References

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Energy Star. n.d. "Commercial Real Estate: An Overview of Energy Use and Energy Efficiency Opportunities." Available at https://www.energystar.gov/sites/default/files/buildings/tools/CommercialRealEstate.pdf.

IEA. December 2019. *Global Status Report for Buildings and Construction 2019*. Available at https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019, License: CC BY 4.0.

Project Deliverables

Technical Tasks

Task 2: LARGE-AREA COATING EQUIPMENT

- Test Plan Report
- Large Area Tools Integration Report

Task 3: LARGE-AREA COATINGS

- Coating Process Report
- Coating Progress Report

Task 4: ADJUSTABLE WIDTH COATINGS ON LARGE AREAS

- Adjustable Width Coating Summary Report

Task 5: LARGE-AREA ENERGY-GENERATING LITE FABRICATION EQUIPMENT

- Laser Build Report
- Backend Fabrication Tool Report

Task 6: LARGE-AREA ENERGY-GENERATING LITE FABRICATION

- Transition from Benchtop R&D to Large-Area Coating Report
- Commercially Scalable Module Summary Report

Task 7: FABRICATION OF INSULATED GLASS UNITS AND DEMO WALL

- Demo Wall Report

Task 8: FABRICATION OF LARGER MODULES WITH COMMERCIAL PARTNERS

- Pilot-size Module Report

Task 9: VALIDATION AND UPDATING COST, MARKET AND BENEFITS

- Updated Unit Level Cost Model Report
- System Level Cost Model Report
- Stakeholder Engagement Summary
- Ratepayer Benefits Report

Task 10: PILOT PRODUCTION LINE

- Integrated Production Line Report

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

CALIFORNIA ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Project Performance Metrics

July 2024 | CEC-500-2024-080

APPENDIX A:
Project Performance Metrics

Project Performance Metrics Table

Project Performance Metric	Benchmark Performance	Current Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric	Actual Final Value and Report Ref.
Implement controls on the Air Table to effectively improve uniformity of heat-strengthened glass	N/A	Current methods of slot die coating are performed on non-heat-treated glass with very low substrate variation.	Confirmed by Recipient to work within current uniformity standards.	Confirmed by Recipient to work better than current uniformity standards.	Comparison to inhouse R&D coating methods.	Aesthetic uniformity is critical to achieving high-performing modules.	Confirmed by Recipient to work better than current uniformity standards. LARGE-AREA TOOLS INTEGRATION REPORT
Repeatability and uniformity of coated films on Large-Area Coater	Color Uniformity (B, between units and W, within unit panel) Transmission DeltaE2000 < 4.5 as per ASTM C1376	DeltaE2000 = ~2 for films deposited on R&D lab coater	DeltaE2000 < 4.5	DeltaE2000 < 2	Samples measured within a sample will be measured at four locations and compared to the average color as per industry standards such as ASTM C1376.	Aesthetic uniformity is critical to achieving a successful window-integrated product as well as an excellent indicator of good module performance and reproducibility. ASTM C1376 is the uniformity standard for window products.	"All DeltaE2000 values were below 2, the High Target Performance Metric for the project, indicating a high repeatability" (within and between) COATING PROCESS REPORT
Repeatability and uniformity of lab-scale slot-coated modules on Large-Area Coater	Color Uniformity (B, between units and W, within unit panel) Transmission DeltaE2000 < 4.5 as per ASTM C1376	DeltaE2000 =~2 for films deposited on R&D lab coater	DeltaE2000 < 4.5	DeltaE2000 < 2	Samples measured within a sample will be measured at four locations and compared to the average color as per industry standards such as ASTM C1376.	Aesthetic uniformity is critical to achieving a successful window-integrated product as well as an excellent indicator of good module performance and reproducibility. ASTM C1376 is the uniformity standard for window products.	"All DeltaE2000 values were below 2, the High Target Performance Metric for the project, indicating a high repeatability" (within and between) COATING PROCESS REPORT

Project Performance Metric	Benchmark Performance	Current Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric	Actual Final Value and Report Ref.
Repeatability and uniformity of larger slot-coated films on Large-Area Coater	Color Uniformity (B, between units and W, within unit panel) Transmission DeltaE2000 < 4.5 as per ASTM C1376	N/A	DeltaE2000 < 4.5	DeltaE2000 < 2	Samples measured within a sample will be measured at four locations and compared to the average color as per industry standards such as ASTM C1376.	Aesthetic uniformity is critical to achieving a successful window-integrated product as well as an excellent indicator of good module performance and reproducibility. ASTM C1376 is the uniformity standard for window products.	"All DeltaE2000 values were below 2, the High Target Performance Metric for the project, indicating a high repeatability" (within and between) COATING PROCESS REPORT
Repeatability and uniformity of larger slot-coated modules on Large-Area Coater	Color Uniformity (B, between units and W, within unit panel) Transmission DeltaE2000 < 4.5 as per ASTM C1376	N/A	DeltaE2000<4.5	DeltaE2000<2	Samples measured within a sample will be measured at four locations and compared to the average color as per industry standards such as ASTM C1376.	Aesthetic uniformity is critical to achieving a successful window-integrated product as well as an excellent indicator of good module performance and reproducibility. ASTM C1376 is the uniformity standard for window products.	"All DeltaE2000 values were below 2, the High Target Performance Metric for the project, indicating a high repeatability" (within and between) COATING PROCESS REPORT
Repeatability of slot-coated full stack films on multiple sizes of substrates	Color Uniformity (B, between units) Transmission DeltaE2000 < 4.5 as per ASTM C1376	DeltaE2000 = ~3 for films deposited at different sizes on R&D lab coater	DeltaE2000 < 4.5 for all full stack films deposited.	DeltaE2000 < 2 for all full stack films deposited.	Samples measured as an average of four samples of each using a spectrophotometer.	In order to properly optimize device metrics on a lab scale, it is imperative that the technique is scalable to large areas with predictable performances.	"All DeltaE2000 values were below 2, the High Target Performance Metric for the project, indicating a high repeatability" (within and between) COATING PROCESS REPORT "The color uniformity within and between samples is determined to be less than 1. This is a critical value as ASTM C1376 requires color uniformity to have a DeltaE2000 to be less than 4.5. Project

Project Performance Metric	Benchmark Performance	Current Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric	Actual Final Value and Report Ref.
							Performance Metrics also show a High Target to be less than 2.” COMMERCIALLY SCALABLE MODULE SUMMARY REPORT “Results were determined to demonstrate high-quality uniform coated active layers and full stacks by measuring DeltaE2000 within and between samples to be < 4.5 as per ASTM C1376 on samples for each permutation using spectrophotometer. It is shown that DeltaE2000 between samples is 0.81 while within a sample is 0.80 or less.” DEMO WALL REPORT
Defect reduction in large-area lamination	Defect size is 1/16" Max separated ≥ 12"	Defect size is 1/16" Max separated ≥ 12"	Defect size is 1/16" Max separated ≥ 12"	No defects observed from a distance of 10 ft.	**Optically viewing** — From a distance of 10 ft. (3 m) in transmission, at a viewing angle of 90 degrees to the specimen, against a bright, uniform background as per industry standards. **Measurement** — Calipers	Defects should not be readily observed from 10 ft. viewing distance to be deemed acceptable for window industry standards.	No defects observed from a distance of 10 ft. BACKEND FABRICATION TOOL REPORT

Project Performance Metric	Benchmark Performance	Current Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric	Actual Final Value and Report Ref.
Geometric Fill Factor (GFF) optimization on large-area modules	GFF > 95%	GFF = 98-99% on R&D sized substrates	GFF same as current methods.	GFF better than current methods.	Microscope measurements of tolerance of laser patterning of module registration.	Aesthetic of the patterning lines has proven to be a critical metric in achieving a suitable window product with customer surveys. When approaching GFF > 95%, the registration of cells becomes less noticeable to the observer.	"The Large-Area Laser Tool produced a GFF of ~99%, which meets Low Target performance for GFF in the Project Performance Metrics of similar results to current methods (98-99% GFF). Further process development will be performed to increase the GFF and achieve High Target performance." LASER BUILD REPORT
Power output performance of modules fabricated on large-area coater compared to R&D benchtop coater of same size	N/A	Modules of similar size having similar power output performance when fabricated on different R&D benchtop coaters.	Modules have similar power output performance when fabricated on R&D benchtop coater and Large-Area Coater.	Modules have equal or better power output performance when fabricated on R&D benchtop coater and Large-Area Coater.	Measurement using inhouse measurement tools.	Important to predict Performance Metrics can be achieved independent of substrate size or specific tool as rapid scale-up of technology continues.	"When utilizing similar processing parameters for the complete fabrication process of small format modules and large-area modules, the performances were equal within processing error, achieving High Target Performance for the Project Performance Metrics. While the goal of this Task was achieved by demonstrating equivalent power conversion efficiency from small format modules fabricated on Benchtop R&D Coaters and large-area modules fabricated on the Large-Area R&D Coater with processing parameters held constant, higher Power Conversion Efficiencies have been achieved on Benchtop

Project Performance Metric	Benchmark Performance	Current Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric	Actual Final Value and Report Ref.
							R&D Coaters utilizing improved processing conditions which are not yet available for large-area modules. The experiment performed shows that future implementation of these improved processes for large-area modules will allow achievement of the High Target Performance Metrics on large-area modules." TRANSITION FROM BENCHTOP R&D TO LARGE-AREA COATING REPORT
Power output performance of modules fabricated on large-area coater of increasing size	N/A	Modules of different sizes have similar power output performance when fabricated on the same R&D benchtop coater.	Modules have similar power output performance when fabricated on R&D benchtop coater and Large-Area Coater.	Modules have equal or better power output performance when fabricated on R&D benchtop coater and Large-Area Coater.	Measurement using inhouse measurement tools.	Important to predict Performance Metrics can be achieved independent of substrate size or specific tool as rapid scale-up of technology continues.	See above. TRANSITION FROM BENCHTOP R&D TO LARGE-AREA COATING REPORT
Wet Leakage Current Test (IEC 61215)	Any device over $0.1m^2$ should have an insulative resistance, multiplied by the area of the module, should not be less than 40 $M\Omega/m^2$ under applied voltage >500V	PASS	PASS	PASS	Keithley 237 High Voltage Source Measurement Unit to apply > 500 V to module submersed in electrolyte solution.	Passing requirement for IEC 61215-1 and UL 61730 (Safety). Critical for sale of energy-generating window or any solar module.	"IEC 61215 where any device over 0.1 m^2 should have an insulative resistance, multiplied by the area of the module, should not be less than 40 M/m^2 under applied voltage > 500 V." Demo Wall Report

Project Performance Metric	Benchmark Performance	Current Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric	Actual Final Value and Report Ref.
Repeatability and uniformity of largest area slot-coated active layer films on Large-Area Coater	Color Uniformity (B, between units and W, within unit panel) Transmission DeltaE2000 < 4.5 as per ASTM C1376	N/A	DeltaE2000 < 4.5	DeltaE2000 < 2	Samples measured within a sample will be measured at four locations and compared to the average color as per industry standards such as ASTM C1376.	Aesthetic uniformity is critical to achieving a successful window-integrated product. ASTM C1376 is the uniformity standard for window products.	"Results were determined to demonstrate high-quality uniform coated active layers and full stacks by measuring DeltaE2000 within and between samples to be < 4.5 as per ASTM C1376 on samples for each permutation using spectrophotometer. It is shown that DeltaE2000 between samples is 0.81 while within a sample is 0.80 or less." Pilot-size Module Report
Defect reduction in larger area lamination	Defect size is 1/16" Max separated ≥ 12"	Defect size is 1/16" Max separated ≥ 12"	Defect size is 1/16" Max separated ≥ 12".	No defects observed from a distance of 10 ft.	**Optically viewing** — From a distance of 10 ft. (3 m) in transmission, at a viewing angle of 90 degrees to the specimen, against a bright, uniform background as per industry Standards. **Measurement** — Calipers.	Working with a commercial laminator, it is critical to be able to laminate functional larger area modules to de-risk using existing industrial equipment for production.	"Defect reduction in larger area lamination was also a key step that was previously established to produce no defects observed from a distance of ten ft. This high metric from the Project Performance Metrics allowed the team to de-risk using existing industrial equipment for production. This result guided decisions made in EPC-22-011." DEMO WALL REPORT

Project Performance Metric	Benchmark Performance	Current Performance	Low Target Performance	High Target Performance	Evaluation Method	Significance of Metric	Actual Final Value and Report Ref.
Verify that a simple payback of ten years or less is achievable for an average California commercial building.	Simple payback of ten years or less	N/A	Simple payback of 10 years or less is achievable for an average California commercial building.	Simple payback of two years or less is achievable for an average California commercial building.	Net Present Value analysis of the main benefit streams of NEXT technology: - Energy Savings - Accelerated depreciation - Investment tax credit	Simple payback is an investment criterion that building owners, developer, and end users of the technology use to make purchase decisions.	Simple payback of two years or less is achievable for an average California commercial building. RATEPAYER BENEFITS REPORT
Validate a potential projected Levelized Cost of Energy (LCOE) of $0.03/kWh by 2030.	Levelized Cost of Energy (LCOE) of ~$0.06/kWh-$0.40/kWh	N/A	Projected LCOE of $0.03/kWh by 2030.	Projected LCOE of $0.02/kWh by 2030.	Lifetime cost of solar relating to the energy production of the system.	Industry standard for the competitiveness of energy-generating technologies.	"Based on our updated models we expect to achieve an LCOE below $0.03 kWh in 2030 when including currently known tax incentives for 2030. Our calculations also show an LCOE of $0.04 kWh in 2030 could be possible without including the investment tax credit, though that doesn't seem to represent a realistic situation based on current law." RATEPAYER BENEFITS REPORT
Obtain ten or more letters of commitment or support from supply chain partners indicating interest in development, adoption, purchase, or use of our technology.	N/A	Six letters of commitment from commercial partners, strategic developers, or investors.	Ten letters of commitment or support from supply chain partners indicating interest in development, adoption, purchase, or use of our technology.	Fifteen letters of commitment or support from supply chain partners indicating interest in development, adoption, purchase, or use of our technology.	Submit letters of commitment to Commission Agreement Manager.	Validates technology and market value for introduction in building-integrated photovoltaics environment for performance and aesthetics.	14 RAMP Commitment and Support Letters STAKEHOLDER ENGAGEMENT SUMMARY