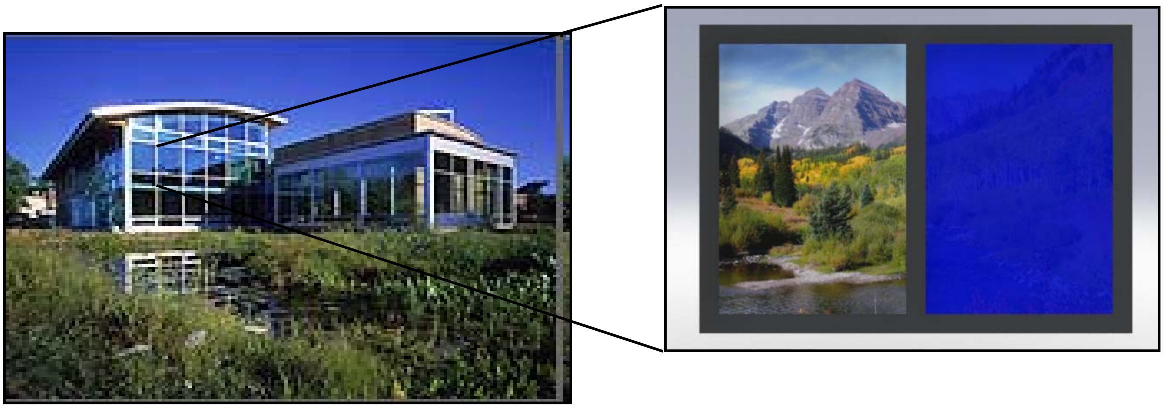
ARPA-E PROJECT FINAL REPORT



Building Efficiency

DE-FOA-0000065

Award:	DE-AR0000019
Lead Recipient:	ITN Energy Systems
Project Title:	Low Cost Electrochromic Film on Plastic for Net-Zero Energy Buildings
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1 Executive Summary

Impact on the Advancement of Electrochromic Windows: Over 4 Quads of energy are lost through windows annually. Passive coatings reduce wasted energy, but energy lost through windows would remain over 2 Quads with complete replacement of Low-E glass. Active control of transmitted light and solar heating with electrochromic (EC) windows can transform the efficiency of energy use within buildings, thereby reducing energy footprints and corresponding greenhouse emissions (Figure 1). Architectural surveys reveal a tremendous desire to offer integrated EC windows in support of net zero energy buildings, but high production, integration, and distribution cost limits adoption of current EC products. Roll-to-roll manufacturing of an EC film can dramatically reduce production and integration cost as well as improved flexibility and responsiveness across the supply chain to improve distribution cost challenges. Similar cost savings have already been validated in the thin-film photovoltaic industry.

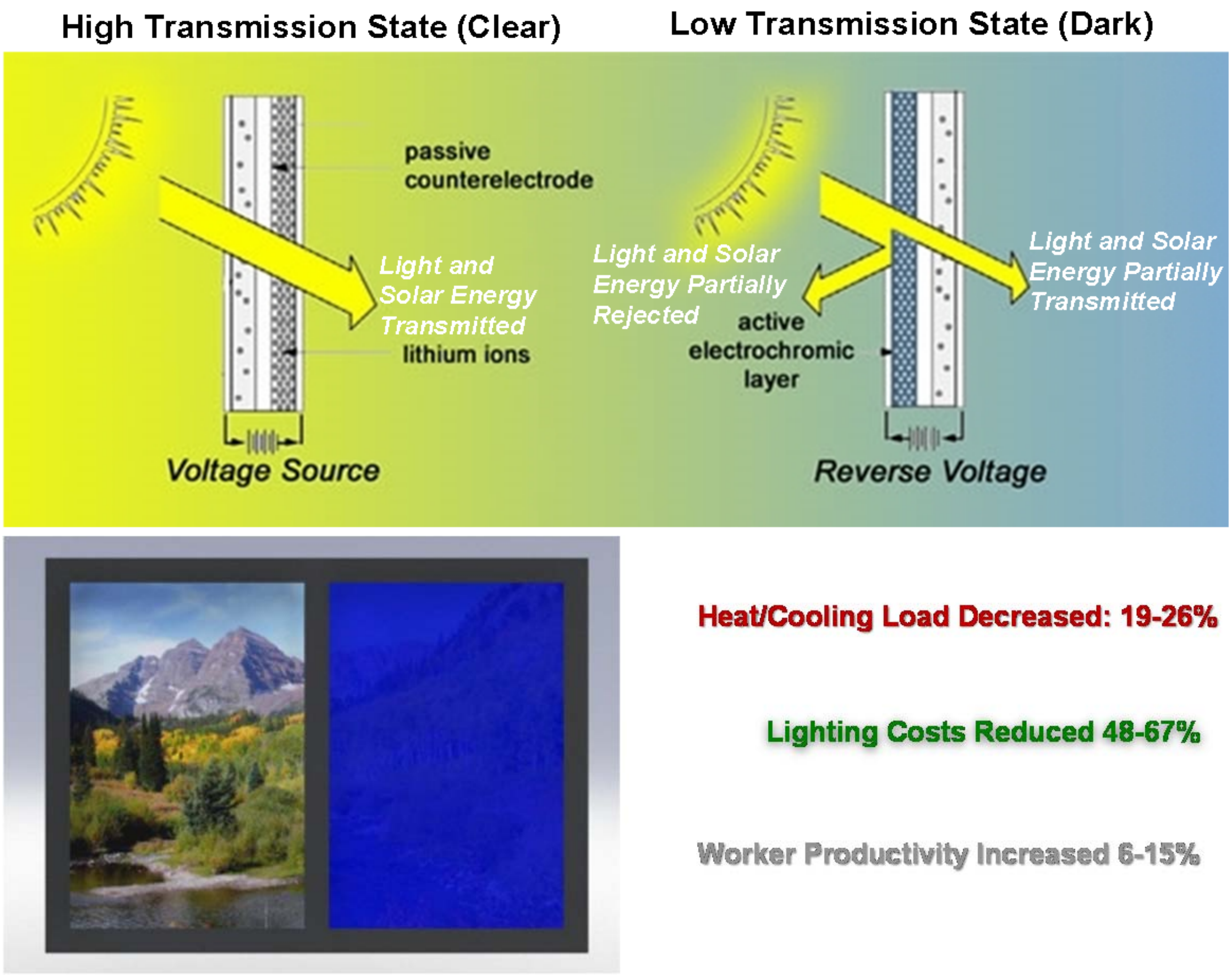

Figure 1. Active control of light & heat transmitted through an EC window (top image reproduced from ref. 1). Reduced HVAC and overhead lighting and increased worker productivity result.

[1] C. Scruton, *et al.* "A Design Guide for Early-Market EC Windows," CEC Report

ITN aimed to utilize its proven heritage of efficiently transitioning technologies from rigid to flexible substrates employing roll-to-roll manufacturing to capture the emerging EC window market opportunity. In collaboration with a vertically integrated team to address technical, business, and market barrier demands that included the Electric Power Research Institute, Southern California Edison (SCE), MAG Automation and Controls, and the Colorado School of Mines, ITN will target an EC film product with dramatically reduced cost that could support widespread commercialization. Successful completion of the effort aimed to mature the technology readiness level (TRL) and manufacturing readiness level (MRL) to reduce investor risk and motivate industry led strategic partnerships to commercialize EC film. Specific objectives/deliverables included:

- ❑ Transition Small Scale Prototypes To Limited 0.5 Meter Wide, Web Coater Production
  - Design and build a 0.5 meter web coater for EC pilot production
  - Validate web coater production with required yield & uniformity
  - Validate detailed cost models for incremental film cost to meet market needs
  - Support large area prototype demonstration articles
  - Develop and implement intelligent process control strategies

- ❑ Satisfy Market Driven EC Performance Metrics on Plastic Substrates
  - Produce large area EC film (>500 cm^2) with T_v 3-65% and high stability in ASTM testing
  - Achieve performance with scale invariant, robust process windows amenable to manufacturing transition

- ❑ Product Development and Commercialization
  - IGU Design (integration protocols)
  - Establish High Rate Processes to Reduce Manufacturing Cost
  - Identify Strategic Partnerships

Technical Efficacy and Economic Feasibility of the Methods and Techniques Investigated: Employing a novel, roll-to-roll manufacturing platform, ITN has established the feasibility of a low-cost EC film that could enable wide spread market penetration. Not only does the flexible substrate enable low cost manufacturing, but it also supports novel integration schemes, such as retrofit and suspended films to support highly insulating windows. i.e. low U-values (Figure 2). A recent analysis for passive low-e film shows for each dollar available for window retrofit or replacement, window film provided 6.6 times greater energy cost savings than total window replacement with new low-E windows over all U.S. climate zones.[2] ITN's Flexible EC film aims to extend the benefits of retrofit films to actively controlled windows. With over 100,000,000

[2] http://www.llumar.com/en/WindowFilmWhitePapers.aspx: *Steve DeBusk*, "Comparative Analysis of Retrofit Window Film to Replacement with High Performance Windows"

existing homes,[3] retrofit products are crucial to achieve widespread energy savings. In development to date, ITN has demonstrated:

- All solid-state, lithium based-electrochromic devices deposited directly on PET substrates
  - Modulated visible transmission from 5% to 65% (solid-state devices)
  - Modulated visible transmission from 3 to 70% (composite devices)
  - Leakage currents less than 100 μW/ft^2 for devices >600 cm^2
  - Durable cycling in aggressive high temperature, high humidity environment
    - Suspended film architectures (>20,000 cycles)
    - Laminated to Glass-- Outside IGU (>10,000 cycles)

- Established limited roll-to-roll production of solid state EC devices on PET substrates
  - Up to 2m continuous production of individual layers on 0.5 m wide web
  - Integrated solid-state devices
  - Initial demonstration of intelligent process controls for individual layers

- Demonstrated monolithic integration, i.e. laser scribing into custom definable devices

- Development of high rate, thin electrolytes to dramatically decrease manufacturing cost

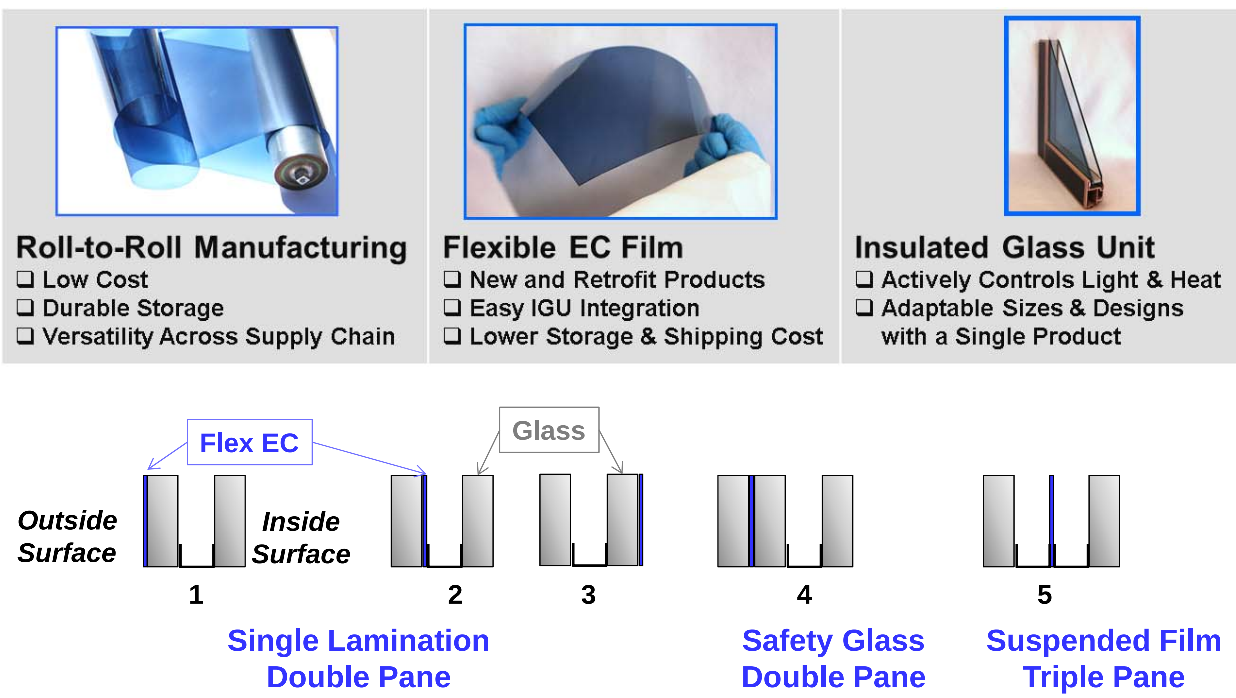

Figure 2. ITN's unique EC product enables wide spread market penetration of new and retrofit markets with a novel low-cost, roll-to-roll manufacturing platform.

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[3] "Residential Envelopes, Future Market Needs," E Werling at DOE Windows and Envelope Workshop, April 2013.

Anticipated Public Benefits of Effort: U.S. buildings today account for 40% of all primary energy used and 38% of carbon dioxide emission in the United States.[4] Energy use associated with windows alone represents 4 quads annually.[5] For electricity generated from coal, this represents one hundred million metric tons of carbon dioxide emission that could be eliminated with more efficient ‘Smart’ windows that actively change lighting and HVAC use in response to external stimuli. Further, that saved energy could instead support a transition from gasoline to electric cars without requiring new generating capacity. While 4 quads is equivalent to ~70 million barrels of oil, inefficiencies in electricity distribution and battery charging reduce the impact. Still, if the energy saved powered electric vehicles, this would result in an annual savings of over 19 M barrels of oil.[6]

Actual energy savings and greenhouse reductions then result from improved performance for EC windows relative to the existing stock and achievable market penetration. Unlike other building components, windows theoretically can be energy neutral or even net contributors to the energy balance.[7] However, almost 2 quads of energy would still leak through windows if all existing window installations were converted to low-E glass. Consequently, new actively controlled smart windows are required to achieve zero energy windows in support of net zero energy buildings. A California Energy Commission study found EC windows could decrease electricity use 40% in some commercial building scenarios.[1] More aggressive estimates show 80% energy savings by combining EC glazing with highly insulating mounts and integrated facades.[8] In these scenarios, EC are actually more efficient than insulated walls.

In support of the DOE’s missions to reduce greenhouse emission, increase energy efficiency, and maintain a worldwide technology lead in advanced energy materials, ITN’s goal is to dramatically reduce EC cost to enable widespread market acceptance. A market penetration of 40-50% is predicted at a price <$50/ft^2 (incremental EC film price of $11-25).[9] ITN’s models indicate that the EC film could achieve these targets, thereby driving higher market acceptance. Figure 3 shows national energy savings projected from EC windows for conservative and aggressive targets. Commercialization of an EC film leads to energy savings up to 26 quads over a ten year period, with a corresponding reduction in greenhouse gas up to 650 million metric tones and 100 million barrels of oil not used.

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[4] U.S. DOE. EIA, State Energy Data 2005: and EIA, Annual Energy Outlook 2008, Mar. 2008.

[5] U.S. DOE: Zero Energy Window Prototype Fact Sheet [website publication] http://windows.lbl.gov/

[6] U.S. DOE “ Electric & Hybrid Vehicle RDD Programs; Petroleum Equiv. Fuel Economy Calculation.”

[7] D.Arasteh *et al.*, “Zero Energy Windows,” [website publication]---http://windows.lbl.gov/

[8] “New and Retrofit Fenestration Solutions for High Performance Buildings,” S. Selkowitz presentation at the Chicago Workshop and Army Energy Summit, Jan. 2009.

[9] M.R. Lapointe, G.M. Sottle, in: C.M. Lampert, et al. (Eds.),Proceedings of SPIE, vol. 4458, 2001, p. 112.

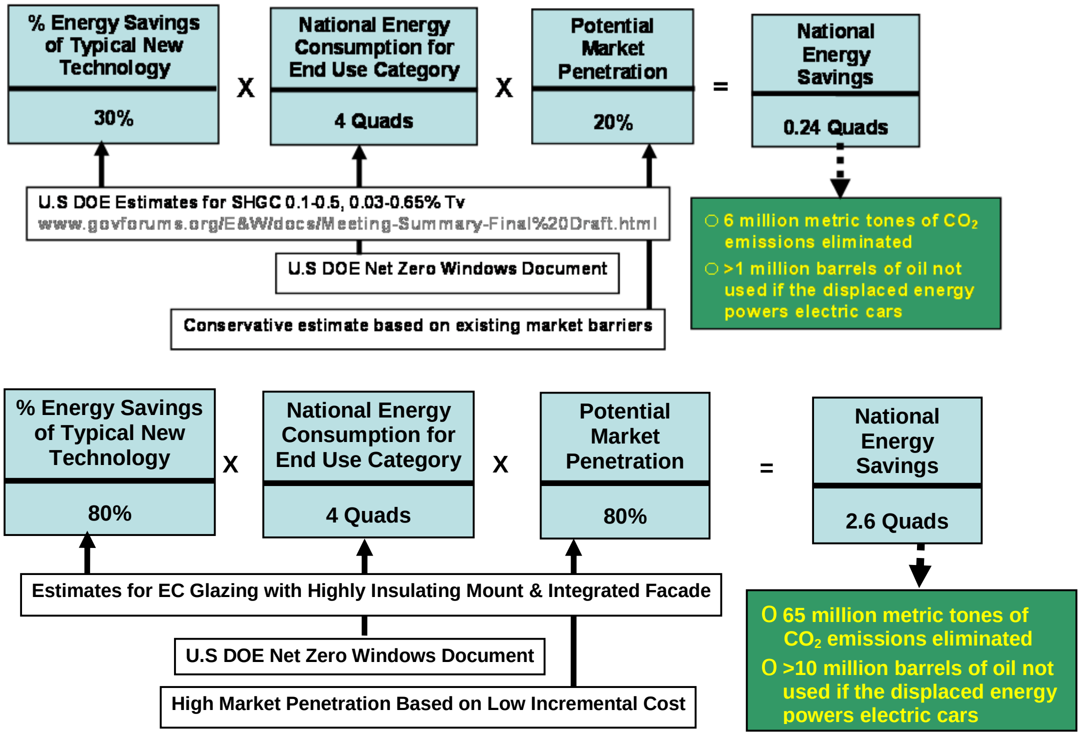


Figure 3. National energy savings with EC windows using conservative projections (top). Energy savings up to 80% have been predicted with ideal windows that include dynamic switching, low U-values, and integrated facades leading to significantly higher national energy savings (bottom).[8]

2 Summary of Accomplishments vs. Project Goals

ITN Energy Systems aimed to develop a solid-state EC film on plastic substrates in order to reduce cost in support of net-zero energy buildings. While there is potential for electrochromic windows to dramatically reduce building energy use through active control of light and solar heat, wide spread implementation has been limited by high cost.[1,10] A transition to volume production by industry leaders may help drive cost down. An alternative and perhaps preferred approach to reducing cost is to use a low-cost, flexible plastic substrate in a roll-to-roll configuration, a proven low cost method in the thin-film flexible photovoltaic industry. EC film on plastic also has the advantage of increased storage life and greater flexibility and responsiveness across the supply chain.[11]

ITN has modeled the manufacturing economics of a number of flexible devices, including EC film. In all cases, product cost is dominated by the large capital investment in vacuum processing equipment required to achieve high performance. Therefore, large volume manufacturing with high yield is required to effectively amortize the capital investment. Roll-coated plastic, with its large device area in a small volumetric footprint, offers tremendous advantage over large format glass to achieve this metric.

[10] http://www.refr-spd.com/resources.asp
[11] F. Wallin, "The Growth and Future of Large Area Architectural Coatings," *SVC Proc.*, **49**, 178 (2006).

The key to successful implementation of this strategy is the use of intelligent, sensor-based process controls to achieve high yield in large volume, roll-to-roll manufacturing. The first step is to establish process-property relationships for vacuum-deposited EC films. ITN aimed to identify critical process variables that impact film performance and a range over which the variables can float and still achieve acceptable product performance. Evaluating deposition processes from a control standpoint ultimately strengthens the validity of control algorithms to handle unanticipated deviation from best case scenarios inevitably encountered in all manufacturing processes with minimal downtime and yield loss to support efficient translation of the EC film into large volume production. The project goal was to reduce investor risk by establishing pilot production of EC film to validate manufacturability and produce scaled prototypes that have been validated in simulated operating conditions.

The project focused on three main efforts (1) Transition Small Scale Prototypes To Limited 0.5 Meter Wide, Web Coater Production, (2) Satisfy Market Driven EC Performance Metrics on Plastic Substrates, and (3) Product Development and Commercialization. Figure 4 and Table 1show that we were successful in establishing the feasibility of limited, roll-to-roll production of all solid-state EC devices on PET plastics. Further, performance was close to the program goals and market metrics. In addition, we established the feasibility of laser scribing as well as lamination/adhesion protocols to integrate the flexible EC film into a variety of IGU architectures, i.e. suspended film, safety glass, and other products as shown in Figure 2. Independent, 3rd party evaluation of the devices was initiated and remains on going. In addition, we were able to dramatically increase the deposition rate and decrease the thickness of the electrolyte layer in support of further reduction in manufacturing cost. Cost analysis of the flexible EC film showed we would be able to meet the market driven metric of less than $50/ft^2$ required for large market penetration.

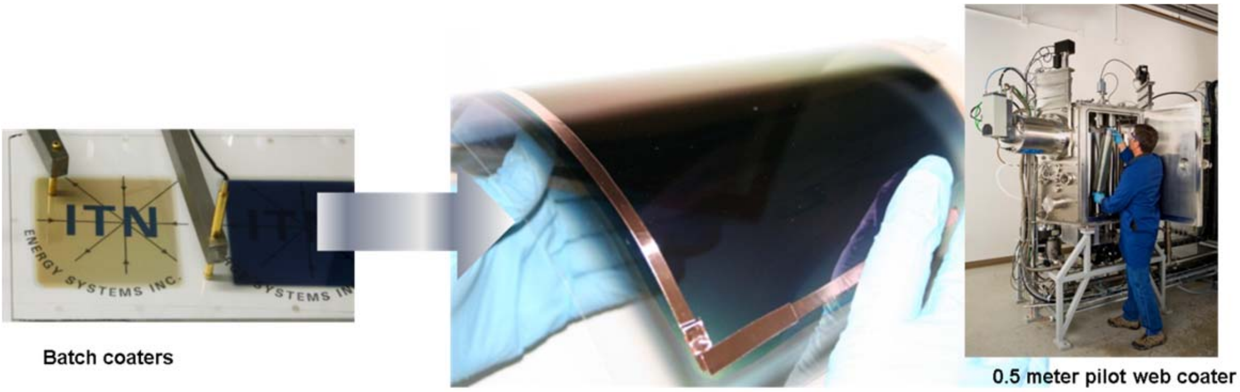


Figure 4. Entering the grant, ITN was producing 25 cm^2 flexible EC devices in our batch tools with a first generation material set. At the end of the program, ITN was producing flexible EC devices greater >1,000 cm^2 in our 0.5 meter wide pilot web coating tool.

Uniformity of all the layers over large areas, particularly as layers were stacked on top of each other, was by far the largest challenge we faced over the course of the grant. Much of the non-uniformity was driven by mistakes in the first generation hardware design for the R2R system. We were able to identify hardware modifications to overcome the non-uniformity issues within the existing Pilot tool as well as more optimal long-term designs for production tools. As capital expenditure for production plants is large, i.e. many millions of dollars, it is important to have substantially reduced these risks in order to attract investment to scale into volume production. With these new hardware designs, coupled with robust process windows established during the grant, we have substantially reduced investor risk. The largest remaining challenges are for validating long term durability in simulated environments and achieving full range switching from all solid state EC devices with generation 2 ion storage materials in the pilot tool.

Table 1. EC film performance at the end of program compared to start of program, program goals, and market metrics. Results are for all solid-state EC devices on PET unless otherwise noted.

Status	EC Area (cm^2)	System	Yield	Transmission (Average Visible)		TRL	MRL	Comment
				Dark	Clear			
Start of Program	25	Batch	~1σ	5%	50%	4	3-4	Gen 1
End of Program	600	Batch	~2σ	7%	45%	6	6-7	Gen 1
	100	Batch	~2σ	5%	66%	6	6-7	Gen 2
	~1,000	Pilot (R2R)	Limited Qty	3%	70%	4	6-7	Gen 2, Composite
	~1,000	Pilot (R2R)	Limited Qty	7%	45%	5	6-7	Gen 1
	~1,000	Pilot (R2R)	Limited Qty	In process		4	6-7	Gen 2
End of Program Goal	~5,000	Pilot (R2R)	Limited Qty	2%	70%	6	6-7	Gen 2
Market Metrics	~5,000	Pilot (R2R)	Limited Qty	3%	65%	6	6-7	Gen 2

3 Technical Results

3.1 Transition to Limited 0.5 Meter-Wide, Web Coater Production

3.1.1 Design, Construction, and Commissioning of a 0.5 meter Web Coater to Support Limited, Continuous Production of EC Devices

A thorough review of requirements and specifications for a 0.5 meter wide drum coater system was completed in Q1 along with a trade study of domestic and international web coater equipment manufacturers. Since the 0.5 meter wide platform was used to develop and qualify each of the layers of the electrochromic device stack as well as ultimately to produce a large area EC device on plastic, the tool had to be versatile as well as reconfigurable to accommodate development changes that occur in the course of the program. Standard drum coating tools from leading equipment manufacturers tend to be expensive, specialized, and application specific with minimal flexibility for reconfiguration or modification. Therefore, based on the demands and unique requirements for a development tool on this program, the decision was made to design and build the tool at ITN.

Figure 5 shows the system, first commissioned in Q5. There are four independent deposition zones, one for each layer in the EC stack (transparent conductive oxide, electrolyte, ion storage layer, and electrochromic layer). A temperature controlled drum in the center of the chamber supports low-cost polymeric substrates up to 0.5 meters wide.

Figure 5. Photographs of ITN's 0.5 meter Pilot Production Tool. There are 4 Deposition Zones, 1 for Each Layer (Transparent Conductor, Electrolyte, Ion Storage, and Electrochromic Layer).

The tool was effective at depositing individual layers with high uniformity both cross web and down web. However, we encountered increasing challenges as we began to stack layers to create a device. Issues with web wrinkling and unacceptable color gradients were observed, particularly after the electrolyte depositions. While process conditions were identified to occasionally produce highly uniform, wrinkle free parts, the consistency was unacceptable for efficient transition to manufacturing. Hardware modifications were identified to improve the robust nature and repeatability of uniform, wrinkle free depositions (Figure 6). The improved hardware had a dramatic impact on the quality of layers stacks produced in the 0.5 meter tool. While the initial modifications dramatically improved the consistent deposition of uniform, wrinkle-free layer stacks and ultimately devices, the materials and designs for the upgrade were not sufficiently robust. A third generation improvement was identified and being validated at the close of the contract. Initial testing looked highly encouraging. The results of both the second and third generation improvements proved the impact of tool design on resultant materials quality and uniformity. While we were somewhat constrained in solving the hardware shortcoming by the compact nature of the development tool, the requirements for a production tool were well established. Given the high capital cost of an EC production facility, it was crucial for us to be able to identify and solve these problems to substantially reduce investor risk during the scale to production phase of the project. Consequently, the ability to mature manufacturing readiness levels with solid tool designs is a major accomplishment of the program.

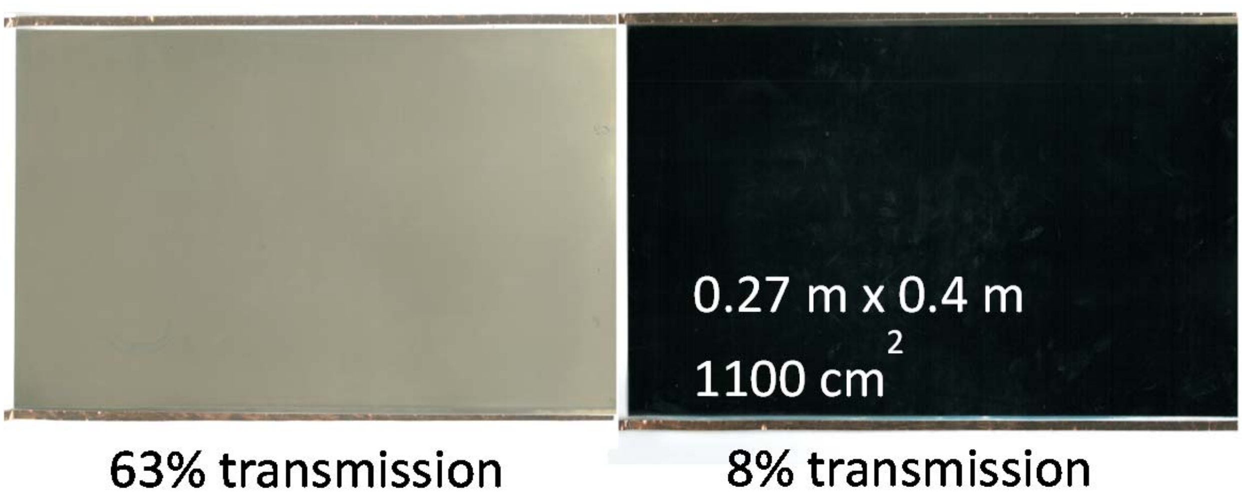
Figure 6. Hardware modifications were identified to overcome initial flaws in the tool design enabling consistent deposition of uniform, wrinkle-free layered stacks and ultimately devices. While the identified solutions lacked durability, the effects of hardware design on material quality and uniformity was well established. The ability to significantly retire investor risk by identifying key design metrics for production tools is a significant accomplishment of the program.

3.1.2 Development of Scale Invariant Processes

Deposition of individual layers in the 0.5 meter production tool was straight forward and effective. In fact, with chambers specifically designed for and dedicated to EC materials, we observed improved performance of materials relative to multi-use, sub-optimal batch tools. For example, we produced indium tin oxide (ITO) transparent conductive layers with high conductivity (~25 Ohms/square) and transmission (~87% visible transmission) at 1/3rd the thickness of poorer performing commercially purchased ITO employed for initial development.

In general, the lessons learned from the batch coaters translated well to roll-to-roll production. While we originally anticipated EC devices with second generation ion storage layers would quickly obsolete the first generation materials, we quickly learned that challenges associated with the electrolyte deposition over the base electrode dominated overall device performance and durability. Since we also encountered challenges optimizing the second generation ion storage layers, we maintained development of first generation materials to help resolve required hardware and process modifications for the electrolyte/electrode bilayer stack optimization.

We developed a composite device to test the performance of individual layers from the drum coater. Separate sheets, one with the ion storage layer deposited on ITO/PET and another with the electrochromic layer deposited on ITO/PET were joined with a composite electrolyte to create an EC. The composite electrolyte consisted of a commercially available li-ion battery liquid electrolyte infiltrated into a nano-porous support that also had adhesive properties. The device was switched in a similar fashion to solid state devices to determine range and uniformity.



	Clear State	Dark State
Typical Composite	8%	63%
Optimized Composite	3%	70%
DOE/Program Goal	2%	70%

Figure 7: Light and Dark states of composite electrochromic device constructed with 2nd generation ion storage layers. In this case, one electrode was a bilayer stack with the solid state electrolyte deposited over the electrode; both electrodes were deposited in the 0.5 m production tool.

Many of the challenges were not apparent until multiple layers were deposited in the production tool. At this point, increased observations of web wrinkling and/or non-uniformities in the appearance of the bilayers began. Non-uniformities were typically visible to the naked eye without the need to fabricate composite devices. The bilayer performance was improved with modifications to the hardware as mentioned in the previous section as well as improved process space. Once uniform bilayers were produced, composite devices were employed where one of the electrodes was a bilayer of the electrode/electrolyte layers.

Figure 7 shows a typical composite device where the electrode materials were deposited in the production tool, with active areas >1,000 cm^2. In this case, second generation ion storage layers, including the electrolyte bilayer on one side of the device, were employed. The device response of ~8-63% average visible transmission with good uniformity was typical of the composite device response. As the second generation ion storage layer was optimized, greater depth of lithium loading, i.e. slightly higher switching voltages ~2-3 volts, could be achieved without delamination of materials. Consequently, the switching range of the devices expanded to ~3-70%, very close to ITN's program goal and DOE's EC windows goal.

Initially, the production coater was run by splicing in small segments of ITO coated PET to a PET carrier web. Small sections of materials were produced to rapidly explore process space and solidify hardware modifications discussed in the previous section. Once the second generation hardware improvements were installed and robust and scale invariant processes identified, we migrated to continuous production of layers and devices. Over long runs, i.e. several hours, the deposition systems can be thought of as dynamic systems with evolving thermal loads and background gas compositions. To prove robust processes, it is necessary to run the tool over longer, continuous runs to make sure adequate control is achieved. Table 2 shows the typical production lengths employed at the end of program. The uniformity of materials over these longer runs, coupled with the initial demonstrations of intelligent process control strategies discussed in Section 3.1.4, indicates a thorough understanding of the appropriate process variables that need to be controlled to maintain materials quality in a production scenario, i.e. high manufacturing readiness level.

Table 2. Typical continuous production lengths in the 0.5 meter production tool at the end of program. Production lengths were constrained only by deposition rates (fastest for ITO and slowest for the electrolyte) and the fact the one tool was responsible for all materials. Run times were sufficiently long that the chamber's dynamic nature would have come in to play. Consequently, we do not expect substantial variation in materials quality with longer rounds.

Layer	Continuous Production Length
ITO	>3 meters
Electrodes	~2 meters
Electrode/Electrolyte Bilayers	~1 meter

3.1.3 Feasibility of Roll-to-Roll Production of EC Devices on Flexible Polymers

All solid-state EC devices were produced in the production tool with both first generation and second generation ion storage layers. First generation materials were more forgiving of imperfections in the hardware and process and thus were easier to establish. Over ten consecutive runs to produce first generation solid state EC resulted in >50% yield of devices with performance typical of baseline 100 cm^2 devices fabricated in the batch tools. The lower performing devices were attributed to handling issues leading to defects and higher than normal leakage currents. Given that the first generation storage materials were unable to achieve marketable product, i.e. limited clear state transmission, we rapidly transitioned to the second generation ion storage layers rather than fully optimze the baseline first generation devices.

Figure 8 shows one of the initial solid state devices from the production tool. In this case, only critical electrode and electrolyte layers were produced roll-to-roll. The device was then completed in the batch tools. While fully functioning solid, state devices were produced with stable cycling behavior, the switching range is limited. The limited switching range is attributed to limitations of the second generation improvements to the production tool as discussed in the previous section. New, more robust materials and designs have been implemented at the time the grant period of performance has ended. Individual layers and bilayers with increased switching range were demonstrated with liquid electrolyte and composite device testing. Consistent fabrication of all solid-state devices, with all layers deposited in the production tool, were achieved at the end of program. Performance and durability testing is underway. We expect performance similar to the batch tools and composite roll-to-roll devices to be completed with ITN funding. Once the performance and initial durability has been demonstrated, ITN will ship devices to EPRI and the national labs for independent performance validation.

Figure 8: 1,000 cm^2 EC device with Gen 2 materials; critical layers were produced continuously in the 0.5 m tool. Visible light transmission: Dark state of 7% and Light state of 26%.

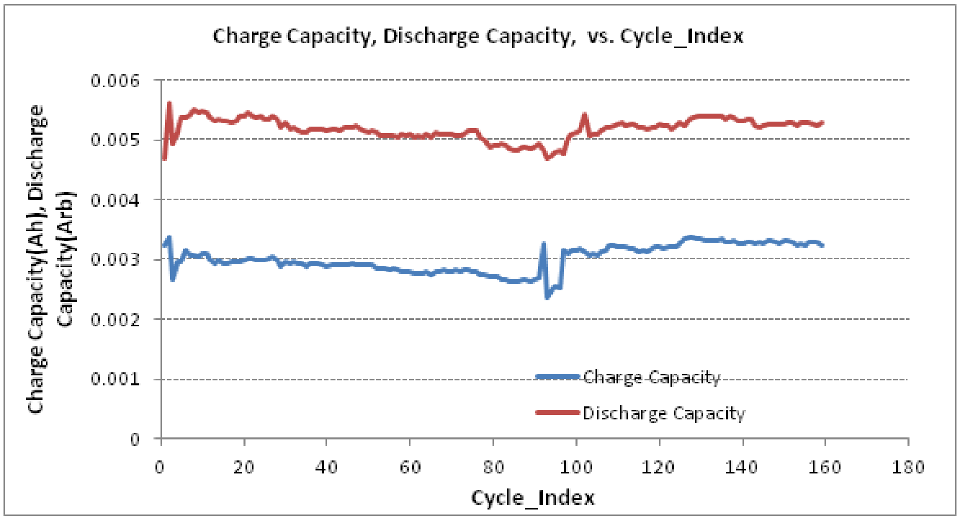


Figure 9: Large area device, shown in Figure 8, with stable cycling over 100 cycles.

3.1.4 Development of Intelligent Process Controls

To manage control of in-run as well as run-to-run repeatability, both of which impact device performance and yield, we developed and demonstrated the effectiveness of a control strategy for reactively sputtering the electrochromic layer. With the potential for tight control of compound chemistry/structure and high rate, low cost processing, reactive magnetron sputtering is being utilized for nearly all of the layers of the EC device. The electrochromic layer was chosen to understand the common factors and characteristics and to then develop a control architecture applicable to reactive sputtering in general. Then, specific factors for each device film deposition process can be built into the control architecture.

To control the flux of metal and reactive species to the substrate, we established methods for estimating species partial pressure, and regulating flow to achieve a desired set-point. The common sensors are mass spectrometer, optical emission sensor (OES), and an optical gas controller. Since utilizing mass spectrometers has several issues including cost, the need to reduce pressure, and the inability to sample near the substrate, OES was chosen as the sensor. Selected wavelengths from the OES sensor were used to create a composite signal that that is proportional to the ratio of oxygen and metal partial pressures in the plasma above the substrate.

The approach toward controlling reactive sputtering was an iterative process. System dynamics were identified, first in our R&D web coater, through system perturbation experiments. A controller was developed based on the system dynamics and then tested. The results were evaluated and the controller was fine tuned. A controller was developed for operation at a specific sputtering voltage. The system was brought to a stable operating point. Figure 10 shows thickness and transmission results for continuously produced electrochromic layers. A thickness variation of 2.47% over almost 10 meters web length was achieved. Chamber operation was not stable and film properties drifted over time without the controller.

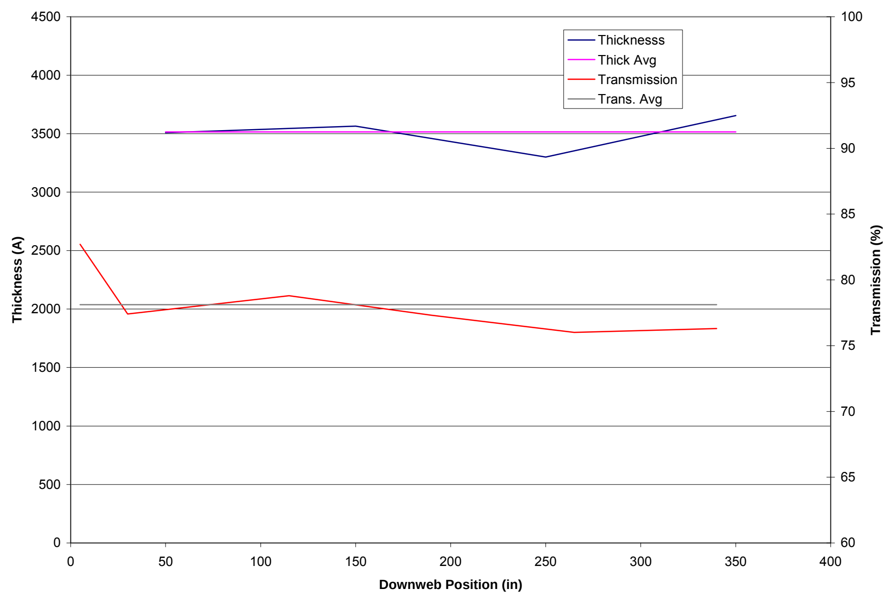


Figure 10 – Thickness and transmission measurements from an OES controlled EC deposition.

The demonstrated process control hardware and control architectures were then installed in the 0.5 meter production tool. Control in this tool was more difficult and additional control variables were added. With a two-state controller, we observed improved ability to maintain the sensor output (blue) about the desired set point (red). Instabilities introduced in the middle of the run before control was restored.

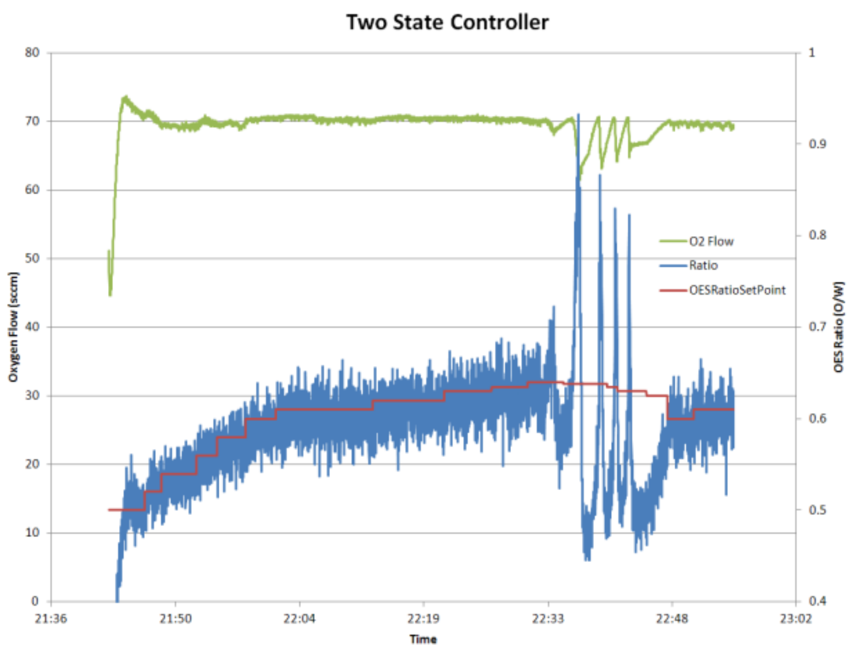


Figure 11. A two state controller for the EC layer maintained control of the output (blue) to match the desired set-point (red).

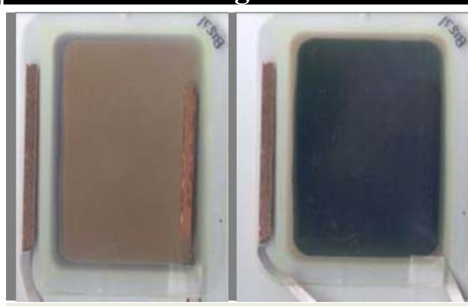
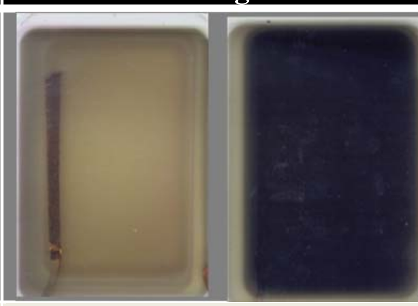
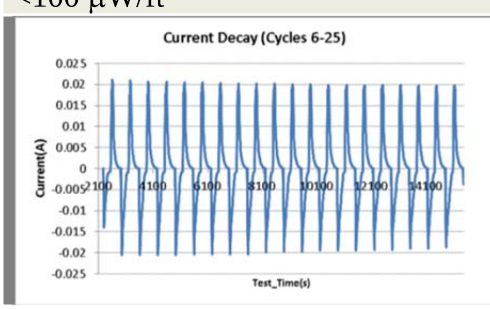
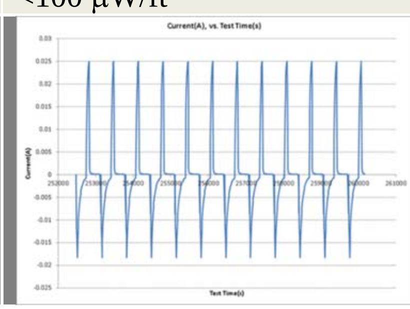
3.2 Satisfy Market Driven EC Performance Metrics on Plastic Substrates

Gen 1 EC metrics, i.e. range and speed, were insufficient to meet the market demand. While we intended to switch to Gen 2 materials that improve device performance early in the program, the first generation materials also suffered similar uniformity and performance challenges in EC production. As a result, much of the work to establish robust process and resultant durability testing, etc. was performed with Gen 1 materials. Initial transition to the Gen 2 materials has mirrored the Gen 1 results. The remaining transition will be aided by hardware improvements and scale invariant processes demonstrated in batch/production tool at the end of program.

3.2.1 Performance Optimization

Thin film EC consists of an electrochromic layer (EC), an ion source layer (IS), an electrolyte and transparent conducting oxides. Each individual process was optimized to yield low impedance layers/interfaces with consistent transmission and stress thresholds over a 100 cm^2 area. Electrochemical properties for each layer were analyzed in a liquid electrolyte and optical measurements verified performance and protocols for quality control. Subsequently, as each of the layers was incorporated into the multi-layer EC device, processing parameters for each unit operation were modified in an iterative approach to optimize device level performance. **Table 3** shows Gen 2 materials are required to achieve target transmission range and device speed.

Table 3. Comparison of Response for 100 cm^2 EC devices with Gen 1 and Gen 2 Materials.

	Gen 1 Ion Storage	Gen 2 Ion Storage
Typical Images (Light and Dark State)		
Dark State Typical	7%	5%
Best	5%	5%
Light State Typical	42%	60%
Best	50%	66%
DOE Goal	2 to 70%	
Switching Times	<4 Minutes	< 2 Minutes
Leakage Current	<100 µW/ft^2	<100 µW/ft^2
Current Transient		

3.2.2 Durability Testing, Including Simulated Environments

Most commercial and residential windows are warrantied for a minimum of ten years. Therefore, the EC must be able to cycle >20,000 cycles if they are switched twice a day, every day over that period. While accelerated tests are limited in value, i.e. continuous cycling of EC devices is known to accelerate aging of the EC beyond that observed in normal operation, ASTM testing is the industry standard and is likely required to attract strategic investment partners. Devices were tested according to ASTM protocols for room temperature cycling as well as limited testing of the more exhaustive ASTM 2141-02 test that also includes heat and solar exposure. Traditionally, both room temperature cycling and 2141-02 protocols involve testing of the EC device in desiccated IGU. Since ITN's devices are anticipated to be deployed in retrofit applications, we also performed extensive testing outside the desiccated IGU environment in high heat, high humidity environments using protocols that are similar to those used in the flexible display industry, i.e. 40ºC, 100% relative humidity.

Figure 12 shows stable cycling of EC devices deployed in a suspended film IGU, i.e. glass pane/spacer/EC film/spacer/glass pane architecture. In this case, the spacer is a commercial "Super-Spacer" material typically employed for IGU. A commercial secondary seal material is also used with the EC leads breaching both the primary and secondary seals. The IGU was fabricated in an argon glove box to limit moisture in the IGU during the fabrication process. In this case, ITN's EC IGU was then placed in a sealed chamber above a pool of water, i.e. 100% relative humidity, and cycled continuously at room temperature. The sample was periodically removed from the humidity chamber and the transmission was measured in the clear and dark states. The sample was then returned to the humidity chamber for additional testing. Nearly 20,000 cycles with essentially no change in switching range were achieved. This devices employed first generation ion storage materials.

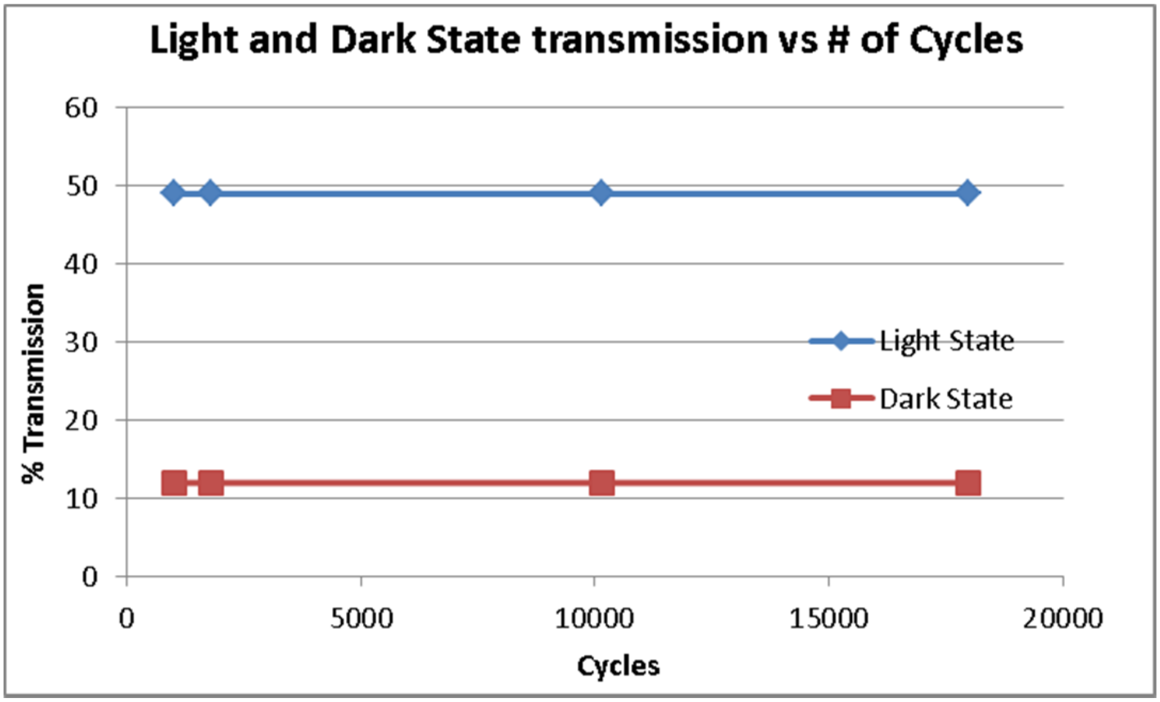


Figure 12: Transmission remains stable with cycling of an EC suspended in an IGU in 100% RH.

Figure 13 shows durability testing of a device with second generation ion storage layers. In this case, the test coupon was solely a flexible EC layer with no other packaging tested in open air. The device was continuously cycled at room temperature. In this case, the device performance improves with time and over 5,000 cycles were demonstrated. Tests were suspended at that time due to a limited number of test channels. Given some of the challenges encountered in the program, there was less second generation ion storage layer device testing.

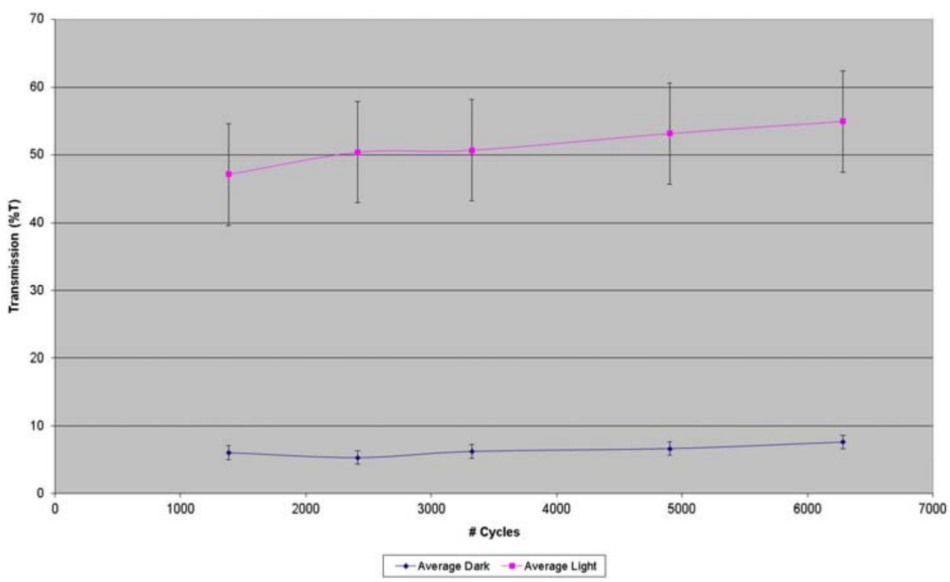


Figure 13: Transmission versus color/bleach cycle lifetime for a Gen 2 device at room temperature.

More extensive ASTM 2141-02 testing was also explored with Gen 1 devices. Figure 14 shows a Gen 1 device exposed to ~1 sun and elevated temperature during continuous cycling. The device was laminated to a glass plate with PVB interlayer and tested in air (outside sealed, desiccated IGU). During our initial development we established that EC charge and discharge capacity was a reasonable proxy for stable transmission over time. Given the limited spectrometer channels, some of the device tests used capacity stability as a proxy for stable device operation. As with the room temperature results, the device switching is highly stable. A thermocouple attached to the device during cycling showed the device itself heated up significantly more in the dark state than clear state, as might be expected due to the absorptive nature of the device. Figure 23 shows the device reached temperatures over 100ºC during the test, well above temperature specified in the ASTM document. The lamp employed also over sampled the UV so this device survived a very aggressive exposed environmental test.

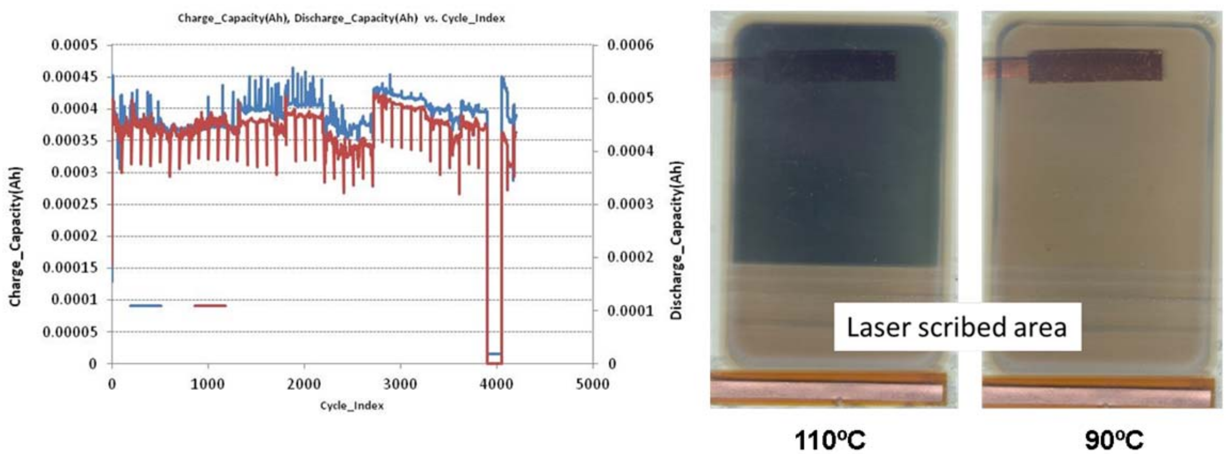


Figure 14. Charge/discharge capacities for a Gen 1 100 cm^2 device exposed to ~ 1 sun and over 60ºC prescribed by ASTM 2141-02. The device was cycled continuously in these conditions. The images show the colored (left) and bleached (right) states after 5,000 cycles. The bottom half of the device shows the laser scribe areas are also stable at high temperature, solar exposure.

Given the likely deployment outside of a desiccated IGU for retrofit applications, we also tested devices in difficult environments, i.e. high heat and humidity. In these cases, the EC was laminated to a glass pane with PVB interlayer and a commercial, flexible moisture barrier was employed. Figure 15 shows stable cycling over 8,000 cycles. The packaging using thin film barrier material also demonstrates the suitability of our EC devices for retrofit type applications.

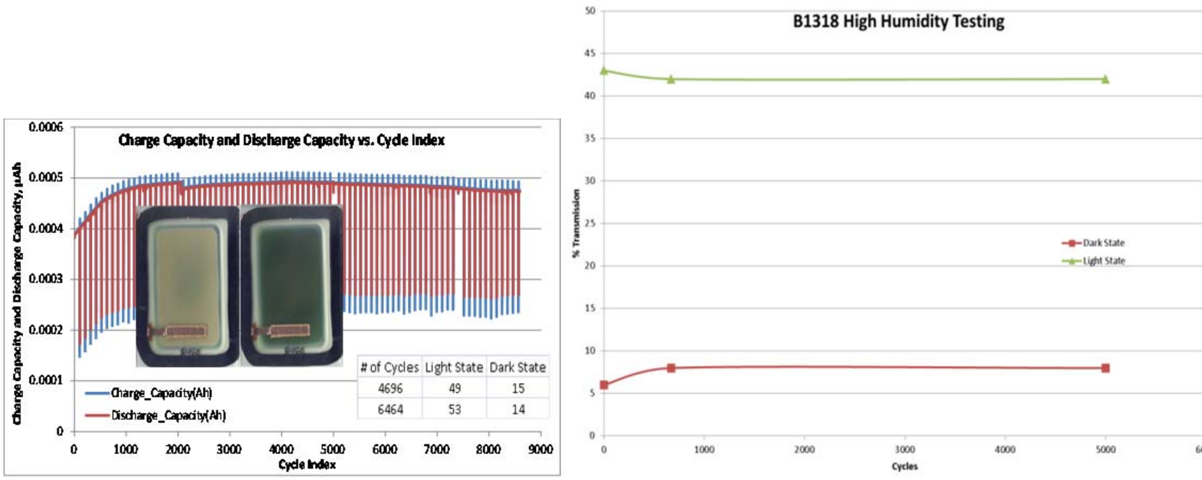


Figure 15. Stable operation of a FlexEC device encapsulated with a flexible thin film moisture barrier in 40ºC and 100% relative humidity testing. Given limited spectrometer channels available, the durability is shown as a combination of stable transmission over cycles (right) and stable charge/discharge capacities (left).

3rd Party Durability Testing: Devices were sent to a 3rd party organization for independent testing. Figure 16 shows photographs of one of the devices after 2,500 in-house cycles and 1,000 cycles at the National Lab. During the initial testing uniform colored bleached and colored states were maintained. However, as the device continued to cycle, non-uniform degradation appeared, coincident with a period of high humidity in the testing lab. At this point, ITN developed additional packaging protocols to enable consistent operation in high humidity. Additional samples will be tested at the National Lab with this new packaging. Note the yellow color in the background is from a post-it note place behind the samples with the identifier.

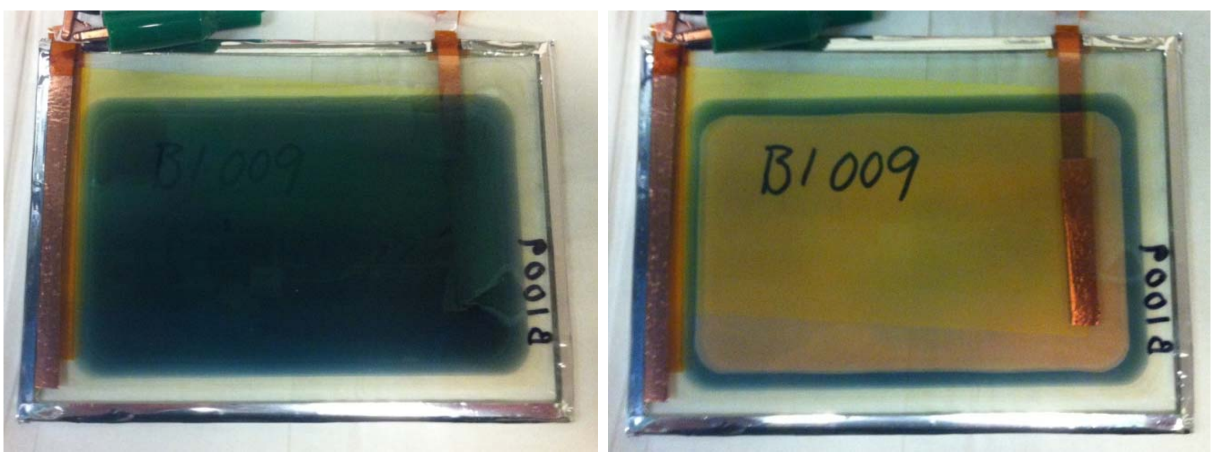


Figure 16. ITN's 100 cm^2 EC device images in the colored (left) and bleach (right) states after 2,500 in-house cycles and an additional 1,000 cycles at a 3rd party organization. Note, the yellow color observable in the background is from a post-it note under the device and does not represent the color of the device itself.

3.2.3 Improved Manufacturability (Cost-Reduction)

As the electrolyte deposition rate and thickness is a major factor in overall manufacturing cost of the flexible electrochromic device, we aimed to develop process improvements to achieve a ten-fold increase in the electrolyte deposition rate and reduce the required thickness by half. ITN cost models predict these two changes can reduce capital investment required by almost $2/3^{rds}$ for 10 million square foot per year production. Further, the flexible EC film cost would be cut in half. Figure 17 shows performance, i.e. speed, range, and leakage current, as well as durability was unaffected by an electrolyte layer with one-half the initial thickness and four times faster rate. Device yield was also unaffected by these changes. Similar results were achieved with larger, 600 cm^2 devices (Figure 18).

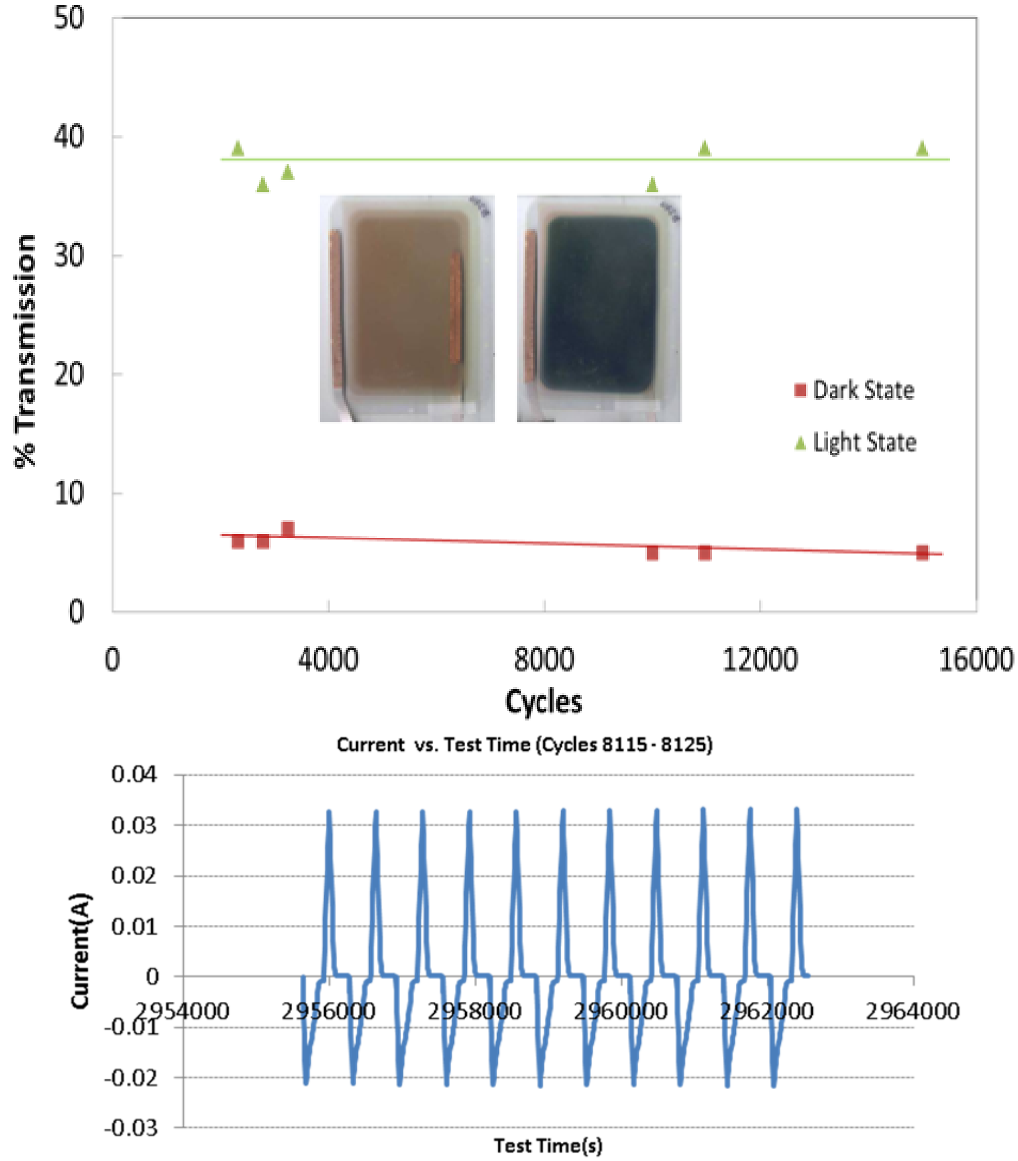
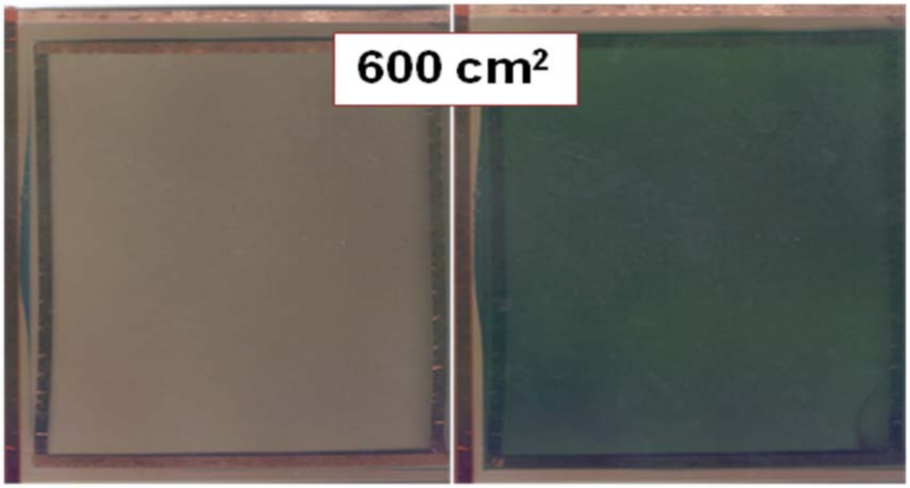


Figure 17. EC devices-100 cm^2 devices with first generation ion storage layers- with ½ thickness electrolytes show stable operation for over 15,000 cycles with no substantial degradation in coloration range, leakage current, or capacity.



Clear Transmission	Dark Transmission	Leakage Current	Area	Time
45%	15%	3-30μW/ft^2	600 cm^2	<5 minutes

Figure 18: Large area EC (600 cm^2) incorporating 4x increase in electrolyte deposition rate and thinner electrolyte with uniform end states. Switching times, transmission range, and leakage currents are similar to optimized devices with the initial electrolyte deposition rate and thickness.

The higher electrolyte deposition rate was achieved using ITN's proprietary enhanced plasma processing (EPP). Deposition rates up to four times faster than the baseline rate were achieved in the large area batch coater without fully optimized EPP. Smaller batch tools were employed to further develop the electrolyte deposition process. Figure 19 shows that deposition rates up to eight times faster than the baseline rate were achieved for the electrolyte. Ultimately, we ran into hardware limitations that are unique to the small-scale nature of the batch tools. With additional development, higher deposition rates, up to ten times the baseline are likely still possible.

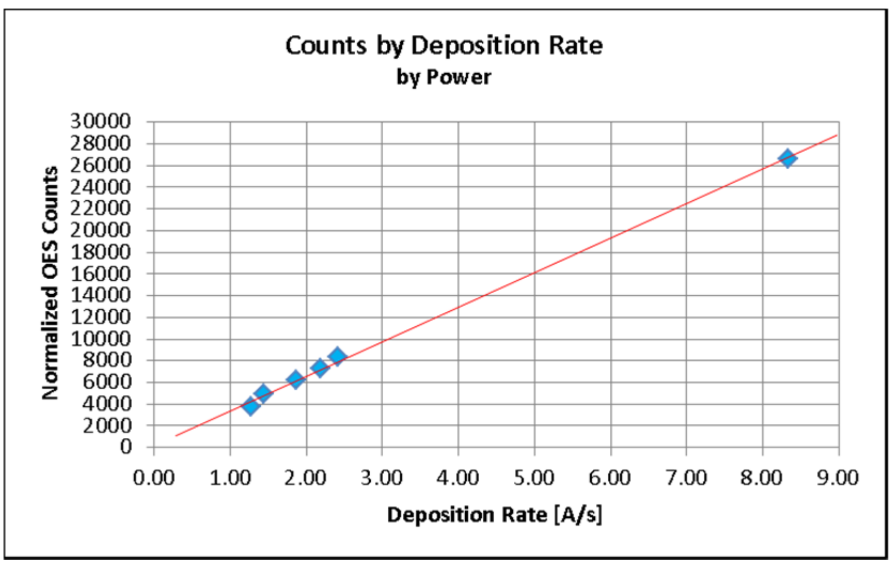


Figure 19. Optical emission spectrometer (OES) signals were calibrated against deposition rates of the resulting electrolyte films measured with a Dektak profilometer. As the OES signals are linear with deposition rate, the OES signals can be used to more efficiently explore EPP parameters.

3.3 Product Development and Commercialization

3.3.1 Monolithic Integration

Good device layout will be key to the success of ITN's FlexEC product. Layout will control a number of effects, voltage distribution on the device and device integration into IGUs for example. A number of factors were identified as critical in the design of a flexible EC layout or architecture; specifically, a layout must 1) Maximize yield/performance in processing by managing defects (lateral, through thickness, and at edges), 2) Enable monolithic (modular) integration, 3) Enable uniform switching over large areas, and 4) Be inherently durable.

EC device layer patterning could be completed during each deposition process or after the deposition of all the layers. Blanket deposition followed by laser scribing provides the greatest flexibility in defining customizable products at the IGU manufacturing site. Using SEM analysis with energy dispersive x-ray analysis (EDX) of film composition inside and outside the scribe lines, we were able to confirm the ability to create all three required scribe lines to support creation of an EC film roll with all device layers that could be ship for processing of customized window sizes at the IGU vendor site. A schematic of the device layout incorporating laser scribing is shown in Figure 20. Laser scribe processes were initially developed on small scale devices from the batch coaters. Subsequently, we modified the laser system to support patterning of window films up to 1 meter x 1 meter. Laser scribing of web coated film stacks were patterned into individual devices with high durability with the larger, upgraded scribing hardware (Figure 21).

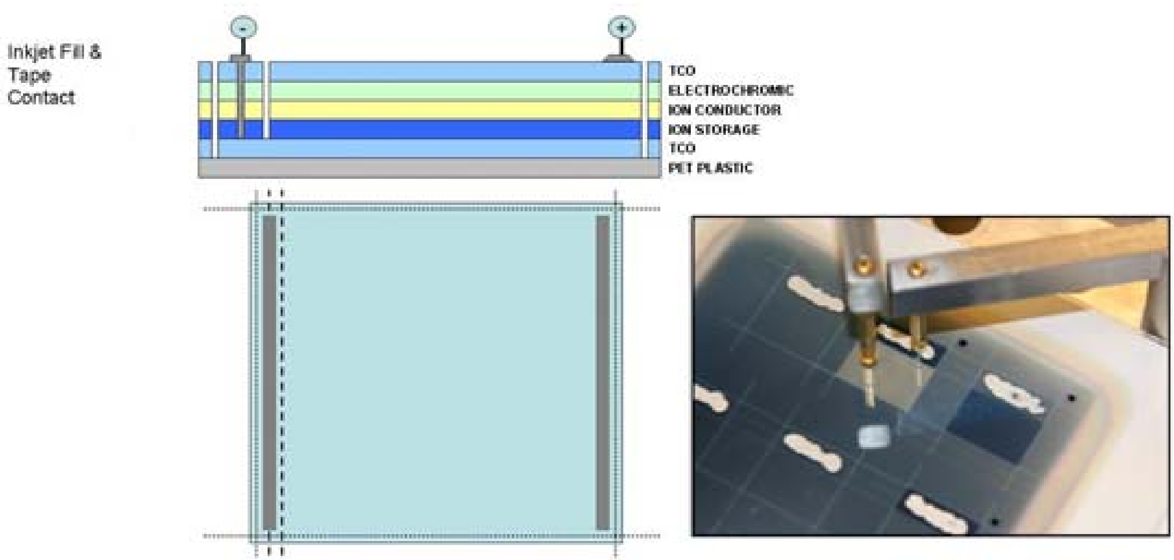


Figure 20 : Flexible EC film design using laser scribing for patterning and isolation(left) and example of laser isolated switchable area from small area batch devices (right).

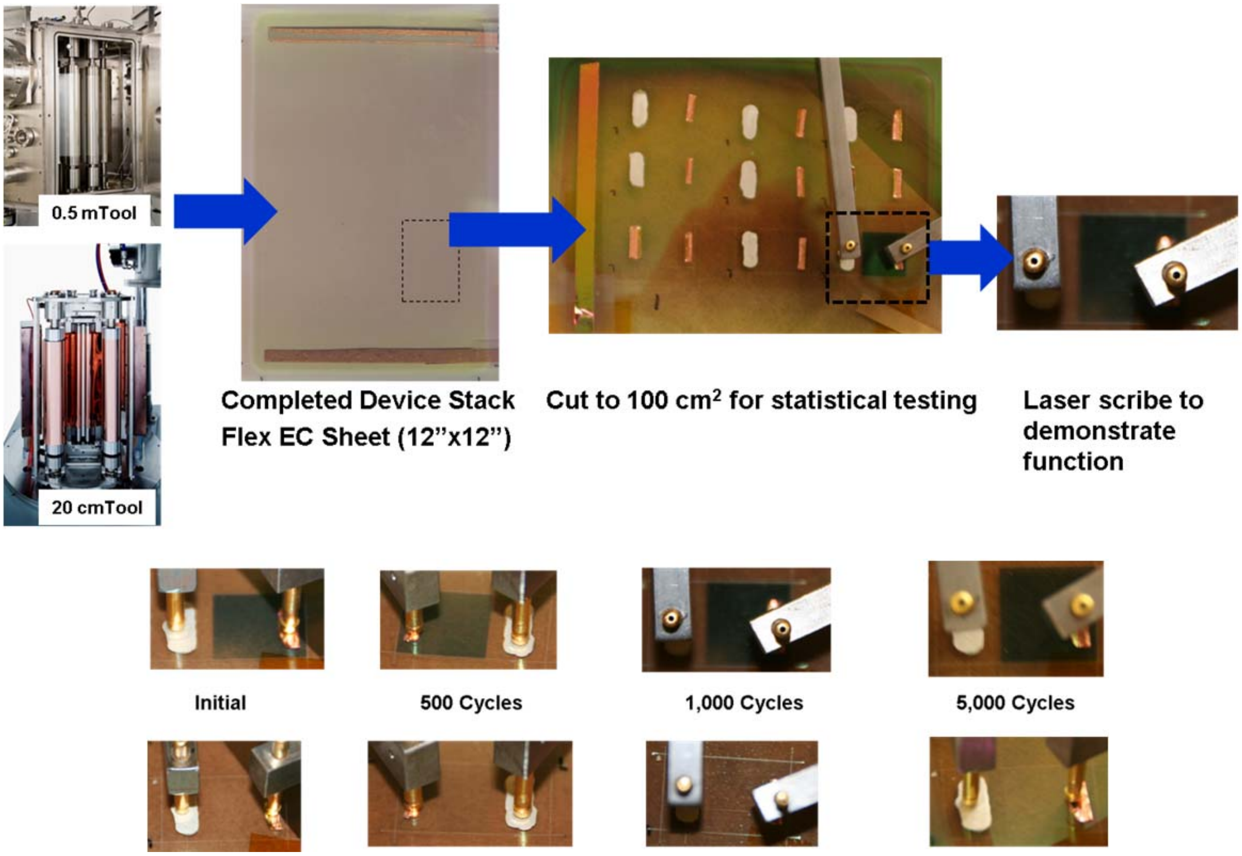


Figure 21. Laser scribing of Gen 1 EC devices produced with roll-to-roll deposition. The resultant laser scribed devices show performance and durability commensurate with the batch processes employing shadow masks to pattern each layer.

3.3.2 Product Design and Integration into IGU

Considerable effort was spent to define products and specifications for a flexible EC in new and retrofit markets by conducting a review of current IGU designs and equipment operations for IGU and lamination as well as conducting on-site visits to window and door manufacturers. All standard IGU configurations, such as dual and triple pane, laminated, and suspended were reviewed and discussed by the team in regard to integration of the unique features of the flexible EC film and its associated power management requirements. A flexible form factor is most closely aligned with the suspended configuration although can also be incorporated into growing trend in laminated construction for safety and security as well as the widely adopted, double pane construction. Keys to any IGU configuration will be the accommodation of electrical cabling, contacts, and feedthroughs with current spacer and edge seal technologies.

In-house fabrication capabilities, including lamination and sealing, were established to build prototype IGUs. Prototype assemblies were fabricated using both laminated and suspended film configurations. Electrical and power management designs were developed with the goal of integrating these designs into prototypes. We continue to collect performance and pricing data on competitive market offerings, both EC, other smart glass, and standard window offerings.

A laminated flexible EC is shown in Figure 22. Lamination procedures employed an industry standard PVB interlayer in a flatbed laminator at elevated temperature and pressure. Device performance and durability was not degraded by lamination. Some properties, such as overall transmission were improved due to the index matching benefits of the PVB and glass materials.

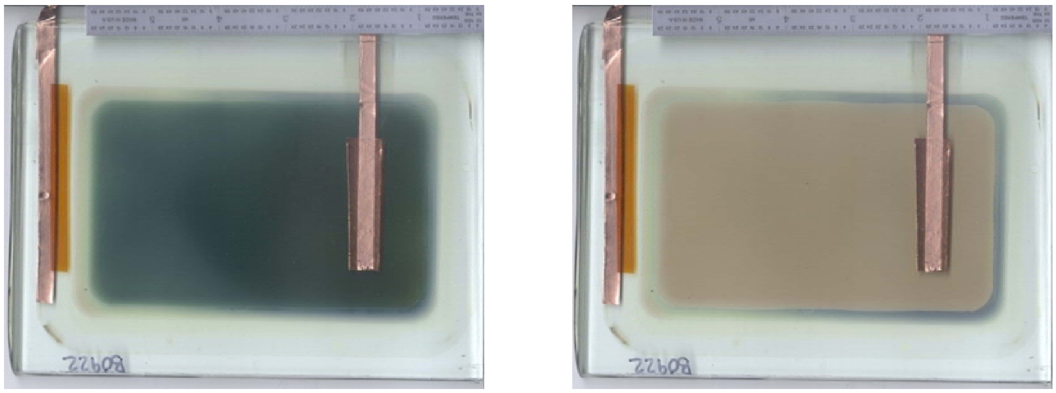


Figure 22: Laminated Gen 1 devices in colored and bleached states after 1,000 cycles (Note: index matching of PVB and glass layers decreases reflectance, increases overall transmission).

MAG led initial designs for integration of a flexible EC film into an electrochromic window product. This includes strategies for EC film integration into the IGU, i.e. suspended film, lamination to glass, etc., as well as supporting hardware requirements, i.e. electrical connectors and framing materials. The resulting prototypes are shown in Figure 23.

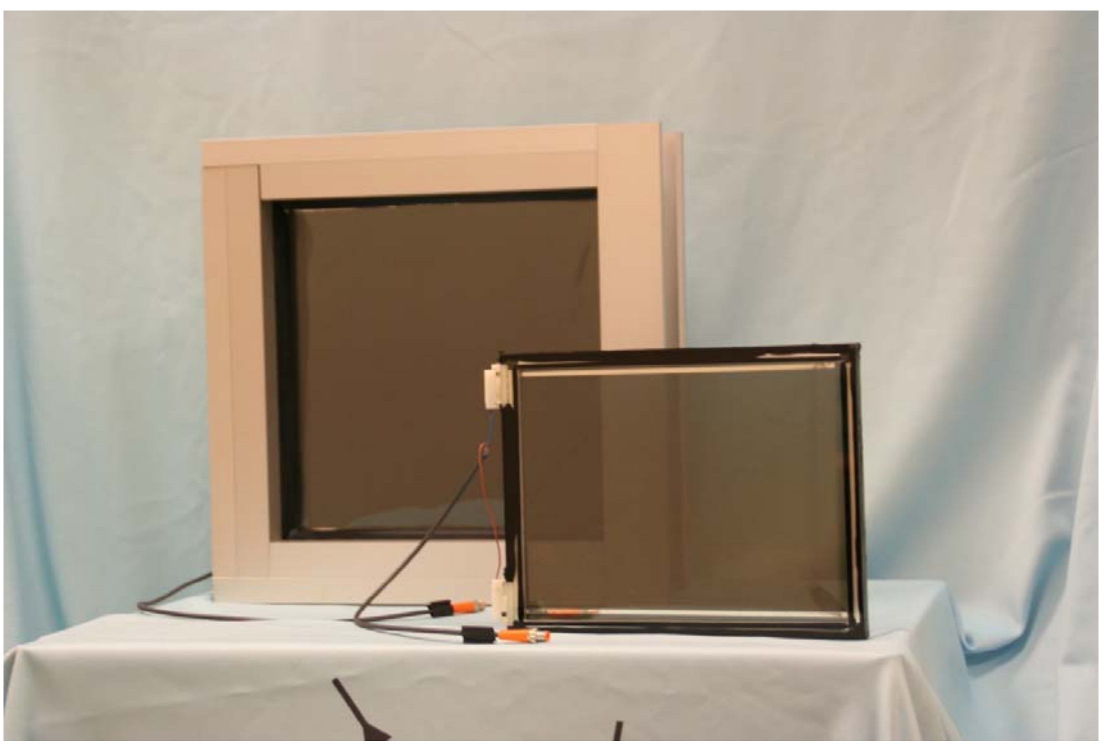


Figure 23. Photograph of product integration designs for IGU (front) and framed (rear) including novel electrical connectors that will allow low-cost, facile integration at the construction site.

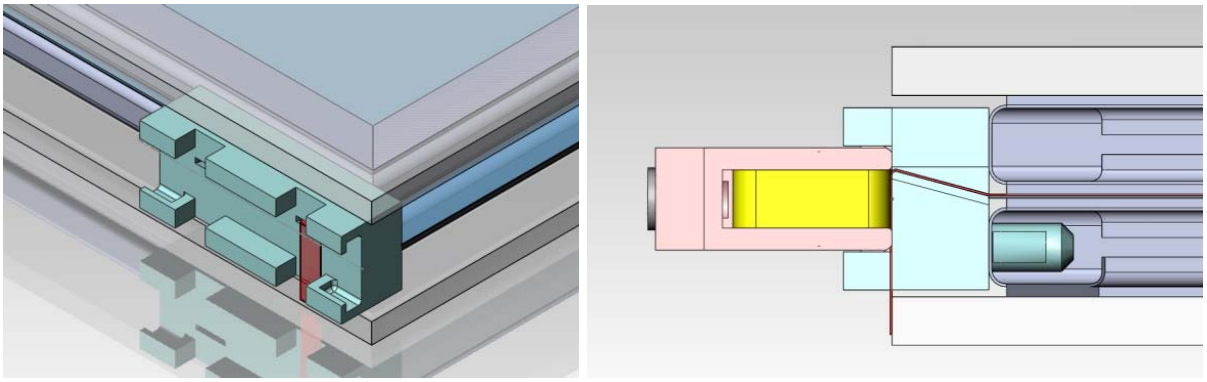


Figure 24: Innovative electrical connectors that maintain hermetic seals in the IGU.

Through ITN's partnership with MAG, details in product design such as the electrical feedthrough depicted in Figure 24 have already been thought through and implemented. Product design features such as this are vitally important to product acceptance.

3.3.3 Energy Savings Models

As part of the project, ITN employed the suite of DOE windows modeling software, i.e. Windows 6 (Research Version), COMFEN, and RESFEN software, to explore potential energy savings of a unique flexible EC product. Window performance as well as projected building energy savings was explored for a variety of products including a suspended film architecture and retrofit EC Film installed on the exterior glass surface.

Efforts to model the window performance were somewhat hampered by challenges encountered in developing devices incorporating second generation ion storage layers. As a result, we couldn't measure fundamental properties, i.e. visible transmission, reflectance, etc., of a typical EC film with metrics that met market demands. These properties are required as inputs to the models to calculate fundamental properties such as SHGC and U-Value as well as project energy savings in various building scenarios. Given this handicap, we chose to employ optical properties of SAGE glass from the DOE windows library to extract lessons for how the EC film might ultimately be most effectively integrated into a window. Figure 25 shows how the SHGC and U-Value vary, depending on the placement of the EC film within the window.

More detailed modeling will be required on an optimized EC film, however, some lessons learned from the initial modeling include:

- U-Value:
  - An EC-lowE layer on 2 or 3 gives the same U-Value. This is due to the fact that the thermal resistance to radiative heat exchange between 2 and 3 is the same.
  - Having the EC-lowE layer on layer 1 gives a higher U-Value, because heat transfer on this layer is driven by convection, and depends little on temperature. The radiative resistance between 1 and outside is very big compared to the convection resistance.
  - Having the EC-lowE layer on layer 4 gives a reasonable U-Value, since a big part of the heat transfer from inside to layer 4 is by radiation.

- SHGC:
  - The SHGC is lower for an EC-LowE coating placed on the outside glass, since the thermal resistance is lower from the outside glass to the outside, thus the heat gained by the window is evacuated easily.

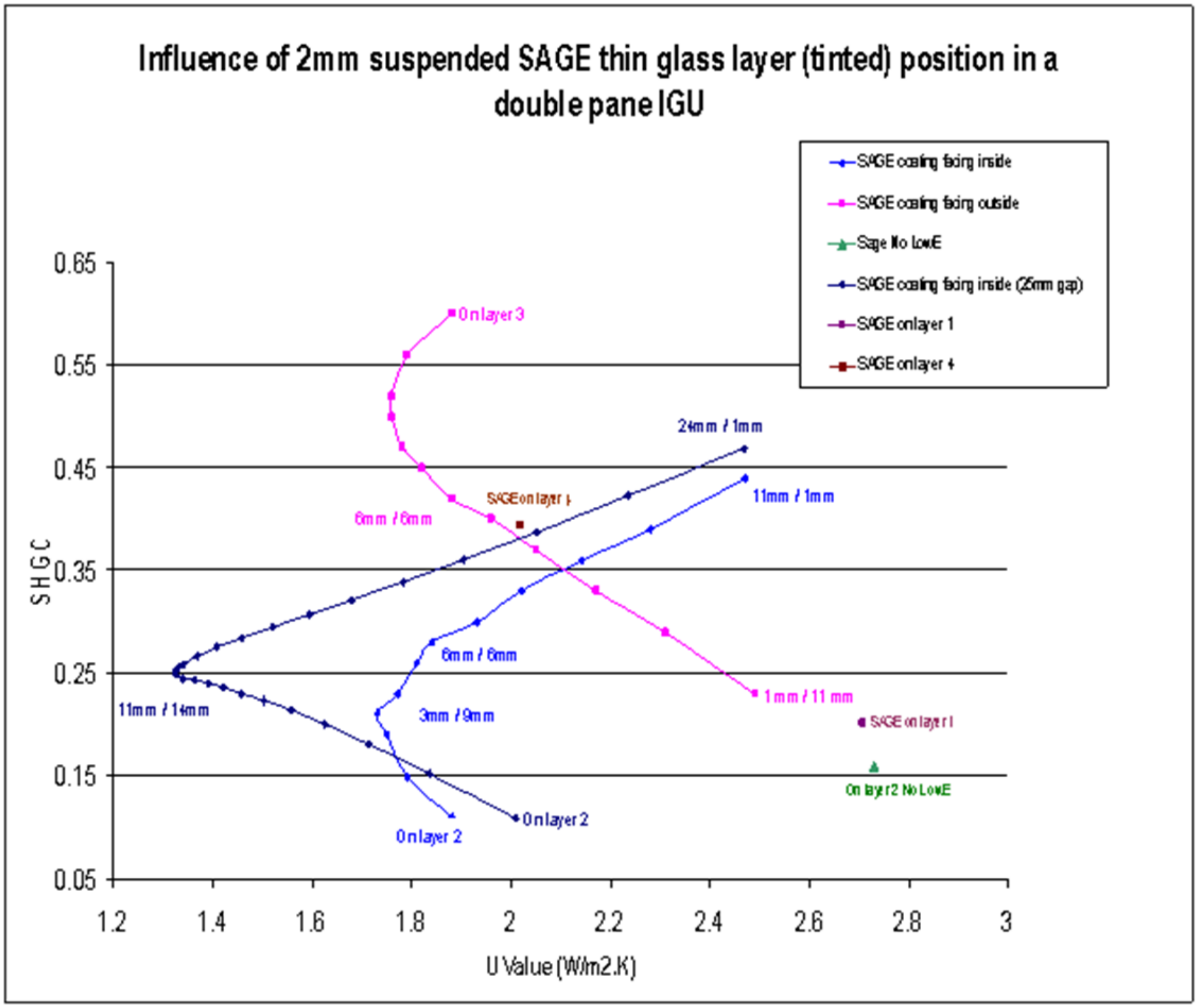


Figure 25. Windows modeling of an EC film suspended in a double pane window. Optimal window performance is a function of where the film is placed. Low U-values and SHGC can be obtained.

EPRI then used RESFEN to calculate savings in buildings for various scenarios with suspended window film and retrofit applications. A flexible EC film product has the potential to realize great energy savings in both the commercial and residential buildings. Figure 26 shows a heating dominated climate where energy use is minimized with the EC layer on surface 4 and low-e on surface 2. Most commercial EC windows place the EC on surface 2. Flexible EC film provides integration versatility to meet regional demands. Figure 27 shows energy savings in commercial buildings for different regions in the U.S. Energy savings are similar for all regions, but slightly greater in southern and western regions where air conditioning costs dominate over heating costs.

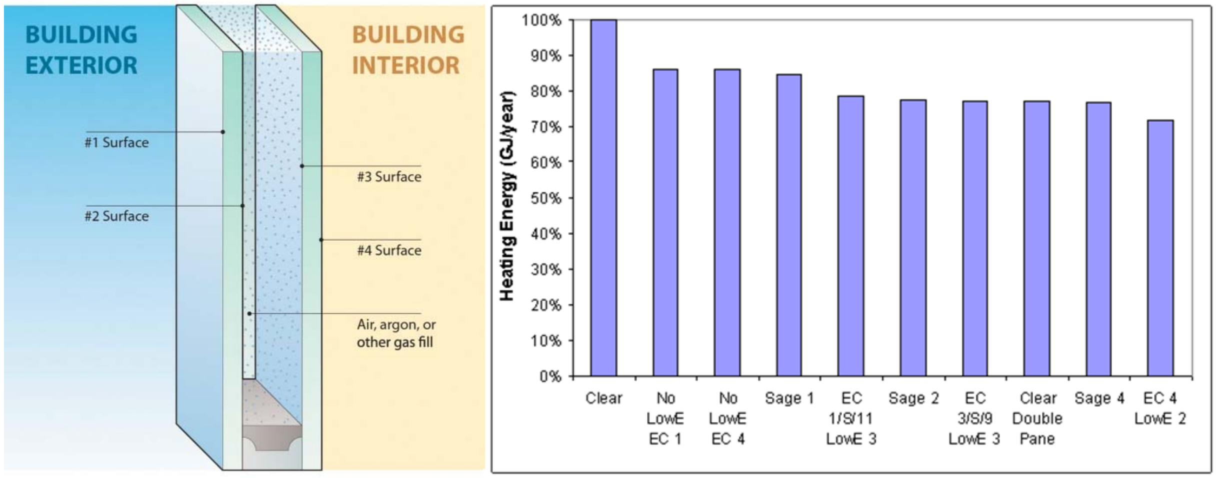


Figure 26: Typical House Heating Energy Use in the Northeastern Region for Various Window Types. The EC mounted on surface 4 with a low-e on surface 2 uses the least amount of heat. A flexible EC film allows products that are readily customized to meet regional demands. [12]

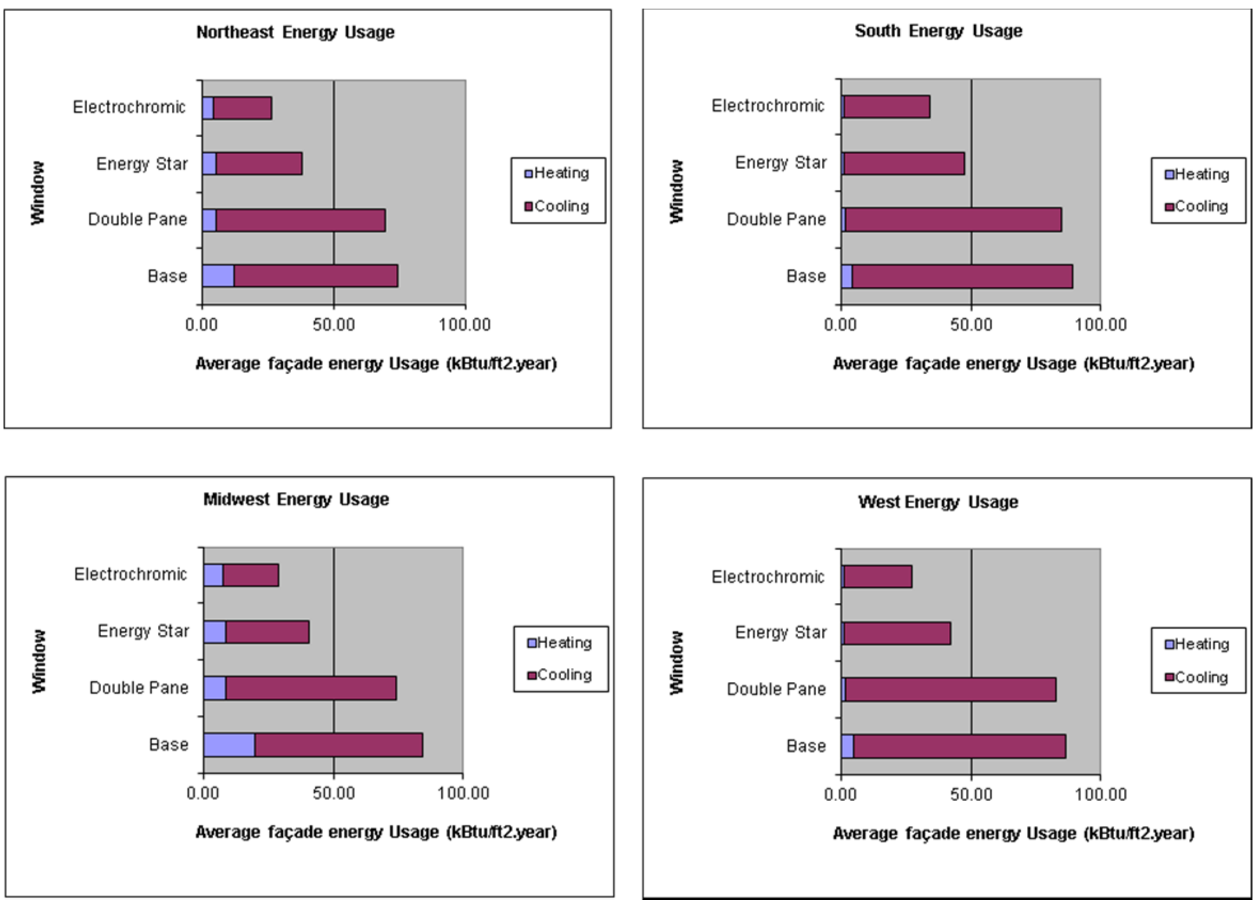


Figure 27. Façade Heating and Cooling Energy Usage for four different windows in the four US census regions. EC windows are the lowest energy use in each case.

[12] Window image from http://www.ppgresidentialglass.com/window_glass/understanding_IGU.aspx

3.3.4 Technology to Market Assessment

Market surveys conducted by the Freedonia group indicate a rapidly growing market for smart glass products over the next several years.[13] Approximately 2/3rds of this demand is expected to be in electrochromic products. The largest expected markets are in the architectural glass and non-residential markets. However, residential and automotive markets are far from insignificant, and the automotive market is particularly interesting for a flexible EC film. In this case, the laminated EC film provides a safety glass property in addition to energy management.

Customer and installer preferences represent another key area of product development and commercialization focus. Customer/installer preference information has been gathered, and includes demands such as: integration of the power supply/control mechanisms into the window frame, integration of photovoltaics into the window frame, ability to manually adjust electrochromics tinting, ability to automatically adjust electrochromics tinting through pre-set/pre-determined preferences, ability to retrofit product to existing windows, integration of temperature/light sensors into product, etc. Product cost, however, remains the major hurdle to widespread use of EC window technologies.

One of the potential concerns with a flexible EC film product is that the potential high cost of installation may overwhelm any cost savings associated with low-cost, high volume roll-to-roll manufacturing. ITN and MAG evaluated various strategies to integrate the EC film into windows, considering lessons learned from adjacent photovoltaic markets as well as discussion with those in the IGU and framing industry. To gauge the cost associated with product finishing, ITN and MAG established several process flows for integrating the flex EC into a framed window including plans for laser integration, bus bar application, electrical connection through the IGU and framing, integration into an IGU, framing, and installation costs. Figure 28 shows one conceptual manufacturing floor plan for integration of the laminated EC film product. The process flow and manufacturing plan have been used to produce cost models for finishing of the EC film into a window unit. The added costs of laminating an EC film can be less than 10% of the total installed window cost in some scenarios. The expected cost savings from high volume roll-to-roll manufacturing more than offset this added expense.

[13] Freedonia, Advanced Flat Glass to 2014 - Industry Market Research, Market Share, Market Size, Sales, Demand Forecast, Market Leaders, Company Profiles, Industry Trends

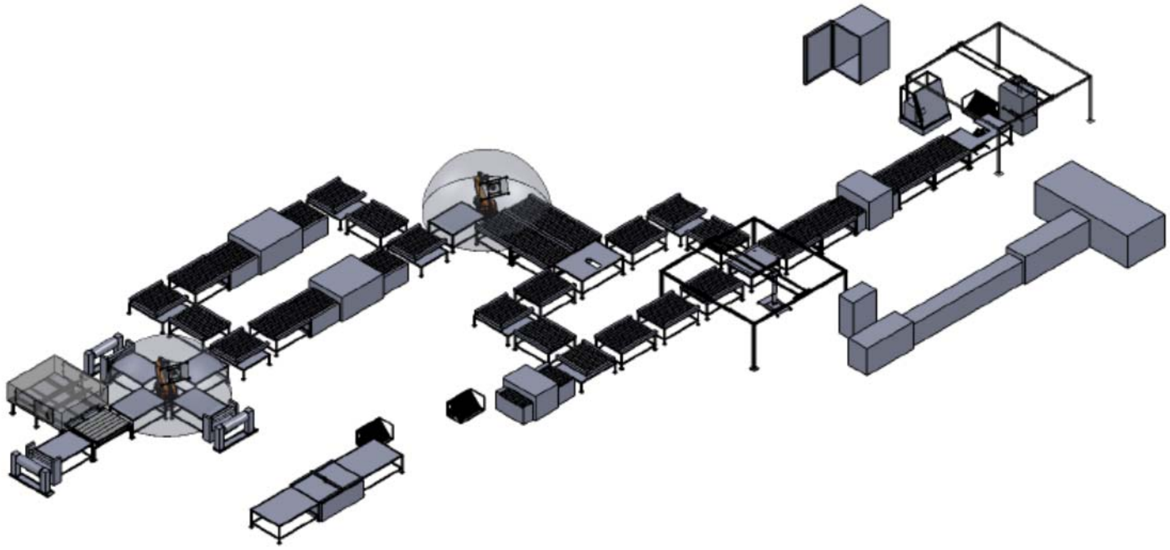


Figure 28: Modular manufacturing plant for the integration of FlexEC into IGUs in either laminated or suspended configuration

In order to have the best chance to transition the technology to a commercial product, a range of requirements must be considered, i.e. technical performance, cost, and non-technical market barriers, for an EC window product to receive widespread market penetration. Given the maturity of dynamic windows, non-traditional market considerations will likely play a major role in the initial market acceptance and EPRI provided an initial evaluation of these considerations.

Requirements for an EC window to be part of a utility incentive program: As explained by the National Action Plan for Energy Efficiency, the setting up of an incentive program for energy efficiency improvements in a utility territory requires that the program's cost-effectiveness be demonstrated. Cost-effectiveness in its simplest form is a measure of whether an investment's benefits exceed its costs. Key differences among the cost-effectiveness tests that are currently used include the following:

- **The stakeholder perspective of the test**. Is it from the perspective of an energy efficiency program participant, the organization offering the energy efficiency program, a non-participating ratepayer, or society in general? Each of these perspectives represents a valid viewpoint and has a role in assessing energy efficiency programs.

- **The key elements included in the costs and the benefits**. Do they reflect avoided energy use, incentives for energy efficiency, avoided need for new generation and new transmission and distribution, and avoided environmental impacts?

- **The baseline against which the cost and benefits are measured**. What costs and benefits would have been realized absent investment in energy efficiency?

The five cost-effectiveness tests commonly used across the country are listed below:

- Participant cost test (PCT).

- Program administrator cost test (PAC).
- Ratepayer impact measure test (RIM).
- Total resource cost test (TRC).
- Societal cost test (SCT).

These cost-effectiveness tests are used differently in different states. Some states require all of the tests, some require no specific tests, and others designate a primary test. California has been at the forefront of promoting energy efficiency in general and has even funded considerable early market adoption studies for dynamic windows through the California Energy Commission. While EPRI examined several state and municipal programs in California, New York, Florida, Texas, and even France, we will focus on California as an example in this report.

The California Public Utility Commission relies on the **Total Resource Cost Test (TRC)** as the primary indicator of energy efficiency program cost effectiveness, consistent with its view that ratepayer-funded energy efficiency should focus on programs that serve as resource alternatives to supply-side options.[14] The **Program Administrator Cost (PAC)** test of cost-effectiveness should also be considered in evaluating program and portfolio cost-effectiveness.

Total Resource Cost (TRC) Test[15]

<u>Definition:</u> The Total Resource Cost Test measures the net costs of a demand-side management program as a resource option based on the total costs of the program, including both the participants' and the utility's costs. The test is applicable to conservation, load management, and fuel substitution programs.

<u>Benefits and Costs:</u> This test represents the combination of the effects of a program on both the customers participating and those not participating in a program. The benefits calculated in the Total Resource Cost Test are the avoided supply costs, the reduction in transmission, distribution, generation, and capacity costs valued at marginal cost for the periods when there is a load reduction. The avoided supply costs should be calculated using net program savings, savings net of changes in energy use that would have happened in the absence of the program.

The costs in this test are the program costs paid by both the utility and the participants plus the increase in supply costs for the periods in which load is increased. Thus all equipment costs, installation, operation and maintenance, cost of removal (less salvage value), and administration costs, no matter who pays for them, are included in this test. Any tax credits are considered a reduction to costs in this test.

<u>Test Results:</u> The results of the Total Resource Cost Test can be expressed in several forms: as a net present value, a benefit-cost ratio, or as a levelized cost. The net present value is the primary

[14] Energy Efficiency Policy Manual, http://www.calmac.org/events/Policy_Manual_V3_1.pdf
[15] California Standard Practice Manual - Economic Analysis of Demand-Side Programs and Projects, 2001.

unit of measurement for this test. Secondary means of expressing TRC test results are a benefit-cost ratio and levelized costs.

Net present value is the discounted value of the net benefits to this test over a specified period of time. Net present value is a measure of the change in the total resource costs due to the program. A net present value above zero indicates that the program is a less expensive resource than the supply option upon which the marginal costs are based.

The benefit-cost ratio is the ratio of the discounted total benefits of the program to the discounted total costs over some specified time period. It gives an indication of the rate of return of this program to the utility and its ratepayers. A benefit-cost ratio above one indicates that the program is beneficial to the utility and its ratepayers on a total resource cost basis.

The levelized cost is a measure of the total costs of the program in a form that is sometimes used to estimate costs of utility-owned supply additions. It presents the total costs of the program to the utility and its ratepayers on a per kilowatt, per kilowatt hour, or per therm basis levelized over the life of the program.

More information about calculating the TRC can be found in California Standard Practice Manual.[15]

Program Administrator Cost (PAC) Test[15]

Definition: The Program Administrator Cost Test measures the net costs of a demand-side management program as a resource option based on the costs incurred by the program administrator (including incentive costs) and excluding any net costs incurred by the participant. The benefits are similar to the TRC benefits. Costs are defined more narrowly.

Benefits and Costs: The benefits for the Program Administrator Cost Test are the avoided supply costs of energy and demand, the reduction in transmission, distribution, generation, and capacity valued at marginal costs for the periods when there is a load reduction. The avoided supply costs should be calculated using net program savings, savings net of changes in energy use that would have happened in the absence of the program.

The costs for the Program Administrator Cost Test are the program costs incurred by the administrator, the incentives paid to the customers, and the increased supply costs for the periods in which load is increased. Administrator program costs include initial and annual costs, such as the cost of utility equipment, operation and maintenance, installation, program administration, and customer dropout and removal of equipment (less salvage value).

Test Results: The results of this test can be expressed either as a net present value, benefit-cost ratio, or levelized costs. The net present value is the primary test, and the benefit-cost ratio and levelized cost are the secondary tests.

Net present value is the benefit of the program minus the administrator's costs, discounted over some specified period of time. A net present value above zero indicates that this demand-side program would decrease costs to the administrator and the utility.

The benefit-cost ratio is the ratio of the total discounted benefits of a program to the total discounted costs for a specified time period. A benefit-cost ratio above one indicates that the program would benefit the combined administrator and utility's total cost situation.

The levelized cost is a measure of the costs of the program to the administrator in a form that is sometimes used to estimate costs of utility-owned supply additions. It presents the costs of the program to the administrator and the utility on per kilowatt, per kilowatt-hour, or per therm basis levelized over the life of the program.

More information about calculating the PAC can be found in California Standard Practice Manual.[15]

Example of Southern California Edison (SCE) utility company – TRC above 1.1

For SCE, the TRC of an incentive program for an energy efficient product such as EC windows has to be **above 1.1**.[16]

SCE has already set up an incentive program for energy-efficient windows. The program is entitled "Multifamily Energy Efficiency Rebate Program". One of the many rebates offered is $0.75 per square foot of high performance dual-pane, low-e windows. **The TRC** of the program is **2.27** and the **PAC** is **1.39**.[17] Similar analysis will be completed for Flexible EC film products as we transition from the feasibility stage into commercialization.

3.4 Discussion and Conclusions

The project aimed to establish the feasibility of roll-to-roll production of electrochromic devices on flexible polymeric substrates as a means to dramatically reduce manufacturing cost and enable widespread market penetration. Building on encouraging performance of ITN's EC devices on PET substrates performance entering the program, the project focused on three main efforts (1) Transition Small Scale Prototypes To Limited 0.5 Meter Wide, Web Coater Production, (2) Satisfy Market Driven EC Performance Metrics on Plastic Substrates, and (3) Product Development and Commercialization. The overall goal was to substantially reduce investor risk to motivate private investment in a production facility to further transition and scale this promising technology.

A 0.5 meter roll-to-roll web coater was design, constructed, and commissioned at ITN to support EC development effort. The chamber has four independently controlled deposition zones, one for

[16] EPRI, Personal Communication with Paul Delaney (SCE)
[17] Multifamily Energy Efficiency Program, http://asset.sce.com/Regulatory/Energy%20Efficiency%20Filings/SCE2502MULTIFAMILYENERGYEFFICIENCYPROGRAM.pdf

each layer in the EC stack. With this tool, we were able to establish the feasibility of roll-to-roll production of both Gen 1 and Gen 2 EC devices. Individual layers were continuously produced at lengths up to 3 meters with good uniformity, both down web and cross web. When deployed in composite device structures, we were able to verify that individual layers were able to achieve a transmission range of 3-70% transmission average over the visible portion of the spectrum. This is near the program goal of 2-70%. Initial development of intelligent process controls led to verification of a 2-state controller employed during deposition of the electrochromic layer.

Challenges of web wrinkling and non-uniform coloration were encountered when we began to stack layers together. Hardware and process modifications were identified to address these challenges and were successfully deployed for limited continuous production of Gen 1 and Gen 2 devices. While the hardware modifications were successful, the materials and designs were not sufficiently robust for operation over long periods. A third generation, more robust hardware upgrade was identified and implemented at the end of program. Initial experimentation with the 3rd generation hardware was encouraging and we expect fabrication of fully optimized, continuously produced Gen 2 devices in the production tool with continued development. Given the high capital cost of an EC production facility, it was crucial for us to be able to identify and solve these problems to substantially reduce investor risk during the scale to production phase of the project. Consequently, the ability to mature manufacturing readiness levels with solid tool designs is a major accomplishment of the program.

The project also successfully bridged from Gen 1 to Gen 2 devices to increase performance in line with market needs. While Gen 1 material sets proved useful throughout the program to help resolve issues such as web wrinkling and non-uniform coloration, they are fundamentally limited in transmission range and speed to be able to achieve the programs aggressive performance goals to bring the product in line with both market needs and DOE goals for EC windows. As expected, Gen 2 materials provided increased transmission range and faster switching times for both small area batch parts and large area composite materials. With both Gen 1 and Gen 2 materials sets, we were able to demonstrate durable cycling over 10,000-20,000 cycles in a variety of architectures including suspended films in an IGU and films laminated to glass tested in open air representative of retrofit applications. Retrofit type samples were sent to the National Lab for independent validation. However, the cycle life was limited due to testing in high humidity conditions. A more robust packaging technique was identified and samples proved durable even in 40ºC and 100% relative humidity outside the IGU environment. Additional independent validation of parts is underway with this new packaging.

As cost is a major driver for market penetration of EC window products, ITN focused on improving rate limiting processes, particularly for the electrolyte deposition to further drive down production costs. Electrolyte layers with half the initial thickness and four times faster deposition rate were demonstrated in EC device fabrication. The EC devices made with these electrolyte enhancements performed as well as the baseline devices. Further, enhanced plasma processing showed electrolyte deposition at eight times the initial rate is possible. In fact, the

EPP enhancements were limited by hardware constraints that are unique to the small scale batch tools. Further improvements, up to ten fold increases in the deposition rate are likely with additional development.

Finally, product design and development was completed in collaboration with our development partners with a high degree of input from the end user community. All standard IGU configurations, such as dual and triple pane, laminated, and suspended were reviewed and discussed by the team in regard to integration of the unique features of the flexible EC film and its associated power management requirements. A flexible form factor is most closely aligned with the suspended configuration although it can also be incorporated into the growing trend in laminated construction for safety and security as well as the widely adopted, double pane construction. Keys to any IGU configuration will be the accommodation of electrical cabling, contacts, and feedthroughs with current spacer and edge seal technologies.

In-house fabrication capabilities, including lamination and sealing, were established to build prototype IGUs. Prototype assemblies were fabricated using both laminated and suspended film configurations. Electrical and power management designs were developed with the goal of integrating these designs into prototypes. We continue to collect performance and pricing data on competitive market offerings, both EC, other smart glass, and standard window offerings. Monolithic integration processes to support blanket deposition of EC materials were also developed and demonstrated. First, laser scribing parameters were established on small area parts from the batch tools to show the ability to create independent switching areas from a larger area deposition. Subsequently, the processes were refined and verified on materials processed in the web coaters.

Market evaluations based on 3rd party market reports as well as direct discussions with IGU manufacturers, window producers, architects, etc. all revealed a growing interest in EC window products tempered mainly by the high cost of current offerings. With help from EPRI, ITN explored the requirements to enable the EC Film technology to be considered for rebate programs. ITN also completed detailed cost modeling, including the projected costs for product finishing into a framed window and installation to allay concerns that cost savings for a roll-to-roll product would be offset by high lamination costs and/or specialty installation of the resultant window film. Further, energy savings models showed the benefits of the EC Film will vary depending on unique regional drivers. The EC Film enables non-traditional EC window structures to match these regional requirements from retrofit applications to suspended films.

4 Products Developed Under the Award

4.1 Publications

Quarterly reports were filed with ARPA-E over the course of the project. In addition, ITN sponsored a booth annually at the ARPA-E showcase highlighting progress on the award. Several branches of the government also interested in EC technology, i.e. the Advanced Manufacturing Office and Energy Efficiency and Renewable Energy Office of the DOE as well as branches of the DoD, have also been briefed on ARPA-E development progress.

4.2 Websites Featuring Project Work of Results

ITN’s website was updated to include a press release on the initial ARPA-E award and EC product development (http://www.itnes.com/lithium.html).

4.3 Networks/Collaborations Fostered

ITN has initiated dialogue with over 50 potential investors and strategic partners, over 20 of which have led to in-person meetings or teleconferences. Given the nature of the relationships, it is often not possible to disclose the names. However, below are some highlights:

- Several contacts were made with major world side glass and specialty plastic suppliers interested in EC technologies as part of their product portfolios. Several of these partners have participated in initial evaluations of our baseline technology to facilitate funding and technical collaborations to move the technology into commercialization transition. EC samples have been provided for their internal testing to facilitate the evaluations.
- Collaborations with the National Labs, i.e. NREL and LBNL, in regards to performance modeling and durability testing.
- Established relationships with a windows consultant, who had previously held executive position in advanced technology development at Pella windows. Consultant provided insight into market forces for residential windows and sealing technologies.
- Subcontractor established relationships with window sealing materials suppliers and IGU manufacturers. The relationships were used to develop EC film product integration and finishing designs, automation strategies, and costing.
- Subcontractor established additional relationships with window sealing materials suppliers and IGU manufacturers. The relationships were used to develop EC film product integration and finishing designs, automation strategies, and costing.
- Series of One-on-One at ARPA-E Summit and TechWorld Summits with both Strategic Partners and VC funding sources on request of the Strategic Partners and VCs.

4.4 Invention Disclosures

Four invention disclosures have been filed as a result of the ARPA-E development efforts.

4.5 Patent Applications

All four invention disclosures have been converted to provisional patent applications and are in the process of being converted to non-provisional patents.

4.6 Media Reports

"ITN Energy Systems Awarded $4.9 Million ARPA-E Grant from U.S. Department of Energy." *Business Wire NewsTrak*, 10 November 2009

"Thin-film technology fuels ITN Energy Systems" *Denver Post* April 2013

http://www.launch.org/innovators/ashutosh-misra LAUNCH Summit Video.

ITN also attended several showcases including the NREL Growth Forum, TechConnect World Summit, etc. In several of these, i.e. Emerging Technologies Summit (sponsored by CA Utilities in Sacramento, CA), TiE Rockies Local Chapter Meetings, and the LAUNCH Summit, ITN was an invited speaker to present an overview of our EC commercialization efforts.