Final Report

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Project Objective: The three building envelope functions with the largest impact on the energy usage are illumination, energy flux and energy production. In general, these three functions are addressed separately in the building design. A step change toward a zero-energy building can be achieved with a glazing system that combines these three functions and their control into a single unit. In particular, significant value could be realized if illumination into the building is dynamically controlled such that it occurs during periods of low load on the grid (e.g., morning) to augment illumination supplied by interior lights and then to have that same light diverted to PV energy production and the thermal energy rejected during periods of high load on the grid. The objective of this project is to investigate the feasibility of a glazing unit design that integrates these three key functions (illumination and energy flux control, and power production) into a single module.

Background: The work focuses on the “proof of concept” research related to the design and fabrication of a glazing system that combines transparent photovoltaics for energy production (PV), dynamic optics (D) for control of illumination and energy flux, and static IR rejection (IRR) for baseload energy flux management into a single unit. The contribution and control of each subcomponent in this module were designed from a systems perspective such that the energy contribution from the overall unit is maximized in a commercial building application.

The Glass and Fiberglass Research group at PPG Industries has expertise in the design and fabrication of glazing units, the facilities necessary to measure and quantify the power production function and modeling expertise to assess the performance of an integrated unit in a building application. That group performed the research activities related to the power production and static control of the energy flux subcomponents of the system and fabrication of the units. RavenBrick LLC was a subcontractor to PPG and performed the research activities related to improvement of the Dynamic Optic subcomponent.

Summary: Several designs and approaches were considered and investigated for the photovoltaic power producing subcomponent. In one of these, it was shown that subsurface patterns in the glass could be designed such that incident light could be directed to PV cells mounted on the edge of the glass. However, in all cases with this design, the amount of power generated was deemed to be too low for an economically viable commercial application (i.e., the cost of adding the power generating function exceeded the value of the power produced). The final design approach was to use full size PV cells behind the front glass pane in a nonvision area of the glazing unit.

Early in the project, the thermochromic dynamic optic work conducted by Ravenbrick resulted in some advances in the component. Also, new dynamic optic was created by Ravenbrick in which the transmission of light is specular in the off-state, and the reflection is diffusive in the on-state. However, this initial sample had a fairly low contrast ratio which would require much further development work. Later in the project, an alternate thermochromic dynamic optic material from Pleotint LLC was evaluated. Further, during that activity, a method to measure full solar range transmittance was developed by PPG. Pleotint's commercially available SRT™ (sunlight responsive thermochromic) material was chosen for the switchable component for the prototype fabrication and building energy analysis.

A prototype unit was constructed that combined PV power generation, dynamic optics, and static IR rejection into a single unit. The unit was evaluated and measured in outdoor conditions and compared to a baseline prototype without the dynamic optic. The power generated by the PV subcomponent was in agreement with expectations and the dynamic element performed as expected (based on laboratory measurements and modeling). EnergyPlus was used to evaluate these technologies in a curtain wall example using the data acquired from the prototype.

Considering the required manufacturing processes and associated yields and costs, the dynamic glazing and photovoltaic elements are likely to be better suited and optimized when fabricated as separate components. Both dynamic glazing and BIPV glazing can be used in commercial buildings, but this project did not find a combination of the two into a single unit that appears worthwhile for continued study. Therefore, the recommendation is a “No Go” for phase 2 funding.

Detailed Activities by Task:

Task 2

The statement of project objectives was as follows for Task 2:

Task 2.0 Subcomponent data for glazing system design

Laboratory measurement of the subcomponent for each function will be done to understand the operational behavior and contribution of each within the system to enable design of the glazing system. In addition, evaluation of various PV designs will be done to identify the best technology for the energy producing subcomponent. The expected outcomes for this activity will be the data and characterization of the operation of each subcomponent suitable for design of the unit. Such data will include such data as the thermal and optical transport properties, dynamic response and energy production of each subcomponent.

Subtask 2.1 Subcomponent measurement and characterization

Optical and thermal properties of individual subcomponents will be measured so as develop a database for performance at different times of day and year for modeling.

Subtask 2.2 Evaluation of PV technologies for energy production function

Using small-area units on a solar simulator make angular dependent measurements and characterize different PV approaches for energy production in the glazing system.

Optical and thermal properties of commercially available glass products are generally well known at a level suitable for 1-D modeling. In this work, however, models were developed using ray tracing methods and more accurate property data of the materials of construction were necessary for that approach. Therefore, the optical properties of various sub-components used in the mini-module construction including PPG glass products, PPG optical films, other optical films, and interlayer materials were measured. These data have been incorporated into the ray tracing modeling software in terms of refractive index, absorption, scattering, etc. to more accurately model power sub-component designs on a continuing basis. The properties of dynamic optic elements were a main focus of subtask 2.1 as described below.

The thermochromic behavior of materials and components is not a characteristic that is typically measured in a glazing product. During this project, PPG commissioned the fabrication of a new type of thermochromic switching optical subcomponent from Ravenbrick, LLC (see Task 3). The desired behavior for this subcomponent is one in which the transmission of light is specular in the off-state, and the reflection is diffusive in the on-state. Using samples of cholesteric liquid crystal (CLC) films (obtained by PPG from a major chemical manufacturer), Ravenbrick successfully fabricated four units by mounting the CLC films over a glass thermotropic liquid crystal cell. These initial units were fabricated as proof of concept devices, and thus, for simplicity the liquid crystal polarization films used in this work had a limited spectral range in which they displayed polarization (600-900 nm). The use of CLC technology allows control of polarization for particular wavelengths of interest; as such this type of thermochromic device is unique for its potential as a spectrally selective window film. The performance of these units is shown in Figure 1.

The subcomponents display thermotropic behavior in the designed spectral range demonstrating the proof of concept for this approach. However, the contrast ratio between states was ~1.3:1 which is too low for commercial application. Further development work would be required to raise the contrast ratio and broaden the spectral response. Further, these units exhibited considerable off-axis color shift and this too would need to be addressed in any future development activities.

Figure 1: The transmission (left) and reflection (right) spectra of the PLC based infrared thermochromic filter in the switched (hot) and unswitched (cold) states

In early 2011, discussions were held with Pleotint, LLC, and they provided samples of their SRT™ (sunlight responsive thermochromic) material for use with this project. The Pleotint material is an interlayer of unique design that is laminated between two pieces of glass and can be used in existing fabrication processes. Two studies using these samples were completed to determine (1) the darkening time with different tinted glasses and (2) the optical transmission at different temperatures.

For the design of the prototype (see Task 4), the darkening study data were used for determining the glass to be used in the “glass package” (i.e., the combination of front and back glass lites) that best met the design criteria of shortest switching time. Five laminated samples were made for the study, all with 6mm low-iron STARPHIRE® front glass, three layers of 30-mil PVB (polyvinyl butyral), a layer of 2-mil PET, a layer of Pleotint SRT, and a 6mm back glass. The five laminates differed in the type of PPG back glass used: STARPHIRE®, clear, OPTIBLUE®, AZURIA™, or SOLARGRAY® glass. Each sample was tested using a solar simulator light source, with a ½” gap spacing the laminate from a piece of 6mm SOLARBAN® 70XL solar control low emissivity glass to create an unsealed insulating glass unit (IGU). Thermocouples were placed on the top of the front glass, on the bottom of the bottom glass of the laminate, inside the IGU airspace, and on the bottom of the monolithic lite. The IGU was placed a couple of inches above a solar light intensity meter, and the temperatures and light intensity were recorded as a function of light exposure time. The setup for this experiment is shown in Figure 2.

Figure 2. Experimental setup for Pleotint heating study (light source off for photograph).

For each laminate, the temperatures increased with continued light exposure time, and each experiment was terminated when the temperatures reached saturation. As the sample temperature increased, the light transmission decreased as expected. A summary of the data is shown in Figure 3, which shows the relative transmitted light intensity as a function of light exposure time. This data shows that, with a low iron (STARPHIRE), low absorbing front glass, a tinted (high absorbing) back glass is needed to achieve shorten the “switching time”. The glass chosen for the prototype based on this data and aesthetics / appearance for this construction was OPTIBLUE, which darkened to 17.5% of room temperature transmittance after 1 hour in this experiment. Note that the solar light intensity meter used for this study uses a silicon detector, and therefore the transmission metric is weighted based on silicon response and is not a photopic (human eye visible light) metric. Also note that the darkening as a function of time would be dependent upon the light intensity used; however, since the intention of this experiment was to rank the various glass constructions, the absolute “switching times” presented here are not meant to represent expected results for any specific geographic location or outdoor condition.

Figure 3. Normalized transmittance as a function of light exposure time for glazings using Pleotint Sunlight Responsive Thermochromic material and various tinted glasses.

The second study determined the optical transmission at various temperatures. Glazing materials other than thermochromics do not change optical properties as a function of temperature; therefore, only room temperature measurements are required for full characterization. So there is no standard protocol or equipment to measure optical properties at elevated temperatures. During this project, a method was developed to measure laminate transmittance at elevated temperatures using a Perkin-Elmer Lambda 950 UV/vis/NIR spectrophotometer where the sample holder was modified to allow for temperature control of the sample being measured. The experimental setup is shown in Figure 4, and consists of insulation, a fan heater, and a temperature controller.

Fig 4(a) empty sample chamber

Fig 4(b) additional components

Fig 4(c) insulation closed

Figure 4. Experimental setup for making transmission measurements at elevated temperatures.

A series of preliminary measurements was made to finalize the testing protocol. It was found that separate calibrations are not required at each elevated temperature, and a single calibration at room temperature was sufficient. It was determined that holding the sample at a fixed temperature for about 10 to 15 minutes allows for an accurate steady state reading at that temperature. A reference sample was fabricated with two pieces of 6 mm STARPHIRE glass, the Pleotint SRT interlayer, and an imbedded thermocouple placed between the interlayer and one of the pieces of glass. The full solar range transmittance was measured at 25, 35, 45, 55, 65, 75, and 85 °C (77, 95, 113, 131, 149, 167, and 185 °F). The values for the full solar range transmittance are shown in Figure 5 and the full solar range spectra data were used to estimate system performance in Task 4.

Figure 5. Full solar range transmittance measurements of Pleotint laminate with 6mm STARPHIRE.

Subtask 2.2 was the evaluation of PV technologies for the energy production function. The laboratory work for this evaluation involved I-V (current-voltage) characterization of the PV subcomponent for each configuration / design using the equipment shown in Figure 6.

Figure 6. Laboratory equipment for characterization of PV subcomponents included: Sciencetech 1.6kW Solar Simulator (left) with xenon arc light source, fully reflective design, and air mass 1.5 global (AM 1.5G) filter and a Keithley 2440 5A Sourcemeter (right). Not shown is a computer with custom LabVIEW® program for data acquisition and control.

Data relating the angular impact of the incident light on the glazing unit on power production was critical to understanding the feasibility of the various designs of the PV subcomponent. Before these data were obtained, the response of the measurement system under similar conditions was determined to separate measurement system / unit under test (UUT) behaviors. Data from measurement system evaluation using a sample population of 10 measurements with illumination at normal incidence on the sample shows (Figure 7) the reproducibility of this system to be less than 0.3% for Pmax and less than 0.1% for Isc. The data for the angular response of Isc and Pmax (Figure 8 left and right respectively) shows that the system behaves as expected when corrected for geometry of the sample. This indicates that the optics of the system are in alignment and there are no uniformity issues in the illumination at the sample plane. The deviations seen at high angles of incidence (low $\text{Cos}(\theta)$) are expected due to reflective losses near Brewster's angle and the associated effects related to the differences in reflectances of the two polarizations in that region.

Figure 7 – Reproducibility data for a Spire 5"x5" Si photovoltaic cell laminated to PPG's SOLARPHIRE® PV low-iron glass. Standard deviation for the 10 sample measurement population is 0.12% for Pmax and 0.04% for Isc.

Figure 8 – Angular response for the Isc (left) and Pmax (right) from a Spire 5"x5" Si photovoltaic cell laminated to PPG's SOLARPHIRE PV low-iron glass. The trend lines are least squares fit for a linear fit between the cell response and the $\text{Cos}(\theta)$ of the incident angle.

Earlier work had shown that optical structures in the power generating subcomponent could enhance the guiding and directing the photons onto the PV cell(s). Thus, light scattering / guiding structures were fabricated in samples and the change in power output measured with the expectation that such structures would result in higher energy production in the final unit. Early in the project, equipment suited for fabrication of such optical features in glass was specified and purchased. The unit selected uses a 532nm wavelength laser as the energy source for forming the structures. The focal resolution is such that the beam can be focused within the compressive stress region of a tempered glass part so that the optical structures can be formed without breakage. This level of control in focal region and micron resolution in X-Y positioning enable the fabrication of either or both surface and subsurface optical features in parts. The unit is capable of producing 5-10 patterned parts as large as 60cm x 120cm; this is a size well suited for prototype fabrication (Task 4).

Initial work for the power production (PV) subcomponent investigated different geometries and designs of these optical structures. Early experiments focused on the viability of mounting of PV cells on the periphery of the glass pane as compared to more traditional BIPV mounting where PV cells are fixed directly to the rear face of the glass pane. For a 'peripheral' design the cells would be mounted along the edge of the glass panel so that they could be placed outside the viewable area. The 'peripheral' configuration has implicit benefit since this design minimizes the number of required PV elements, be protected from the environment, and would have a minimal effect on the viewable area for vision glass applications. Conceptually the 'peripheral' design would also be synergistic with the diffusive reflecting thermotropic Ravenbrink film element.

In order to investigate this, small mini-modules were constructed using PPG STARPHIRE glass and Kyocera polycrystalline strip cells fixed with Momentive Silicone RTV 615 potting compound in peripheral and conventional configurations (Figure 9). The conventional configuration, with cells in-plane with the glass panes is also referred to as 'marginal' because the idea is that the cells would be placed in the margin (i.e., near the edge) of the glazing unit.

Figure 9: Experimental mini-modules of 'marginal' configuration (top) and 'peripheral' configuration (bottom)

An experiment was conducted where a 'peripheral' configuration mini-module was constructed and measured using the solar simulator in the presence of a white diffusive background at various angles. As seen in Figure 10 a measureable power can be detected even when the light source is at a high angle relative to the PV cells. This experiment demonstrates the possibility of using a diffuser such as the Ravenlight film as a way to direct light to edge mounted PV elements.

Figure 10: Experimental configuration for the angular dependence of power output into a 'peripheral' design.

In a related experiment, the 'marginal' configuration mini-modules were measured in the presence of various backgrounds. In this case the use of the background is to simulate the effect of the thermally switchable element. The use of mirror simulates the effect of the Ravenreflect film in the switched state, a white background simulates the Ravenlight film in the switched state and a black background represents a zero state where the Ravenlight film is not thermally switched or absent. It can be seen that a white diffuse reflector provides a benefit to the PV system (Figure 11). This suggests that the Ravenlight film may provide a benefit to this type of design.

Figure 11: Effect of backing reflectivity on the power generation of a marginal (in-plane) cell.

In the design of the power producing element to this program it was apparent that there is a nearly limitless number of possible configurations and optical elements that can be utilized to direct light to the PV elements. For any single design the aesthetic value, daylighting value, thermal transmission and reflection, the PV production in various lighting conditions, angular dependence of illumination, as well as seasonality should be considered. To reduce the experimentation and optimization required with these factors a non-sequential ray tracing software package, TracePro, was used to model and evaluate designs.

An initial evaluation focused on the 'peripheral' design with edge mounted mono-facial PV cells for a test model that could be validated experimentally (a 150 mm square). To this design an optional sheet of acrylic (Ravenbrick film) was present in the center of the glass. Borders were added to evaluate the effect of light directing elements in close proximity to the PV cells. These elements were modified to have the optical properties of a mirror or diffuse reflector as a parallel to previous experiments (Figure 12).

Figure 12: A 'peripheral' design 150 mm square window for use with TracePro

A window unit was then added to the virtual test stand (Figure 13). This stand was a 150 mm aperture in a 'wall' that could be illuminated from a number of positions. This simulation focused on the five positions of the sun at equinox of a South facing vertical 'wall' at 42° latitude (e.g., Chicago). The illumination on the aperture was weighted for diffuse and direct illumination for values from the IES lighting handbook for the various positions of the sun. The symmetry of the system makes three of the positions unique (8 AM, 10 AM and 12 Noon) for symmetric window designs. Calculations were made for the 2 PM and 4 PM positions for two non-symmetric designs. In these simulations light passing through the window was 'collected' by the interior surfaces and similarly light incident on the PV elements determined and the flux at those locations integrated across those areas. Thus, this simulation could provide the relative efficiency of power generation and the total amount of interior lighting for different designs.

Figure 13: A model of a window exposed to lighting conditions of a South facing window at 42° latitude (e.g. Chicago) with direct and indirect illumination at 2 P.M.

Several variants of the simple ‘peripheral’ design were considered (Table 1). Not all designs conceived were as forward moving possibilities but were included to provide validation of the model. Several conclusions from these simulations were:

- Diffuse reflective borders are strongly beneficial to power generation in this configuration.
- For power generation the borders alone are as effective as having the entire window with diffuse reflector.
- The bottom border is the most important contributor for power generation.
- By comparing the asymmetric designs (‘2 mirrors, 2 cells’ and ‘2 cells’), it was found that light is coupled into the window and internally reflected to the solar cells
- Due to low total power and high angle of incidence to the window the 8 AM (and 4 PM) position of the sun is of negligible design importance

Table 1: Experimental configurations for various ‘peripheral’ designs used in this simulation. The elements of the design seen in Figure 12 had their optical properties defined as mirror, a cell (a PV cell made of Silicon), or a diffuse reflector.

Configuration Name	22mm Borders	Top Edge	East Edge (Cell 1)	West Edge (Cell 2)	Bottom Edge	Ravenbrick Film
2 Cells	Diffuser	None	Cell	None	Cell	None
2 Cells, 2 Mirrors	Diffuser	Mirror	Cell	Mirror	Cell	None
3 Cells	Diffuser	Mirror	Cell	Cell	Cell	None
4 Cells	Diffuser	Cell	Cell	Cell	Cell	None
4 Cells, Mirrored borders	Mirror	Cell	Cell	Cell	Cell	None
4 Cells, No Diffusers	None	Cell	Cell	Cell	Cell	None
4 Cells, All Diffusers	Diffuser	Cell	Cell	Cell	Cell	Diffuser

The evaluation of different power generation designs involved the down selection of conceptual designs through modeling using Tracepro Expert and follow on performance measurements of experimental mock-ups. Before using the software to evaluate specific subcomponent designs, additional experiments were conducted to validate the various modules in the software package. For example, ‘Direct Source Lighting’ experiments were run to test the correlation between the performance of the modules under lab evaluation conditions using the solar simulator and the performance of BIPV subcomponent modules in ‘virtual space’. In these ‘Direct Source Lighting’ experiments, modules were designed in virtual space and subjected to direct (collimated) lighting of a fixed intensity. This approach is in contrast with results reported earlier which utilize both direct and diffuse lighting of varying intensity but allows for direct comparison with experimentally measurable conditions using a solar simulator. BIPV subcomponent test pieces, corresponding to the virtual designs (Figure 14), were constructed and experimentally evaluated and test stands corresponding to the compound angles used in the virtual study were constructed (Figure 15) for experimental evaluation and allow for direct comparison.

**Figure 14: 'Simple Module Designs' as modeled (top) and experimental mock-ups (bottom).
[Pink color in modeling is for contrast while viewing and not present in the model]**

Figure 15: Test Stands for 'Direct Lighting' experiments. Test stands hold mini-modules at compound angles corresponding to the 8:00, 10:00 and 12:00 conditions at South facing equinox for 42° Latitude.

Excellent correlation exists between the illumination of the solar cells in the virtual model and the experimental measurement for the 12:00 condition (Figure 16). For illumination at shallower angles of incidence to the window, as in the case of the 8:00 and 10:00 (and the corresponding 14:00 and 16:00 positions), the model predicts a reduction in performance for the modules. The model appears to accurately describe a penalty in performance at the 8:00, 10:00, 14:00 and 16:00 illumination conditions. However, the model underestimates the rate at which the performance is reduced as the angle to the window is reduced. This is likely due to an artifact of light injection into the PV cells that was not included in the model. The experimental data is much closer to the cosine loss that was expected from the angle alone. In fact the experimental data is a little lower than the cosine loss at the steeper angles, which was expected due to the additional losses of front glass reflection and increased glass absorption due to longer optical path lengths.

Figure 16: A comparison of modeled module designs (dotted lines) and their experimentally determined counterparts (solid lines).

As is known, the tilting of solar cells towards the sun improves coupling of the sunlight into the photovoltaic cell leading to an improvement in performance. A 'Louvered IGU' design was developed and evaluated which uses this design concept and displayed considerably more power output per cell than a traditional flat module type design mounted in a vertical configuration. The simulation showed (Figure 16) that this 'Louvered IGU' design not only receives a greater amount of light on the solar cells, but it blocks a smaller portion of the viewing area (i.e., yields a higher interior illumination).

The initially proposed peripheral module designs which would benefit for the integration of a dynamic optical component were theoretically modeled and mock-ups were fabricated. For the peripheral design concept, incoming light is redirected within the glass by internal reflections to photovoltaic cells mounted on the periphery of the glass pane. Early work focused on the use of a reflective border to couple light into the glass. This concept could utilize a dynamic reflector switching between a state where the light was coupled to the solar cells and a state where all light was allowed to pass through the module for illumination. Mirrored, diffusively reflective, and black backing frames were considered in these evaluations. These conditions approximate the optical effects of the Ravenlight® and Ravenwindow® ER films.

One design investigated was based on the concept that that not all edges of the unit would require solar cells for light collection, but mirrors could be used instead on two of the four surfaces thereby redirecting light to the edges where solar cells would collect the sunlight. (Figure 17). In such a case the cost could potentially be reduced from a four cell design.

Figure 17: Peripheral module designs utilizing two cells. Reflectors were positioned on the surfaces opposite to the solar cells.

The performance metrics of power/cell and power/ft² were considered due to their importance in terms of cost and building integration. The performance metrics of selected peripheral designs are summarized in Figure 19. Of the designs considered, the following results were found:

- For peripheral designs using a reflective border, the top cell was largely ineffective. The performance of this design was dominated by the upward facing (i.e., bottom) cell. (Figure 18). Thus, on a power/cell basis a peripheral design with a single upward facing cell would be the most beneficial.
- A design utilizing a PPG developmental patterned glass was more effective at redirecting light to the edges of the peripheral design than designs with non-patterned glass. (Figure 19)
- In peripheral designs, the modeling results indicated that mirrors on the edges (TIR mirrors - TIRM) of the module perpendicular to the glass can provide a small increase in power output. The experiments confirmed that only a slight increase in power output occurs with this design.

Figure 18: Power production of each of the four solar cells in a four cell peripheral design utilizing a 22mm mirror border.

Figure 19: Power Density and Solar Cell Utilization of Various Peripheral Designs.

In preparation for the delivery of the laser patterning system, work was done to model patterns which could potentially be fabricated in PPG glass products using the laser patterning system. An example of this can be seen in Figure 20. In this example a subsurface pattern is made to provide a lensing effect onto scattering centers located on the surface with a goal of enhancing light scattering into the glass at non-normal incidence.

Figure 20: A theoretical laser patterned glass engineered to improve light injection. The green spheres represent sites of laser damage with a higher refractive index than the bulk. The insets to the left depict the theoretical path of light incident from the right hand surface normal (below) and off axis (above).

Figure 21. Left: ProtoSCRIBE Laser Scribing Station by Vyteck. Center: laser induced haze centers (subsurface pattern). Right: concept of using pattern to increase solar cell power generation.

The laser patterning tool (Figure 21 - Left) for this work was purchased from Vyteck Industries. Using subsurface patterns to increase power production was investigated to determine whether this approach is (1) practical from a tool / manufacturing standpoint and (2) whether the increase in power output would justify the cost of fabricating the pattern. The initial work in this area was to evaluate different pattern designs (e.g., Figure 21 – Center) for redirection of light to peripherally mounted cells (Figure 21 – Right).

One approach investigated with the laser patterning tool was to improve the appearance of BIPV units where the photovoltaic cells are in the visual frame of an external observer. This approach utilizes patterning of the glass such that the cells are screened from view while still allowing the light from the sun to reach them. This is done using an angled louver formed by subsurface patterning in the glass (Figure 22). Initial patterns demonstrated the desired effect however a prototype showed reductions in power output ranging from 13% to 45%, depending on angle, compared to a unit with no pattern. This significant reduction suggests that the approach loses too much power, and this design was removed from further consideration.

Figure 22: Concept drawing showing unit with the front glass patterned with an internal louvered structures to conceal a solar cell for improved aesthetics of a building façade.

Other designs were evaluated in which the effect of the pattern on PV power was measured and the results are summarized in Table 2. All time-referenced data are for 42° latitude equinox conditions on a South facing vertical surface. An example of the detail level of the design parameters and measurement results for the evaluation for each design is shown for Design 2 in Table 3, Figure 23, and Table 4. This design consists of a pattern of laser-induced haze centers within a 6" x 6" sample with 2" checkerboard pattern (9 squares – 5 patterned, 4 with no pattern).

Table 2. Summary of power generation results for glass-edge mounted PV cells.

				one cell power at noon (mW)	
Design name		laser pattern in glass	layer structure	black background	white background
Reference Design		none	n/a	13	17 (22mm white border)
Design 1		22mm margin frame	500 dpi, 2 layers near bottom	20	25
Design 2		2" checkerboard	200 dpi, 6 layers near bottom	25	33
Design 3		solid	200 dpi, 6 layers near center	18	23
All samples were 6"x6" 10mm low-iron glass; polycrystalline Si cell, 4" by 5/16", facing the bottom edge.					

Table 3. Details of construction for Design 2.

Resolution	200 dpi
Glass	10mm STARPHIRE®	
Size	6"x6"	
Pattern Layers	6 alternating layers (pixel checkerboard)	
Pattern Shape	9-square checkerboard	
Pattern Location	Near bottom of glass thickness	
PV cells	Mounted on 2 edges of glass (polycrystalline Si, 4" by 5/16")	
PV Measurements	Each cell for Normal Illumination, 8AM, 10AM, and 12 noon angles, various backgrounds

Figure 23. PV cell power results for Design 2.

Table 4. Power and current data from the bottom cell of the 9 square 2" checkerboard for 12:00 noon for Design 2. Orientation of the unit is such that light reaches the "front" first.

Backing	Pattern Orientation	Power		Current	
		Pm (mW)	Improvement*	Isc (mA)	Improvement*
black	none*	13	-	37	-
black	to front	21	54%	57	53%
black	to back	25	88%	68	81%
white	to front	26	97%	76	102%
white	to back	33	148%	86	130%
mirror	to front	30	124%	84	123%
mirror	to back	40	197%	101	169%

*The first line of data is for the Reference Design with no pattern, and the improvement is relative to this.

The results in Figure 23 and Table 4 show there is an improvement in the power generation as a result of the checkerboard pattern. There is also an improvement if the pattern is located towards the back of the glass rather than towards the front of the glass. The improvement is greatest at higher angles, such as at the 8:00 AM condition when the checkerboard pattern to the back of the glass gives a power of 8.4 mW compared to the power of the reference sample with no pattern of 2.1 mW, an improvement of 300% (both with black backgrounds).

For the approach of patterns in the glass to make sense for large windows, it is important to know the amount of power that can be generated from light that is scattered by the pattern and travels a greater distance through the glass. An experiment was done in order to investigate the impact of the location of the laser-induced pattern on the output of the PV cell with the cell mounted on the edge of the glass. This experiment involved starting with a 6" by 24" piece of low-iron, high-transmission glass, mounting a solar cell to one edge, and making a "solid" 6"x6" pattern at the opposite end. After making measurements, one to three inches of the patterned sample was cut off and corresponding amount (closer to the cell) was then patterned. The power output was then compared with the distance of the pattern from the PV cell. The details for this experiment are shown in Table 5 and the results are shown in Figure 24.

Table 5. Details of construction for experiment used to study path length of light in glass.

Resolution	200 dpi
Glass	10mm STARPHIRE®
Size	6"x24" glass size to start; 6"x6" pattern size always
Pattern Layers	6 alternating layers (pixel checkerboard)
Pattern Shape	solid
Pattern Location	Near center of glass thickness
PV cells	Mounted on 1 edge of glass. (polycrystalline Si, 4" by 5/16")
PV Measurements	Normal illumination (0°), 30°, 45°, (side-to-side angles with cell in front). The sample was covered with black felt from the cell to the pattern, so the only part of the sample exposed to the light was the pattern. Therefore, the only light to strike the cell had to travel through the glass.

Figure 24. PV cell power for bottom cell as a function of illumination angle and distance of illuminated pattern from cell for Design 4.

The data in Figure 24 shows that light traveling through glass is mostly absorbed by the glass, even for a highly transmissive low-iron material such as STARPHIRE®. These results are consistent with the expected absorption of the solar spectrum through this distance of glass. Therefore, harvesting or injecting light more than a few inches away from the cells appears to be of limited value, and the data in Table 2 represents adequate information to evaluate the viability of this general approach being studied.

As a comparison to the data in Table 2, a single cell of the same size laminated in the plane of the glass produced 33 mW at the noon condition. This was equal to the most power produced by any of the edge-mount designs tested (Design 2 with white background). An additional design was considered of a “staircase” pattern using multiple non-overlapping laser pattern layers to avoid internal shading. However, this approach likewise did not yield sufficient light scattering, with less than 1% decrease in visible glass transmittance caused by the pattern. Optical measurements of a solid pattern (200 dpi, 6 layers) were also taken in an attempt to explain the relatively low power levels shown in Table 2. For this case, the visible glass transmittance decreased by 4.5%, while the total visible glass reflectance stayed about the same. There was a change in diffuse reflectance as well as an increase in diffuse transmittance (haze), but these effects would not couple light into the plane of the glass. Only the reduction in total transmittance (4.5%) could couple into the plane of the glass. Since the pattern does not direct the light in a particular direction, this would result in (at most) half of the light reaching the desired edge if the pattern were close to that edge. For a pattern that is further away, this amount would decrease according to distance and width of the edge.

The maximum power at noon in Table 2 is 33 mW (Design 2). Power measurements made in this work were taken at a consistent 1100-watt output power level on the Solar Simulator. It was determined that the light intensity at the location of sample measurement was slightly less than 0.5 sun (about 486 W/m²). For a whole window power estimate, a 5 foot wide by 6 foot high IGU was used for a typical commercial size. It was determined that only fourteen 4” cells could be used across the 60 inch bottom span due to spacing requirements. Thus, power generation would be slightly less than 1 watt at noon for the entire window. It is assumed that the cost to produce and wire this type of window would far exceed the value that 1 watt would bring, and therefore this approach was deemed to be not feasible.

An alternate approach was considered for power generation that does not involve the patterning of the front glass. This idea is to make a “PV spacer,” which would allow for solar cell integration on the entire top surface of the bottom IGU spacer. This idea seems to have manufacturing advantages over the mounting of solar cells on the bottom of the glass. Also, any light that is redirected inside the IGU only needs to travel through air rather than glass to reach the cell (much less absorption). A prototype of this configuration was built as shown in the pictures in Figure 25, in which thick foam tape was used as the spacer material. Power measurements were made for the prototype shown in Figure 25, which used one of the 4” by 5/16” polycrystalline Si cells. With a black background, the cell produced 39 mW of power at the noon condition, which is more than any of the edge mounted designs tested. Several geometries of white surfaces on the front side of the rear glass pane (i.e., inside the IGU) were tested to evaluate light scattering within the IGU in order to increase the cell power output at the noon condition. With a 1/2” white frame, the power was 42 mW, for a 1” white frame, the power was 47 mW, and for a solid white, the power was 49 mW. It seems that a 1” margin of white frit on the glass would be possible to make and still allow the unit to be perceived as a window with minimal obstruction. However, the total noon power estimate for a whole 5 ft by 6 ft window is only about 1.5 watts for a black background and 1.8 watts for a 1” white frame.

Figure 25. Prototype of IGU with a “PV spacer.”

Figure 26(a) no features

Figure 26(b) white backsheet

Figure 26(c) laser pattern

Figure 26. Single-cell “modules” with features for light redirection.

In an effort to generate a greater amount of power per window (so as to make the approach economically viable), work was initiated to study larger area cells in the plane of the glass. Single-cell modules were made using 5” (125mm x 125mm) monocrystalline silicon cells and 8” x 8” (6 mm) glass plates. Several approaches to increase the power output of the cells by directing more light to them are shown in Figure 26. The module shown in Figure 26(a) is an example of no features for light redirection. The module shown in Figure 26(b) has a white PV backsheet inside the glass laminate between the cell and the back glass. The module shown in Figure 26(c) is an example of a 2” x 5” laser-scribed pattern in one of the glass sheets (visible in the top portion of the photograph).

The effect of the white backsheet in the laminate is 10 to 15% higher current than no feature. This improvement range is similar for peak power (P_m) at normal incidence as well as P_m and I_{sc} at noon and 10AM conditions. The improvement is slightly lower for 8 AM conditions, with an average of 7% improvement in current and 9% improvement in power. The use of a white backsheet may also have aesthetic advantages, particularly from the building interior. The addition of laser-induced patterns, such as shown in Figure 26(c), resulted in no measurable benefit in power production.

Additional work was done on single-cell modules using 5” (125mm x 125mm) monocrystalline silicon cells and white backsheets using the sample shown in Figure 26(b). Various areas of the module were shaded (masked) and the resulting power values are shown in Table 6. These data confirm the power increase due to the white backing and show as expected that limiting the amount of white around the cell affects the power output. Due to the arrangement of multiple cells adjacent to each other as anticipated for the prototype, the net effect of power boost is expected to be less than the full 10%.

Table 6. Summary of results for single-cell module with various illumination patterns.

Illuminated area	I_{sc} (mA)	
All	2,577	} Effect of white = 244 mA (10% boost)
Cell only (all white masked)	2,333	
Cell & white above (white on sides & bottom masked)	2,425	
White only (cell masked)	207	

Another approach investigated for directing additional light to the in-plane solar cells utilized the holographic film technology from Prism Solar Technologies, Inc. Prism Solar fabricated a series of mini-modules each with two pieces of 6mm STARPHIRE low iron glass. The mini-modules used either full size or 25mm wide monofacial or bifacial solar cells. Samples of these four types were fabricated both with and without strips of holographic planar concentrator (HPC) film adjacent to the cells. Measured power generation is angle dependent, but for the case of full size (5”) monofacial solar cells, the HPC film boosted the power by less than 10%. The greatest power boost was found for the case of 25 mm bifacial strip cells (3 cells and 4 strips of HPC film), with the improvement ranging from 13% to 50%, depending

on lighting geometry. The total area of HPC film in this configuration; however, was greater than the total cell area, which would result in a lower total power per given area compared to just using solar cells. Given the limited area for power production for a glazing unit with a vision area section and the vertical angle of the application, the HPC approach does not appear optimal for BIPV glazing at this time.

Task 3

The statement of project objectives was as follows for Task 3:

Task 3.0 Dynamic Optic subcomponent improvement

The methods and materials for fabrication of the DO subcomponent will be investigated with a goal of identifying an approach for a DO having improved optical and IRR performance and lower cost. Expected outcomes for this activity include technical data for an improved DO and identification of paths for cost reduction (e.g., materials and process improvements).

Subtask 3.1 DO subcomponent performance improvements

Investigate materials for asymmetric transmission / reflection behavior and higher extinction ratio for improved illumination and heat flux control functionality.

Subtask 3.2 DO subcomponent cost reduction

Investigate materials and methods for fabrication of the DO and identify paths for cost reduction of this subcomponent.

Task 3 was completed under subcontract by Ravenbrick LLC.

A key area of focus for this task (Task 3.1) is development of a new polarizer that is optically specular in the transmissive state and optically diffuse in the reflective state. This is expected to be more aesthetically pleasing while also increasing the power output from the PV subcomponent. In Q4 of 2009 a diffractive-type polarizer was investigated. While the polarizer worked, it was successful only in polarizing reflected light and then only at small angles. In addition, the usefulness of Cholesteric Liquid Crystal Polarizers (CLCPs) was investigated for use in thermoreflective filters in the DO subcomponent. These polarizers have four distinct advantages: they are diffusive in reflection, specular in transmission, and can be adjusted fairly easily to block or transmit particular wavelengths of light, thus producing any desired tint in either or both of the transparent and reflective states. Finally, the bandwidth of these polarizers can be extended into the infrared with relatively little effort, as compared to other reflective polarizer technologies. Unfortunately, they are circular rather than linear polarizers, which again create significant off-axis color effects that cannot be corrected through a simple adjustment to the pre-tilt angle. Rather, this polarizer type appears to demand a different type of LC cell, called a “pi” cell, and/or a fairly intricate series of birefringence compensation films.

The construction of a dynamic component in which the transmission of the light is specular in the off-state, and the reflection is diffusive in the on-state was further pursued. Suitable Cholesteric Liquid Crystal Polarizers (CLCPs) for construction of a prototype filter were acquired by PPG and transferred to our subcontractor (Ravenbrick, LLC) to fabricate a prototype dynamic component. A dynamic optical component in which the transmission of light is specular in the off-state, and the reflection is diffusive in the on-state was demonstrated. Although this component displays excellent spectral band selectivity with thermochromic behavior in the important 600-900 nm range, the contrast ratio of reflectivity between the hot and cold states for these filters is low (1.3:1, see Task 2). Additional work (outside the scope of this exploratory project) would be needed to produce a component with acceptable contrast ratio.

It was determined that modifications can be made to the assembly process to reduce the cost of the glazing system. The original approach utilized high-cost materials, was time consuming, and exhibited high yield losses. The work in Subtask 3.2 was successful in addressing costs in each of these areas.

The DO subcomponent consists of a liquid crystal (LC) layer, a LC alignment layer, two polarizer layers, adhesives to bond the structure together and a hardcoat and sealing gasket for durability. To further extend the life of the unit, the adhesive chosen also provides UV-blocking to reduced damage to the LC. Two different adhesives with UV-blocking functionality were identified and coating tests on polarizer layers were conducted. It was found that the application process for thin adhesive coats is sensitive to the presence of particulates due to the hardness of the adhesive. A manual process was developed for the coating of pressure sensitive adhesives onto polarizers.

A major increase in cost occurs when processing of contaminated or damaged films or alignment layers continues without the damage being detected. Seven inspection approaches were investigated to identify damaged films so that they can be removed from the fabrication process immediately after the damage occurs. During this investigation it was found that buffing of the hardcoat cleaned the part such that uniformity and yield is improved regardless of the inspection result. Thus, while some inspection is deemed necessary, especially before the alignment layer is added, this step greatly improves the yield resulting in a reduced cost of fabrication.

Substantial cost was incurred with the original gasketing system for sealing the edges of the DO unit. A number of new gasket designs and gasket adhesives were tested with a goal of reducing the cost of sealing the DO unit. The most durable was found to be a Loctite 4307 gasket with stiffeners, which has survived more than 1800 hours of perpendicular sunlight at 75 °C and more than 60 ASTM-compliant thermal cycles. This is not as manufacturable as some other gasket designs that were evaluated, but with a proper mercury lamp curing system it requires only about 10 minutes of extra process time per filter, and 5 minutes of curing time, and so is considerably more manufacturable than the gasket initially in the design.

Three new film types for improvement of the performance of the DO filter were investigated. As a result of this work, a “universal overcoat” formulation was found that provides good heat and chemical resistance, makes a good alignment layer for the LC, bonds strongly to the standard polymers used in the current polarizers, and can be easily processed to yield a LC pretilt angle small enough to eliminate significant off-angle color shifts. This is also significant because it permits the choice of polarizer material to be changed without significant impact on the rest of the process. This hardcoat was applied to polarizer materials and subjected to accelerated environmental testing. Issues such as circular pits in the hardcoat and outgassing leading to bubble formation were identified and studied.

A number of slip-free hardcoats have been evaluated for chemical resistance, liquid crystal pretilt angle, and ability to form an alignment layer through rubbing. A number of candidates have been found from both Bekaert Specialty Films and Sartomer. Unfortunately, adhesion to the TAC (triacetyl cellulose) substrate has been moderate significantly poorer than for the previous hardcoats, such that the gaskets are now significantly stronger than the surface on which they’re sitting. As a result, there is a new failure mode in some filter stacks wherein shear stress on the edge gasket peels the hardcoat off the TAC. One approach is to work with suppliers to improve this adhesion. Another approach is the evaluation of filter designs that do not rely on the hardcoat as a structural component. Rather, the hardcoat forms a chemical barrier to prevent the LC from interacting with the TAC surface of the polarizer, but the edge gasket is adhered to the TAC substrate and not to the hardcoat. This involves stripping the hardcoat off from the edge prior to gasketing -- a process that adds approximately five minutes to the time required to produce a filter. This is a workaround that should not be necessary in the long term, but may facilitate a Version 1.0 product in the (unlikely) case that a suitable hardcoat solution is not found.

New materials for a hardcoat alignment layer and gasketing were developed for the DO subcomponent. Further, a DO subcomponent assembly process was developed that is expected to increase the yield. Because of progress in these areas, it is expected that the necessary reduction in cost will be achieved. The primary purpose of the Subtask 3.2 milestone was a determination of whether a path forward exists for a reduction in cost of the DO subcomponent. With this determination, Subtask 3.2 is complete and that milestone achieved.

To summarize, materials and process improvements have been investigated and a path forward identified for achieving the performance and cost reductions needed to demonstrate feasibility. Additional development and engineering is needed for commercialization.

Task 4

The statement of project objectives was as follows for Task 4:

Task 4.0 Glazing system design and feasibility demonstration

Utilizing the data from Task 2.0 – Task 3.0, a design for the glazing system integrating the three functions will be developed using industry standard modeling tools. Small area subcomponents will be produced based on the design specifications and prototypes fabricated. The performance of these units will be measured relative to the three desired functions. This data will be used in modeling of a commercial building to evaluate the impact of the energy usage. The expected outcomes for this activity will include one or more designs and small prototypes that indicate feasibility of this approach.

Subtask 4.1 Glazing system design and modeling

Utilizing the Optics/Windows/Therm suite of tools from LBNL one or more glazing systems that integrate the illumination and energy flux control and energy production functions will be designed. Successful completion of this activity will be a Critical Milestone and will be a “Go/No Go” decision point before proceeding with prototype fabrication.

Subtask 4.2 Small area prototype fabrication

Utilizing the specifications developed in Subtask 4.1, fabricate the subcomponents and prototype unit for that design.

Subtask 4.3 Feasibility demonstration

Measure and characterize the prototype unit(s) and model overall expected energy performance in a building using the EERE EnergyPlus tool to demonstrate feasibility. Successful completion of this activity will be a Critical Milestone. A “Go/No Go” recommendation for Phase 2 funding will be delivered.

The design for the prototype glazing system incorporates the dynamic optic and power generation functions discussed in Task 2. The layout of the glazing design is shown in Figure 27. The front glass is high transmittance low-iron STARPHIRE glass to allow the most light to reach the solar cells. The encapsulation layer used was polyvinyl butyral (PVB). Behind the cells is a white PV backsheet as discussed in Task 2. There is a PET separator layer (10 mil) between the PVB and the Pleotint material, as suggested by Pleotint. The design uses 6mm glass, as that is a common thickness of glass for commercial glazing in the United States.

Figure 27. Cross section representation of glazing system design (not to scale).

Three of the most important figures of merit for a glazing system design are the U-value (resistance to heat flow), Tvis (visible light transmittance), and SHGC (solar heat gain coefficient, the fraction of incident

solar radiation admitted through a window). These values are often given as “center of glass” (COG) values, which are valid for the center of the glazing, and do not take into account the frame of the window or the edge portion of the glazing (within 2.5 inches of the frame). The complete energy modeling of the glazing system design cross section shown in Figure 27 is not straightforward using the industry standard Optics / Window / Therm suite of software modeling tools from LBNL because that software is not designed to handle e.g., PV cells incorporated into the glazing design or temperature dependent optical characteristics of the various materials.

The COG U-value for the glazing system shown in Figure 27 (with 95% argon gas fill) is calculated as 0.226 BTU/h-ft²-°F, since the PV cells, white backsheet, and PET separator can be ignored for this winter nighttime calculation. This U-value is very good and is a result of the extremely low emissivity of the SOLARBAN® 70XL coating (less than 0.02); the power generation and dynamic optic subcomponents don't affect the U-value. The SOLARBAN® 70XL glass is a spectrally selective solar control glass that provides excellent static IR rejection.

The COG Tvis for the glazing system shown in Figure 27 will be dependent upon the temperature of the Pleotint material. There will be three COG Tvis values – for the area with the cells, for the area with the white backsheet and no cells, and for the vision area – which can be area-weighted for an overall value. However, the Tvis through the vision area is typically of most concern. A sample laminate of the cell area was measured for optical properties and the resulting Tvis for this area is 0.0%. A sample laminate of the white area was measured for optical properties with STARPHIRE as the back glass instead of OPTIBLUE and the resulting Tvis for this area is 0.1%. If this section were measured with OPTIBLUE, the resulting Tvis for this area would be either 0.1% or 0.0%, and can reasonably be ignored (assumed to be 0.0%). The vision area of the glazing was determined with the Optics and Window software to have a Tvis of 36.5% at room temperature and 8.4% at 149 °F (65 °C).

As noted above, the COG SHGC for the glazing system shown in Figure 27 is not something that can be properly calculated using the current versions of Optics and Window. These programs use temperature as an independent variable and currently have no functionality to handle optical properties that change with temperature. The SHGC calculation uses a predetermined set of environmental conditions, and the resulting temperature of the thermochromic layer under those conditions is not known. Using optical data collected for the Pleotint material at 149 °F (65 °C), Window calculates a SHGC of 0.127 for the vision area of Figure 27. While the accuracy of this number is unknown due to an uncertain temperature of the Pleotint thermochromic material, this does give some estimate of the solar control ability of this glazing design.

A summary of the modeled or estimated figures of merit for the glazing system design are shown in Table 7. Also shown in Table 7 are other designs for comparison. The SHGC for the area of PV cells was estimated by increasing the reflectance spectra as a way to account for the power production of the cells (and thus an energy loss to the system).

Table 7. Center of glass (COG) values for prototype glazing system design and reference designs (95% argon gas fill; reference Figure 27 for glass thickness and color).

	IGU width, inches	U-val	Tvis	SHGC	
				position of SB70XL in gap:	
Prototype Design (ref Figure 27, which has SB70XL on interior side)				exterior	interior
area of cells	1.30	0.226	0.0%	n/a	0.059
area of white	1.30	0.226	0.0%	n/a	0.053
area of vision with Pleotint SRT - room temp (77 °F)	1.30	0.226	36.5%	0.193*	0.247*
area of vision with Pleotint SRT - 149 °F	1.30	0.226	8.4%	0.105**	0.127**
Reference Design 1: laminated outer lite, no SRT (120 mil PVB total)	1.29	0.227	45.8%	0.227	0.296
Reference Design 2: typical laminated outer lite (30 mil PVB total)	1.20	0.231	45.9%	0.223	0.295
Reference Design 3: Lami: Optiblu—Pleotint SRT—Clear – room temp	1.21	0.230	35.8%	---	0.239*
149 °F	1.21	0.230	8.2%	---	0.119**
Reference Design 4: no laminate; monolithic OPTIBLUE as outer lite	0.95	0.235	46.3%	0.221	0.299

n/a = Optics would not allow modeling addition of coating to a measured laminate.

* = SHGC for thermochromic material at room temperature is not a valid number, but might give some indication of instantaneous solar control performance when glazing has not heated up from the sun.

** = SHGC for thermochromic material at 149 °F is not completely accurate, as the material temperature is not known under steady state SHGC environmental conditions.

Additional thermochromic property estimation and modeling is beyond the scope of this project (DE-EE0001332). However, due to the issues with properly modeling thermochromic materials with the current versions of the industry standard software, PPG has initiated discussions with LBNL on this topic. The major goals that need to be achieved to overcome the hurdles currently hindering thermochromic windows from entering the market are to develop the proper dynamic glazing performance measurement protocol, develop a new version of the International Glazing Database (IGDB), create a procedure for providing thermochromic data for entry into the IGDB, and create updated versions of energy simulation tools to support data from dynamic glazing (i.e., Optics and Window).

Two 24" x 48" prototype IGU were constructed for this project: one unit with the Pleotint SRT material (Dynamic Prototype) and a reference unit that did not use the Pleotint SRT material (Static Prototype). The reference unit used another layer of 30-mil PVB instead of the SRT layer (for a total of 120 mil PVB), and it did not need the PET separator. Both units used eight 5" (125mm) monocrystalline silicon solar cells arranged in electrical series in two rows of four cells along one edge (top or bottom) of the units. Thermocouples were added inside the laminates as well as inside the IGUs to monitor temperatures during outdoor exposure conditions. While the lamination of the two prototype laminates did result in some cell breakage, the units are still functioning and valid measurements can be made. The placement of a thermocouple behind one cell in each laminate caused some cell breakage despite the prior success of laminating a single cell test laminate with a thermocouple. A custom tilting frame was designed, fabricated, and attached to a wheeled cart for the outdoor measurements of these two units, and the incline tilting mechanism of this cart frame allows for the positioning of the units in 5 degree increments. The instrumentation and measurement system developed for these prototypes allowed for the collection of the following information shown in Table 8. The completed prototypes mounted on the cart with the instrumentation system is shown in Figure 28.

Table 8. Instrumentation and measurement system developed for outdoor prototype evaluation.

Computer controlled data acquisition with custom LabVIEW program¹:	
Full I-V curve trace of 8-cell string in Dynamic Prototype	every 22-23 seconds
Full I-V curve trace of 8-cell string in Static Prototype	every 22-23 seconds
25 temperature channels ²	every 11-12 seconds
Autonomous instrument data collection³:	
Light meter reading (Si response) – direct	every 10 seconds
Light meter reading (Si response) – behind Dynamic Prototype	every 10 seconds
Light meter reading (Si response) – behind Static Prototype	every 15 minutes
Handheld instrument readings:	
Front glass temperature in front of each individual solar cell with infrared (IR) thermometer ⁴	several times per measurement day
Light meter reading (visible photopic response) ⁵ – direct, behind Dynamic Prototype, and behind Static Prototype	several times per measurement day

¹A Keithley 2701 DMM data acquisition system was used to measure all temperatures every measurement cycle. A Keithley 2440 SourceMeter was used to measure full I-V curves on alternating measurement cycles (via alternating front and rear terminal connections).

²Temperatures logged include glass area and cell area locations for each prototype: first surface (glass only), laminate, fourth surface, airspace, and sixth surface. Pseudo blackbody and shade temperatures were taken in direct sunlight and behind each prototype as a gauge for sunlight intensity.

³SDL-1 Solar Data Logger (silicon pyranometer) from Micro Circuit Labs.

⁴Fluke 61 Infrared Thermometer.

⁵Photometer/Radiometer PMA 2100 from Solar Light Co with Photopic Detector PMA 2130 (Lux detector).

Figure 28. Two completed prototype units mounted on the customized tilting cart. Static Prototype is on the left; Dynamic Prototype (unit with Pleotint SRT) is on the right. The units in the photograph are in full sun; however, the units had only recently been brought outside and so the Dynamic Prototype has not yet warmed up and therefore does not appear particularly dark.

Outdoor measurements in the Pittsburgh, PA, area were made of the final prototype units. Due to shading issues from the cart structure when the cells were in the down position, the units were mostly tested with the cells in the up position. Most of the measurements were made with the units in a vertical position oriented due South. Measurements were made over the course of several days with a variety of ambient temperature and cloud conditions. The outdoor measurements of the prototypes were made to investigate three areas of interest: dynamic switching performance, PV power generation performance, and any dynamic-PV interaction.

The dynamic performance was assessed in two different ways, both of which confirm that the switchable Pleotint SRT material performs as expected. Figure 29 shows that the Dynamic Prototype darkens as a function of temperature in line with what was expected based on laboratory optical measurements and Optics/Window calculations. A photopic detector light meter was used for the data in Figure 29, which gives a response similar to the human eye response to visible light. It is a photopic visible light metric that is calculated by Optics and Window, as presented as Tvis in Table 7.

Figure 29. Outdoor measurements confirm that Dynamic Prototype darkens as a function of temperature. Measurement noise is higher on days of hazy clouds, shown with smaller markers. To reduce several effects related to the angle of the sun, the metric used is a ratio of visible light values (photopic sensor) taken within a few minutes of each other (Dynamic/Static ratio). Predicted values are based on lab measurements and Window calculation, and predicted estimate is based on additional optical data at intermediate states.

As the second assessment of the dynamic performance, Figure 30 shows the glass area temperatures at the time of peak Dynamic Prototype laminate temperature. Due to constant movement of the sun and clouds, an exact match to the environmental conditions used for the steady state Solar Heat Gain Coefficient (SHGC) calculation is not expected. However, the data do show general agreement with the estimates made in Window6 using data of 149 °F laminate temperature. Namely, warmer first and fourth surface Dynamic temperatures and slightly cooler sixth surface Dynamic temperatures were observed.

Figure 30. Prototype glass area temperatures at the time of peak Dynamic Prototype laminate temperature. Conditions are not exactly the same as those for a standard Solar Heat Gain Coefficient (SHGC) calculation, but the data do show general agreement with the estimates made (warmer first and fourth surface Dynamic temperatures and slightly cooler sixth surface Dynamic temperature).

The photovoltaic power generation of the prototype samples was assessed using the outdoor measurements. A summary of the power generation potential is shown in Table 9. Since PV cells have a certain amount of cell to cell variation, there was a limited amount of cell breakage, and there is only one prototype of each type (Dynamic and Static), the results in Table 9 were used to assess the absolute power generation expected from this technology and not an analysis of the effect of the dynamic optic.

Table 9. Summary of power generation potential based on outdoor measurements. Prototypes units were vertical and facing due South with cells up. Power and energy numbers are DC.

Date	8/22/2011		8/26/2011		8/29/2011		8/31/2011	
Weather Conditions	partly sunny, mixture of clouds and haze		mostly cloudy/hazy in AM; partly sunny in PM		Mostly cloudy and hazy (some sun with haze in PM)		Mostly cloudy and hazy	
angle corrected sun hours for South vertical*	3.21		3.42		3.57		3.68	
expected energy harvest for full sun for 8 matched 2.6 W cells (Wh)	66.8		71.1		74.3		76.5	
data collection time (hours)	6.53		6.82		4.82		6.22	
% of day (angle corrected) that data was collected*	85%		89%		70%		79%	
Prototype	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static
average Pm over data collection time (W)	5.97	5.75	4.96	4.80	5.40	5.13	5.09	4.94
projected energy harvest for full day (Wh)	45.9	44.2	38.0	36.8	37.1	35.3	40.0	38.9
% of full sun expectation	69%	66%	53%	52%	50%	48%	52%	51%

*Correction for cosine loss of sun angle only. Effect of air mass not considered. (Reflection and transmission as a function of angle also not considered for this summary.)

The modules on average have a project energy harvest of 55% of full sun expectation. Partial cloud cover during the four days of measurements was one main factor for this projection being less than 100%. The small amount of cell breakage (corners) may be contributing approximately 10% (absolute) of the reduction. The additional effects of sun angle – namely, air mass, increased reflection and decreased transmission – also contribute to the reduction as do typical module level effects glass, soldering, etc. Power data (Pm) from 8/26/11 was modeled as a function of cell temperature and light levels. Extrapolating to the standard test conditions of 1,000 W/m² and 77 °F resulted in power levels in the 15.5 to 17.7 W range, which is 75 – 85% of the expected 20.8 W for the string of eight 2.6 W cells. This result is also consistent with the above listed reductions from cell breakage, angle, and module effects.

On an annual basis, the location used for these outdoor measurements (near Pittsburgh, PA) receives and average of about 4.25 sun hours on a South facing vertical surface, assuming no clouds or shading. As above, this takes into account the effect of cosine losses due to the angle of the sun, but does not take into account air mass. The amount of angle adjusted sunlight is the highest at the winter solstice at about 7 hours and the lowest at the summer solstice at about 1.5 hours. In reality, clouds are a part of the climate, and significantly reduce the amount of effective sun hours, from 4.25 to perhaps 2 to 2.5 hours on average. Taking into account the reductions from air mass, increased reflection, and decreased transmittance a value of 2 hours of full sun per day will be used for the following estimate. For each 2.6 W (5 inch) PV cell on a South facing vertical surface in Pittsburgh, about 5.2 Wh of energy would be produced on an average day or about 1.9 kWh per year (or 0.73 kWh/yr per rated W). For a typical size commercial window of 5 ft by 6 ft with 20 cells along the top or bottom (two rows of 10), this equates to 38 kWh per year. For a 12 ft by 12 ft office with two such windows, this equates to about 8.7 W of around the clock power. This is a fairly small amount of power considering the energy needs that could be expected in the office (lighting, computing, HVAC), and would be even lower after considering DC line losses, DC to AC conversion, etc.

One of the main goals of fabricating and testing the two prototype units was to determine if there was an interaction between the dynamic optic and the power generation component. Due to cell to cell variation and the small amount of cell breakage, direct comparison of the absolute power levels for the two units is not a valid comparison to determine the effect of the dynamic component on the power generation. The main effect of the dynamic component on the glass area is a change in temperatures and a change in transmittance. As the dynamic material is behind the PV cells, the change in transmittance should not

effect the power generation. However, the warmer airspace in the dynamic unit glass area could cause a warmer airspace in the cell area and therefore a warmer cell temperature resulting in lower cell efficiency and power production. However, the representative data shown in Figure 31 shows that despite a warmer glass area airspace temperature for the Dynamic Prototype, the cell area airspace and cell temperatures were the same for the Dynamic and Static Prototypes. The manually collected IR temperature data of the front glass in front of the each cell also shows no difference between the two prototypes. In an analysis of 23 reading sets over 5 days of measurements, the average of the eight cell cover areas for the Dynamic Prototype was 115.8 °F and for the Static Prototype was 115.8 °F (the same). The averages of these two groups of cells were always within 1.6 °F of each other for any given reading, despite an average range of any set of 8 cells from the same unit of 5.8 °F.

Figure 31. Warmer glass area airspace temperature for the Dynamic Prototype did not result in warmer cell area airspace or cell temperatures.

A detailed analysis of the PV data show that the ratio of short circuit current (I_{sc}) and open circuit voltage (V_{oc}) between the Dynamic and the Static Prototypes does not change as a function of time of day, cell temperatures, or light level. However, the ratio of maximum power (P_m) does change as a function of light level. Further analysis of the I-V curves reveals that the Static Prototype fill factor (FF) changes as a result of a relative increase in series resistance (indicated by V_{oc} slope). This change is not considered to be anything related to the absence of a dynamic optic, and therefore all of the data collected suggests that there is no discernable effect on the power generation component as a result of the dynamic optic component.

EnergyPlus™ version 6.0 was used to conduct a preliminary investigation regarding the expected building energy performance for the technologies considered in this project. EnergyPlus is a very powerful

simulation engine to model building energy performance. COMFEN is a tool by LBNL that uses the EnergyPlus engine and is “an application for comparing the performance of fenestration and façade systems.” The Curtain Wall Example of COMFEN version 3.1.13 was the basis building for the EnergyPlus work done for this project. The “building” consists of a space that is 20 feet by 20 feet and 10 feet high with one exterior South-facing curtain wall surface and 3 interior walls. The full height (10-foot) glazing units in the example project were modified to 7-foot vision glazing units and 3-foot non-vision (spandrel) glazing units. A graphical representation of the building section (taken from COMFEN) is shown in Figure 32. The following default information in COMFEN was used for Environment: HVAC: PSZ, Lighting Load: 1.25 W/m², Equipment Load: 0.75 W/ft², and 0.96 people.

Figure 32. A graphical representation of the building section used for EnergyPlus modeling. The larger glazing units on top are vision area and the smaller glazing units on bottom are non-vision.

As the experimental work for this project has shown, there is no interaction between the Dynamic Optic and the PV components, so the two functions were modeled as separate structures in the building model, with the photovoltaics in the non-vision (spandrel) area. Since COMFEN does not currently handle custom glazing (glass not in the IGDB), thermochromic glazing, or photovoltaic glazing, the EnergyPlus input (IDF) file generated by COMFEN was modified manually with a text editor to add these functions and the EnergyPlus simulations were launched manually from EP-Launch. The simulation timestep was increased from 4 (per hour) to 20 (per hour). Baltimore (BWI TMY3) was selected as the building location (ASHRAE climate zone 4A), as a representation of the “middle” of the country.

The EnergyPlus modeling considered a total of 8 cases. There were two possibilities for each of the following three elements: glazing (static or dynamic), lighting controls (none or continuous), and PV power generation (none or all non-vision glazing area). The following three paragraphs below describe the choices used of these elements followed by a summary of the modeling results in Table 10.

The static glazing used was Reference Design 1 from Table 7, and the dynamic glazing was the vision area of the Prototype Design from Table 7 and seen on the right side of Figure 27. Reference Design 1 was chosen for the static glazing because it was a similar construction to the Prototype Design such that any effect seen would be due to the presence of the Pleotint SRT dynamic element. Reference Design 1 was also the construction of the Static Prototype for this project. (If photovoltaics were not part of the glazing unit design, the dynamic glazing used in practice would likely be more like Reference Design 3 from Table 7 and the static glazing would likely be more like Reference Design 4 from Table 7 (as long as laminated was not otherwise needed). However, as seen in Table 7, the performance values are very similar to the designs that were used for this modeling and therefore the relative outcomes would also be expected to be similar.)

As EnergyPlus simulates the energy loads on a building throughout the year, it determines the angle and intensity of the sunlight on each building surface considering the building location and the weather file for that location. As such, this is a convenient platform to estimate photovoltaic system output. One of the PV estimation methods available in EnergyPlus is the Sandia National Labs model, which takes into account the temperature of the cells. There are numerous PV modules with SNL model data available for use in EnergyPlus and the one selected for this work was the SunPower_SPR-220_CS module. This module has a high module efficiency of 17.9% and a size of 13.4 ft², which is a fairly good match to the approximately 15 ft² non-vision area glazing unit size being used. EnergyPlus uses the power generated as an energy sink when doing the heat balance calculations and ties in the cell temperature to the building surface for a more accurate prediction of power generation. Four modules in series were used for the cases with PV power generation, and an inverter efficiency of 89% was used (with no additional system losses). The array of four 220 watt modules has a total rated power of 880 watts. Using the back of the envelope estimate for Pittsburgh above (second paragraph below Table 9) of 0.73 kWh/yr per rated W, the quick estimate would be for 642 kWh (2.31 GJ) per year, which is fairly close to the EnergyPlus modeling for Baltimore of 2.74 GJ. For the cases without PV power generation, the same glazing structure was used with a simple PV model and 0% efficiency to represent no PV device.

Table 10. Summary of EnergyPlus modeling results for an annual simulation of a curtain wall in Baltimore.

case	1	2	3	4	5	6	7	8
glazing	static	static	static	static	dynamic	dynamic	dynamic	dynamic
light controls (continuous)	no	no	yes	yes	no	no	yes	yes
PV	no	yes	no	yes	no	yes	no	yes
Window Heat Gain (GJ)	11.74	11.74	11.67	11.67	8.15	8.15	8.12	8.12
	100%	100%	99%	99%	69%	69%	69%	69%
Electricity [GJ] used for								
Lights	6.95	6.95	3.09	3.09	6.95	6.95	3.44	3.44
Cooling Coil	6.51	6.51	5.12	5.12	5.20	5.20	4.09	4.09
Fans	2.80	2.80	2.25	2.25	2.22	2.22	1.93	1.93
Equipment (constant)	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08
Electricity [GJ] made by PV	0.00	2.74	0.00	2.74	0.00	2.74	0.00	2.74
Net electricity (3.18 site-to-source multiplier)								
site	20.34	17.60	14.54	11.80	18.45	15.71	13.55	10.81
source	64.67	55.96	46.24	37.53	58.68	49.97	43.08	34.37
Gas [GJ] for Heating	0.41	0.41	0.50	0.50	0.48	0.48	0.58	0.58
Net energy (source elec + gas)	65.08	56.37	46.74	38.03	59.16	50.45	43.65	34.94
	100%	87%	72%	58%	91%	78%	67%	54%

As can be seen in Table 10, each of the three elements (dynamic glazing, lighting controls, and photovoltaics) reduce the net energy consumed by the building. The PV power generation is independent of the other elements, whereas the dynamic glazing and lighting controls have a small negative

interaction (diminishing returns when used together). However, the same building structure was used for all 8 cases and it was not optimized for any particular use of any of these technologies. Much greater value for the dynamic glazing can be realized if the building were designed to take advantage of its performance properties.

The simple model used is also a limitation when analyzing these results. For example, the cases with static glazing likely have too much light entering the building during the day. In reality, the building occupants would block out the windows with blinds or shades and keep the interior lights on. However, much of the solar energy that is blocked by the blinds or shades will remain inside the building and along with the heat from the interior lights will need to be removed by the buildings cooling system.

The optical data used for the dynamic glazing element was based on Optics5 constructions at the seven temperatures shown in Figure 5 (25°C to 85°C in 10°C increments). EnergyPlus has the ability to accept additional temperature levels (and the EnergyPlus documentation refers to this as extensible with no mention of a limited number of temperature levels). For this preliminary investigation, only the seven temperature levels based on measured data were used. (If desired, the 7 points at each wavelength could be modeled as a function of temperature to obtain intermediate points and additional spectra which could then be used for additional temperature levels for the thermochromic glazing group in EnergyPlus.) At each timestep, EnergyPlus determines the temperature of the glazing and selects the closest thermochromic property data to use. Both the temperature of the glazing and the specification temperature used are available as outputs from EnergyPlus, with an example day shown in Figure 33.

Figure 33. Thermochromic window temperature for one day, October 16, which had the highest peak thermochromic temperature (72 °C) of the yearlong simulation.

EnergyPlus uses the optical properties at the specification temperature (the nearest temperature with specified data). As seen in Figure 33 after each step in specification temperature, the window responds with a sharp increase in temperature of several degrees (or a decrease in the afternoon). This is because the thermochromic layer is more absorbing at higher temperatures. Ideally, thermochromic spectral data would be added for every one or two degrees C into the EnergyPlus input file, which would result in smoother and more realistic temperature curves. Nevertheless, the preliminary approach taken here with limited data points gives an approximation of performance.

It was noted that the thermochromic layer was hottest on a day in October. Due to the thermochromic layers being on a vertical South facing surface, the peak temperatures on sunny days are in fact lowest in the summer. Figure 34 shows the maximum monthly temperature of the thermochromic windows. Also shown is the average temperature of the windows including nighttime, which is more related to average ambient temperatures and helps explain why the autumn is the time of year with highest peak thermochromic temperatures. Subtracting the monthly maximum from monthly average gives quite symmetrical results with a minimum of about 24 °C in June and July (summer solstice) and about 54 °C in December and January (winter solstice).

Figure 34. Thermochromic window temperatures: monthly maximum and average.

Finally, it should be noted that the thermochromic window temperatures reported above depend strongly on the outside convection algorithm used for the EnergyPlus simulation. The surface convection algorithm for the outside used by COMFEN was “SimpleCombined.” This algorithm uses a combined heat transfer coefficient that includes radiation, and results in simulation results in which the thermochromic layer does not get particularly hot (for example case 5 would have a peak thermochromic temperature of 56 °C on October 16). The modeling for the results presented above use the “DOE-2” surface convection algorithm for the outside. The DOE-2 method uses convection only heat transfer coefficients derived from field measurements and radiation heat transfer coefficients calculated automatically by the program. The EnergyPlus documentation contains detailed information on these algorithms. There are other advanced algorithms (TARP, MoWiTT, and AdaptiveConvectionAlgorithm) in

addition to DOE-2 that are available for use with EnergyPlus. While a detailed study of these other algorithms and the effect on predicted thermochromic window temperature was not undertaken under the scope of this project, this would likely be an important topic for further work (combined with thermochromic data at additional temperatures as described above).

Conclusion

This project investigated a wide variety of approaches for a dynamic BIPV glazing. Directing light from the face of the unit to PV cells at the edge was found to be possible to a limited extent, but the power that could be generated was too low for practical applications. The best approach was found to be positioning of large-area solar cells behind a front glass pane (similar to a conventional PV module) in a nonvision area. Dynamic glazing works to improve energy performance of commercial buildings, and BIPV glazing can generate power onsite and reduce the amount of electricity purchased from the grid. A prototype design and a prototype unit were created in order to study these effects and any interaction. The design chosen in Task 4 did not show any interaction between the dynamic element and the PV element. The advantage to an integrated approach occurs if such an interaction is present and can increase performance to the extent that the added cost of integration is overcome. Therefore, considering the required manufacturing processes, these two elements are likely to be better suited and optimized when fabricated as separate components. Both dynamic glazing and BIPV glazing can be used in commercial buildings, but this project did not find a combination of the two into a single unit that appears worthwhile for continued study. Therefore, the recommendation is a “No Go” for phase 2 funding.