Low-Cost, High-Performance Electrochromic (EC) devices

Polyceed, Inc.

Anoop Agrawal, CTO, anoop@dyenamics.com

Project Summary

Timeline:

Start date: July 1, 2019

Planned end date: September 30, 2022

Key Milestones:

1. **June 30, 2020**: Show min. contrast ratio of dye/WO3 device and dye durability to 500 hours under ASTM E2141 environmental conditions;
2. **June 30, 2021**: Show device with WO3/Dye durability to 500 hours under ASTM E2141 environmental conditions

Key Partners:

NREL	DOE partnership
Confidential Chemical Company	Film supplier
Confidential Glass Company 1	Glass supplier
Confidential Glass Company 2	Manufacturing partner
Confidential Window Company 1	Commercial partner
Manufacturing Consultant	Process manufacturing and costing

Project Budget:

To Date (June 30, 2021):

- DOE: $1,417,013
- Cost Share: $416,865

Total Project:

- DOE: $1,500,000
- Cost Share: $384,686

Project Outcome:

- Demonstrate the durability of low cost, custom colored dynamic glass that combines the benefits of inorganic and organic EC materials.

Team

Polyceed

Anoop Agrawal (CTO & DOE Program PI): *Technical and Project Development*

- Automobile auto-dimming mirror co-inventor; 30 years of experience in EC product development, co-inventor of about 100 electrochromic related Patents; early consultant to numerous leading commercialized EC technologies

John Cronin (VP Product Development): *Product Development, Laboratory Leadership*

- Automobile auto-dimming mirror co-inventor; co-inventor of about 70 Patents and ~20 peer reviewed publications related to electrochromic technology; early consultant to numerous leading commercialized EC technologies

Christopher Angelo (CEO): *Commercial and Project Development*

- Background in banking, infrastructure and climate tech investing; CFO solar silicon/cell manufacturing and commercialization; advisor @ New Energy Risk, Sila Nanotechnologies, UrbanX Renewables

NREL

- C. Engtrakul (Ph.D.) – Senior Scientist - NREL
  - Extensive experience in the fundamental EC and nanostructured carbon materials science
- Zbyslaw Owczarczyk (Ph.D.) – Senior Scientist - NREL
  - 30 years of experience in synthetic organic, organometallic & polymer chemistry, OLED and organic solar cells
- Robert Tenent (Ph.D.) - NREL
  - Responsible for NREL windows research program; conducted research numerous emerging fenestration technologies

Challenge

Dynamic Glass represents the next frontier in glass energy efficiency with up to 20% building energy savings and an enormous $8B market opportunity; however, dynamic glass has been commercial since 2010 yet represents only 0.02% of the market.

Existing Solutions' Problem: Cost & Color

- *Cost:* Production costs are currently 10-20x traditional energy efficient Low-E glass such that the glass can't be mass produced in the residential and commercial markets at a sustainable profit; and
- *Color:* Customers are unable to specify and select dynamic glass with independent external reflected and internal transmitted colors comparable to market-accepted static glass alternatives.

Polyceed's Solution:

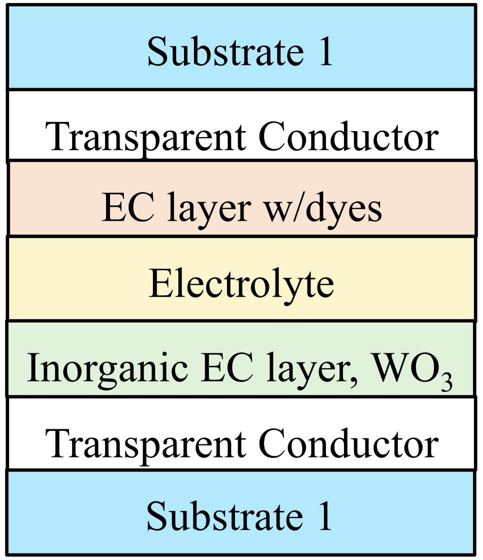
- *Cost:* Polyceed's vastly simplified dynamic glass solution reduces smart glass production and capital costs by 75% and 95% per sqft, respectively.
- *Color:* Polyceed will be the first and only smart glass company in the world to offer color customization.
  - It will allow customers, for the first time, to specify and select smart glass similar to market-accepted and state-of-the-art static glass alternatives.
  - It will permit buildings with EC windows to maintain a uniform external appearance regardless if the EC glass is clear or tinted.

Approach

Summary:

- Polyceed's technology solution overcomes existing commercial technologies' cost and color challenges through the use of a vastly simplified glass structure including a hybrid organic / inorganic EC device (see below):
    1. An exterior-sun-facing inorganic EC layer and
    2. A novel interior-facing organic EC layer containing a UV-stable dye
- The two electrodes are then laminated with a polymeric electrolyte
- Cost problems further addressed by manufacturing with known low-cost coating and assembly methods

Proposed Device Structure:



Project plan and tasks:

1. Model and synthesize EC dyes
2. Deposit WO_3 and dye layers by wet-chemical process
3. Demonstrate EC layers integration **with no pre-reduction**
4. Demonstrate device assembly with a polymeric electrolyte
5. Enhance UV durability by:
    a) Controlling WO3 composition and microstructure
    b) Using UV-stable dyes compatible with WO_3
    c) Using compatible and electrochemically inactive UV stabilization packages in the EC layer and electrolyte
6. Test devices under ASTM E2141 conditions

Approach

- Risk Management Strategy:
  - Commercialization-minded
  - Don't want to scale a highly complex engineering solution
  - Aligned per project task

Project Task	Risk	Mitigation Strategies
EC dyes modelling and synthesis	1. Modelling methods for predicting properties not known (optical, electrochemical and stability properties) 2. Synthetic challenges not known	1. Modelling focus prioritized 2. Synthetic effort focused on specific chemistries but different functionalization. 3. Synthetic assistance from 3rd parties.
EC layers composition and deposition	1. Coating formulations had components with different sensitivity to dispersion and environment. 2. Dependency with Polyceed's WO3 not known	1. Coating formulations with different curing mechanisms evaluated 2. Cycling and UV durability in test cells established early in the program to evaluate interdependence of dyes and WO3
Demonstration of no pre-reduction	1. This was a core processing feature to obtain low-cost devices	1. No back-up plan was made to circumvent this
Device assembly	1. Composition of laminatable electrolyte films selected based on their adhesion to glass and transparent conductors 2. During the program adhesion to tungsten oxide and the dye layer posed severe challenge	1. Lamination with liquid electrolytic formulations which were polymerized in-situ were evaluated 2. Device structure modified by combining dyes into the electrolyte.
Selection of components and device testing (E2141)	1. A very large number of materials and combinations were to be tested. 2. Improvements required extended testing 3. Covid related restrictions caused equipment unavailability at NREL for more than six months	1. NREL accommodate our testing request by making the entire chamber available to us for almost 9 months. 2. Back to Back testing was initiated with alternate sample batches to use the chamber for almost 100% of the time.

Impact

- Polyceed's technology primarily impacts building HVAC and lighting energy usage:
  - 10% building stock adoption will reduce energy consumption and CO2 production by 142TBtu and 32Mt, respectively
  - Lowers peak-loads

Building Stock Type	Energy Market Size (TBtu)*	Energy Savings, %	Primary Energy Savings (Tbtu)	CO2 Emissions (Mt)	Projection Year
Commercial	2,900	20	580	129	2030
Residential	4,200	20	840	186	2030

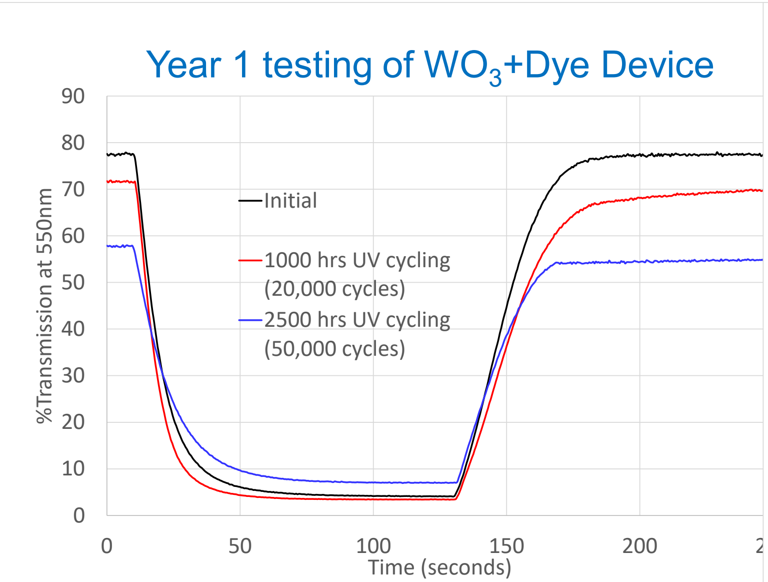
***Based on "BTO Baseline Energy Calculator" for all climates related to HVAC and lighting**

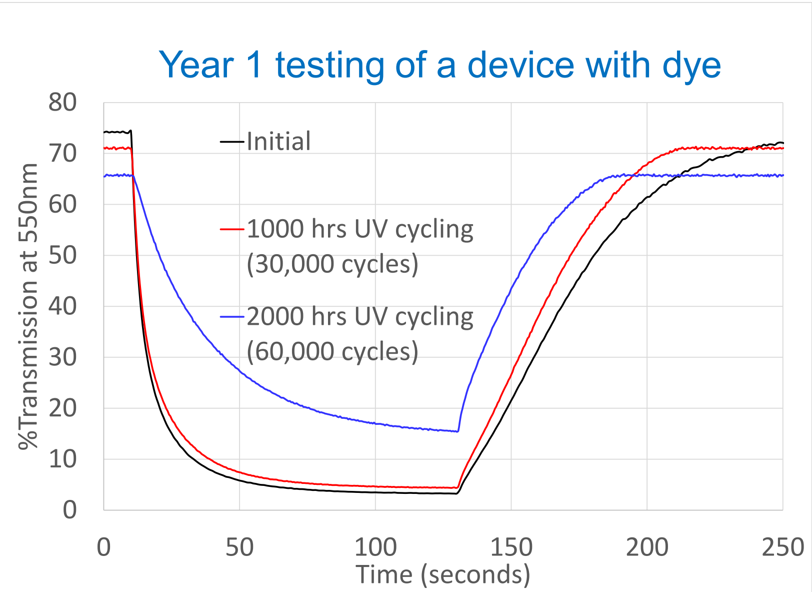
- Building technology office goal alignment:
  - Mass adoption of next generation energy efficient glass to reduce building energy consumption & related CO2 emissions
  - Grid-interactive efficient buildings to optimize grid energy transmission

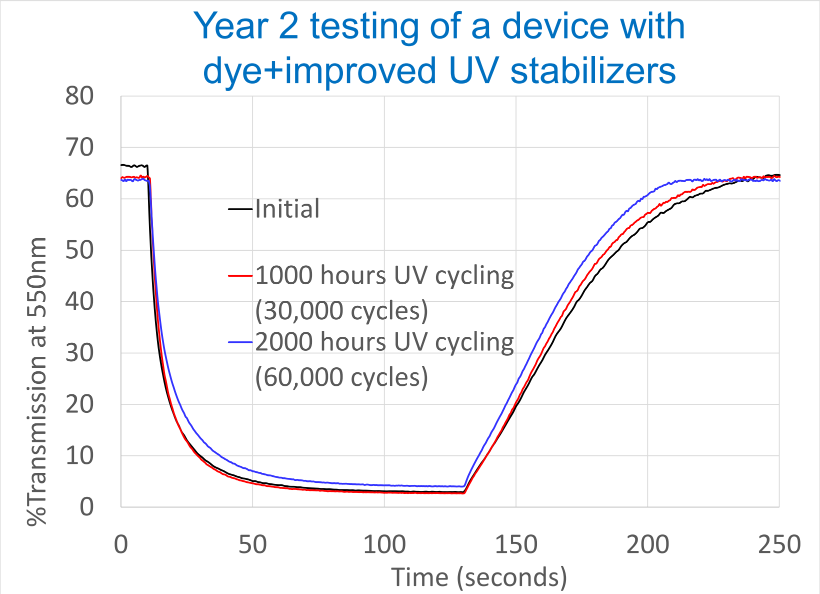
- Comparison to Existing Solutions:
  - Same energy savings, up to 20%, as competing commercial products
  - Although, lower cost and optimized color enhances customer value proposition, and enables mass adoption

Progress

- Project is in *mid*-state
- EC device durability is the most important parameter prior to commercialization
  - Durability tests on individual materials and their interdependence within assembled devices
- Significant development time devoted to material and device UV durability testing
  - 3-4 months evaluation cycles including sample preparation and testing (~1000 hours) *Note: delayed due to Covid*
- <u>Successful</u> device testing up to 60,000 cycles under ASTM E2142 environmental conditions:
  - First known color changing organic EC material to achieve this milestone
  - Program-to-commercial transition ongoing







Progress

- Program Next Steps:
  - Optimize WO3 and UV-stable dye combination with further UV package refinement
  - Final ASTM-E2141 testing

- Program-to-Commercialization Next Steps:
  - Prototyping various sizes, internal and external color combinations, and window applications
  - Partnered with commercial window supplier under JDA to commercially supply by the end of 2022
  - Supported by additional confidential manufacturing and commercial partners

- Budget Scope, Schedule, Budget Status:
  - Program running within expectations to commercialization a product
  - Commercialization imminent despite
    - Cost share increase and no-cost extension due to Covid delays

Stakeholder Engagement

- Project market relevance:
  - Optimized value proposition through consistent engagement with project partners

- Project technology-to-commercial transition:
  - Supported with commercialization checklists, sales strategy review, fenestration testing, and demonstration installations

Company	Summary	Engagement
NREL	DOE partnership	ASTM Testing, dye modelling and synthesis
Confidential chemical Company	Film supplier	Development of electrolyte film and process development
Confidential glass company 1	Glass supplier	Substrate supply, development; EC device testing and selection of low-e for IGU
Confidential glass company 2	Manufacturing and commercial partner	Manufacturability, assessment of capital costs, and product attributes; sales strategy support
Confidential window company 1	Commercial partner	Downstream product attributes, integration, channel market relationships, and distribution
Confidential consultant	Process manufacturing and costing	Detailed manufacturing and product cost model development and analysis

Remaining Project Work

Program Next Steps:

1. Continue hybrid organic/inorganic material and device durability evaluation:
   a) EC dye layer and electrolyte as separate layers
   b) EC dye and electrolyte combined in single layer
2. Scale device size from 10cmx12.5cm up to 20cmx25cm (*ASTM-E2141 test size)*
3. Select materials for final device ASTM-E2141 testing
4. Test devices at NREL under ASTM-E2141 conditions up to 5,000 hours

Commercialization:

Successful device durability testing demonstrates commercialization opportunity:

1. Announcing near-term commercialization
2. Website sales portal in process
3. Filed key device and application patents
4. Partner engagement
   – Providing scaled devices to commercial partners
   – Integrating devices with downstream products and electronics
   – Optimizing future color specification customization

Thank You

Polyceed Inc
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REFERENCE SLIDES

Project Budget

Budget History					
7/1/2019– FY 2020 (past)		FY 2021 (current)		FY 2022 – 9/30/22 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$734,950	$181,195	$682,063	$235,670	$82,987	$250,000 (Est)

Variances:

- Time variance related to longer completion times; scope variance related to the addition of new tasks.
- Variances caused acceleration of expenses in year 2.
- The no-cost extension has caused Polyceed's cost share to exceed the planned amount.

Cost to Date:

- The total program budget including NREL and cost share was $1,884,686, and the total expenses to date are 1,833,878.

Additional Funding:

- Additional funds are over the agreed budget are being provided by Polyceed.
- Polyceed in conversation with DOE to see if additional funds may be available to supplement the program.
- The funds do not include the contributions made by our partners, and
- All program-related equipment expense also contributed by Polyceed investors.

Project Plan and Schedule

		FY 19-20				FY 20-21				FY 21-22				FY 23-24		Comments
Task #	**Task Description**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	
Task 1	***Active EC Coating***									X						**See sub-tasks below**
1.1	Evaluate and select monomers		X													
1.2	Dye selection: modelling, synthesis and testing								X							See Note 1
1.3	Selecting Ingredients & prepartion of coating formulation			X												
1.4	Coating deposition				X											
1.5	Determine coating properties **Go/No-Go decision**				X											
1.6	Demonstrate cyclability of EC cells with these coatings-									X						Delayed due to task 1.2
Task 2	***Fabrication and testing of laminated EC windows***														X	**See sub-tasks below**
2.1	Lamination and sealant process development				X											
2.2	Process devices with extruded electrolyte films															See Note 2
2.3	Test small devices under conditions of ASTM E 2141, **Go/No-Go decision**									X						Delayed due to tasks 1.3, 1.6 and 2.2
2.4	Test IGU against ASTM E2141														X	
Task 3	**Prepare final report for DOE**														X	

original completion **X** Completed by or expected completion

Note 1: Modelling focus changed, Non UV stable dye made in FY19-20-Q4 for task 1.6, one UV stable dye made in FY20-21-Q4

Note 2: Delayed, adhesion issues, explore polymerizable electrolytes, and electrolytes w/dyes

Current and Future work:

1. Evaluate devices with improved WO3, dye layers and UV stabilizers
2. Upon completion of the above, assemble larger devices for final ASTM testing
3. Evaluate tested devices, take corrective actions (if required), and prepare final report