ALBERTA INNOVATES

CLEAN RESOURCES FINAL REPORT PACKAGE

Project proponents are required to submit a Final Report Package, consisting of a Final Public Report and a Final Financial Report. These reports are to be provided under separate cover at the conclusion of projects for review and approval by Alberta Innovates (AI) Clean Resources Division. Proponents will use the two templates that follow to report key results and outcomes achieved during the project and financial details. The information requested in the templates should be considered the minimum necessary to meet AI reporting requirements; proponents are highly encouraged to include other information that may provide additional value, including more detailed appendices. Proponents must work with the AI Project Advisor during preparation of the Final Report Package to ensure submissions are of the highest possible quality and thus reduce the time and effort necessary to address issues that may emerge through the review and approval process.

Final Public Report

The Final Public Report shall outline what the project achieved and provide conclusions and recommendations for further research inquiry or technology development, together with an overview of the performance of the project in terms of process, output, outcomes, and impact measures. The report must delineate all project knowledge and/or technology developed and must be in sufficient detail to permit readers to use or adapt the results for research and analysis purposes and to understand how conclusions were arrived at. It is incumbent upon the proponent to ensure that the Final Public Report **is free of any confidential information or intellectual property requiring protection**. The Final Public Report will be released by Alberta Innovates after the confidentiality period has expired as described in the Investment Agreement.

Final Financial Report

The Final Financial Report shall provide complete and accurate accounting of all project expenditures and contributions over the life of the project pertaining to Alberta Innovates, the proponent, and any project partners. The Final Financial Report will not be publicly released.

Alberta Innovates is governed by FOIP. This means Alberta Innovates can be compelled to disclose the information received under this Application, or other information delivered to Alberta Innovates in relation to a Project, when an access request is made by anyone in the general public.

In the event an access request is received by Alberta Innovates, exceptions to disclosure within FOIP may apply. If an exception to disclosure applies, certain information may be withheld from disclosure. Applicants are encouraged to familiarize themselves with FOIP. Information regarding FOIP can be found at http://www.servicealberta.ca/foip/. Should you have any questions about the collection of this information, you may contact the Manager, Grants Administration Services at 780-450-5551.

CLEAN RESOURCES FINAL PUBLIC REPORT TEMPLATE

1. PROJECT INFORMATION:

Project Title:	**Luminescent Solar Concentrators for Building Integrated Photovoltaics**
Alberta Innovates Project Number:	CTD 2018-054
Submission Date:	March 6, 2024
Total Project Cost:	$1,456,467
Alberta Innovates Funding:	$382,323
AI Project Advisor:	Dr. Paolo Bomben

2. APPLICANT INFORMATION:

Applicant (Organization):	**Applied Quantum Materials Inc.**
Address:	B211, 2011–94 St. Edmonton, AB, Canada, T6N 1H1
Applicant Representative Name:	David Antoniuk
Title:	Chief Executive Officer
Phone Number:	587-635-2060
Email:	dantoniuk@aqmaterials.com

3. PROJECT PARTNERS

Please provide an acknowledgement statement for project partners, if appropriate.

RESPOND BELOW,

We would like to thank All Weather Windows and PCL for their help and contribution to this project.

A. EXECUTIVE SUMMARY

Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.

RESPOND BELOW

In January 2019, Applied Quantum Materials Inc. (AQM) was awarded a grant from Alberta Innovates, under the Climate Change Innovation and Technology Framework (CCITF). The project was to develop Luminescent Solar Concentrators (LSCs) for Building Integrated Photovoltaics. LSCs are photon-management devices designed to manipulate/concentrate incoming sunlight. The sunlight contacts the surface of a material (typically coated glass), and the light is waveguided to the outer edges of the material and harvested by photovoltaic cells. Such a cost-effective approach can be used to enhance stand-alone solar cells by increasing the performance, over a comparably smaller area, while maintaining the same power output. Also, LSC technology allows for the formation of transparent photovoltaic windows that transform energy-passive building fronts into large-area energy generation units.[1,2]

The objectives for the project included five integrated tasks to develop LSCs for Building Integrated Photovoltaics (BIPV). These tasks included the development of near-IR emitting silicon quantum dots (SiQDs), a polymer functionalization of SiQDs, assembly of protypes for LSC waveguiding, coupling our LSC prototype with a photovoltaic (PV) system, and finally, fabricating a functional BIPV system.

Task one was to synthesize the silicon quantum dots (SiQDs). Starting with AQM-synthesized precursors and adjusting our thermal annealing process, we achieved SiQD sizes (ranging from 3-10 nm) with variable photoluminescence (PL) properties (visible to the near-IR range).

---

[1] Meinardi, F.; McDaniel, H.; Carulli, F.; Colombo, A.; Velizhanin, K. A.; Makarov, N. S.; Simonutti, R.; Klimov, V. I.; Brovelli, S. Highly Efficient Large-Area Colourless Luminescent Solar Concentrators Using Heavy-Metal-Free Colloidal Quantum Dots. *Nat. Nanotechnol.* **2015**, *10*, 878–885.

[2] Meinardi, F.; Colombo, A.; Velizhanin, K. A.; Simonutti, R.; Lorenzon, M.; Beverina, L.; Viswanatha, R.; Klimov, V. I.; Brovelli, S. Large-Area Luminescent Solar Concentrators Based on Stokes-Shift-Engineered Nanocrystals in a Mass-Polymerized PMMA Matrix. *Nat. Photonics* **2014**, *8*, 392–399.

Task two was to functionalize the SiQDs with an organic substituent (SiQDs@Organic) and/or polymer moieties (SiQDs@Polymer or SiQDs@co-Polymer) to enhance stability and surface compatibility. Post functionalizing, the SiQDs maintained their size-dependent emissions (quantum confinement phenomenon) with the emission maximum (PL_{max}) increasing with size. To determine the appropriate emission maximum (PL_{max}), we would compare our SiQDs emission maximum (PL_{max}) to the absorption spectrum of current c-Si PV systems. Our study determined the intermediate sized SiQDs provided the appropriate PL_{max} wavelength (*ca.* 800-900 nm), emit the brightest, and show the strongest PL response. In addition, quantum yield measurement of our SiQDs were acquired. The quantum yield (referred to as PLQY and/or QY) is a measure of the efficiency of photon emission as defined by the ratio of the number of photons emitted to the number of photons absorbed. The PLQY, for SiQDs, can depend on three factors: QD size, QDs surface capping agent, and the method used for functionalizing QDs. In summary, by increasing the QDs size, the wavelength for the PL moves to a lower energy region, and the PLQY is expected to increase. Also, the functionalization method by introducing and/or reducing surface defects can alter the PLQY. The target of the synthesized SiQDs should show a PLQY around 70%, which is an exceptional number for an indirect band-gap semiconductor (silicon). Currently, the SiQDs@Organic, depending on their surface chemistry, have QY around 30-45%. However, we are using a new SiQDs@co-Polymer, which shows 40-53% PLQY. Our plan is to further increase to a PLQY of about 68-73%.

The third task was to design and develop usable protypes for LSC waveguiding. Extensive experimental investigation was dedicated to uniformly coating SiQDs on LSC glass-slides. Application using solvent-based dispersion of SiQDs@Organic was viewed to be the most straightforward. Applying the solvent-based dispersion of SiQDs@Organic with an airbrush (or similar spray) was unsuccessful due to the overall quality and stability of the final films. Combining the SiQDs with acrylate-based polymers (SiQD@Polymers) is remarkably well-matched as acrylate-based polymers enhance clarity in the visible and NIR region and significantly long lifetime.[3, 4] Furthermore, the acrylate-based polymers act as surface passivating agent for SiQDs increasing the stability and quality of the films.

The addition of a concentrated SiQDs@Polymer solution by regular air-brush spray was not successful. The unsuccessful result is due to the technique of applying the solution and not the material. Other ways of coating the glass needed to be explored. Alternative options for coating are drop casting or the ultrasonic automated spray setup from All-Weather Windows®. Drop casting showed a noticeable increase in the stability for the coatings. However, over time, the coatings began to lift and crack in some areas of the glass. Drop casting had another issue, as the final formulations were quite viscous and could

---

[3] Hill, S.; Connell, R.; Peterson, C.; Hollinger, J.; Hillmyer, M. A.; Kortshagen, U. R.; Ferry, V. E. Silicon Quantum Dot - Poly(Methyl Methacrylate) Nanocomposites with Reduced Light Scattering for Luminescent Solar Concentrators. *ACS Photonics* **2018**, *6*, 170–180.

[4] Srinivasan, S.; Chhatre, S. S.; Mabry, J. M.; Cohen, R. E.; McKinley, G. H. Solution Spraying of Poly(Methyl Methacrylate) Blends to Fabricate Microtextured, Superoleophobic Surfaces. *Polymer (Guildf).* **2011**, *52*, 3209–3218.

not be used without significant dilution. The lack of transparency and non-uniformity indicated that the solution needed to be diluted and other solvents needed to be investigated.

Applying the results of the drop coating, we focused on using the ultrasonic automated spray setup from All-Weather Windows® for applying films. Initial coatings provided extremely stable and strong films. Clarity was still an issue but was improving. Further experimentation indicated that an adequate mixture of co-polymers and the SiQDs (SiQDs@co-Polymer) would be better to serve as our primary polymer for coating. After the finding of a SiQDs@co-Polymer, the team investigated numerous factors to enhance the protype application. Once the parameters ultrasonic automated spray setup from All-Weather Windows® were optimized, the team conducted dilution studies with SiQDs@co-Polymer. Evidence determined the addition of a secondary solvent improves the solution adhesion to the glass. Also, the clarity and uniformity of the material application had significantly improved. In addition to window applications, these optimized materials and procedures have precedence in other economic areas, such as agriculture, and are currently being explored.

Supplementary to laboratory investigation, AQM was assigned to a model, realize, characterize, and optimize planar LSC structures with Monte Carlo ray-tracing simulations. The work conducted was to predict and optimize the performance of the LSC. Our contractors, Nemsor Technologies Inc., and the University of Alberta Department of Mechanical Engineering, investigated different factors and parameters to perform the simulation identical to our experimental LSC. The optimized results of the simulation tests indicated that our experimental work, once optimized, will be able to reach the desired outcomes for our LSC design.

Lastly, during the testing phase of task four, we proved that our SiQDs can be excited with sunlight to generate an emission spectrum. Although this is a requirement for using SiQDs in any LSC basis application, demonstrating this characteristic (PL of SiQDs under sunlight) is important. Preliminary experiments using our window test frames, unoptimized SiQDs@Polymer coatings, performed positively. The preliminary tests also showed that there are some design flaws with the window frames. Currently, new model window test frames are being fabricated, new SiQDs@co-Polymer pre-coating techniques are being explored, and the project is moving towards the final task and making a fully functioning BIPV.

B. INTRODUCTION

Please provide a narrative introducing the project using the following sub-headings.

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that is being addressed along with the context and scope of the technical problem.

RESPOND BELOW

Sector Introduction

Glass is one of the world's primary building materials. Building glass accounts for 80% of total production including new build and refurbishment. As solar energy markets expand, products such as Luminescent Solar Concentrator (LSC) will replace rooftop solar cells. Market research firm, Freedonia, states that global demand for flat glass will rise 4.1% per annum to nearly 11.9 B m^2 in 2023. Sales of fabricated flat glass are projected to increase $4.7% per annum and be worth US$97.4B. At ~50 W/$m^2$ efficiency, LSC technology coated on 10 M m^2 of glass has the potential to generate ~500 M kWh of renewable power annually by 2025. At $0.10/kWh, this amounts to an energy savings of $50 M annually and 372 kT of CO_2eq removed.

Luminescent Solar Concentrator (LSC) is a novel class of devices that acts by converting the passive glass facades of buildings into distributed energy generation units.[1, 2] The very first concept of LSC has been proposed by Weber and Lambe in 1976 when they called it "a luminescent solar collector".[5] LSCs are considered a promising approach for building integrated photovoltaics (BIPV) as they can be easily integrated into active architectural elements, reducing the costs of photovoltaics by using smaller solar cells, and maintaining the same power output over a smaller area. The LSC, depicted in Figure 1, consists of a polymer waveguide doped with highly emissive chromophores such as organic dyes or quantum dots (QDs). These luminescent particles (chromophores) absorb part of the incident solar spectrum and re-emit at a longer wavelength matching the photovoltaic (PV) cell's absorption. The geometry of LSC and the wavelength or re-emitted light are adjusted in order to obtain a total internal reflection. The transparent media play a significant role in guiding the light towards the edges of the plate where solar cells attached at one or more sides.

---

[5] Weber, W. H.; Lambe, J. Appl. Opt. **1976**, *15*, 2299-2300.

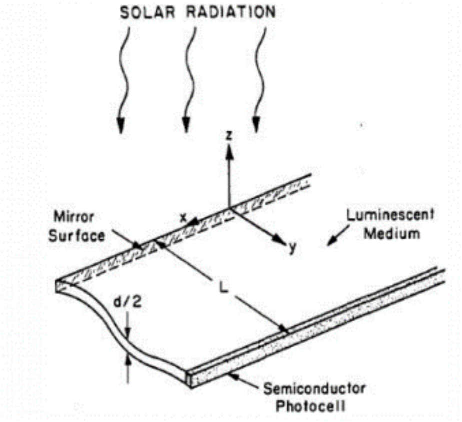

Figure 1. Schematic view of an LSC.[3]

BIPV modules serve the dual function of building "skin"—replacing conventional building envelope materials—and power generator. By avoiding the cost of adding PVs to the sides or roof of the building, the incremental cost of PVs is reduced, and its life-cycle cost is improved. BIPV systems have lower overall costs than PV arrays requiring separate, dedicated, mounting systems. The goal is to convert the passive glass facades of buildings into distributed energy generation units to achieve net zero energy buildings (NZEB).

Knowledge or Technology Gaps

Various types of luminescent QDs have been used in a transparent polymer slab or embedded in a film which were further coated on the surface of a glass to make a LSC device. However, applying silicon QDs (SiQDs) seem to be advantageous over other types of QDs, due to wider absorption spectra of its nanostructures as well as natural abundance and low toxicity of elemental silicon itself. AQM has developed silicon-based quantum dots that can be used to construct a luminescent solar concentrator (LSC). AQM's expertise in the development of silicon nanomaterials, quantum dots and silicon/polymer nanocomposites, has now been applied to glass to create a proof-of-concept LSC. AQM's LSCs are light-management coatings that act as sunlight collectors for PV cells. They represent an effective way to improve operating efficiency and lower the cost of PV systems without using complex tracking and cooling equipment. A LSC concentrates both direct and diffuse sunlight and guides it by total internal reflection to PV cells located inside a window frame. This 2D waveguiding is efficient even with curved glass applications. The LSC down-converts and concentrates the incident high energy UV spectrum into spectrally narrow light that matches the spectral peak of the PV device, thus boosting its power conversion efficiency and attaining maximum energy harvesting. The LSC concept effectively increases the photon density incident onto the PV cell, which boosts its photocurrent.

C. PROJECT DESCRIPTION

Please provide a narrative describing the project using the following sub-headings.

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that will be used to measure the success of the project.

RESPOND BELOW

Knowledge or Technology Description

On-site production of electricity directly from sunlight is an attractive approach which is being advanced by building-integrated photovoltaic (BIPV) technology. A perfect BIPV system can produce light without introducing any change to the status-quo building materials. It also does not need constant maintenance and produces energy without depletion of materials. In this context, glass is one of the most used materials in buildings and acts as the main platform for the BIPV system. The scope of the current project is to develop a functional and scalable LSC prototype which can convert the glass used in an ordinary window into one that generates electricity.

Unlike other solar technologies, LSCs are expected to fit into an existing building system with a comparably lower price and, consequently, a faster market adoption. This technology can increase the efficiency of current solar systems (mainly c-Si) per area unit. This itself can be as important as any PV systems out there for achieving a net zero building, as solar real estate (an area to install the PV) is extremely crucial, particularly in dense city areas.

More than 30% of GHG emissions come from electricity consumed by buildings in densely populated, urban areas. Then, on-site production of electricity without carbon emissions (as is the goal of BIPV systems using LSC windows) can have a significant contribution on lowering GHG emissions and increasing the sustainability of modern civilizations. Lowering GHG emissions is the biggest advantage of PV systems as can be seen when compared to classical fossil fuels (0.03-0.08 kg of CO2e/kWh compared to >1 kg of CO2e/kWh in the case of coal). Proposed LSC technologies can even decrease GHG emission from PV systems by allowing fewer PVs to be used while producing the same amount of electricity.

Project Objectives / Performance Metrics

- *Near-IR QD Scaled Development:* AQM will optimize the production of the appropriate SiQD materials that will down convert high energy to lower energy photons with emission at ~850 nm. These Stoke-shifted photons would then be ideally suited to be absorbed by the silicon solar cells. The QDs will be designed to enhance their long-term chemical stability and compatibility with a polymer matrix. The QDs will be measured for appropriate photoluminescence and quantum yield (QY).

- *Polymer Functionalized Quantum Dots:* The tailored QDs will be incorporated into high optical quality polymer waveguides fabricated via mass polymerization of self-standing bulk slabs or thin film coatings on glass substrates. Both methods have been demonstrated, but the waveguiding efficiency needs to be evaluated. These structures will test the degree of transparency and the form the LSCs will take for efficient waveguiding. Key measurements will be the transmittance and absorption losses/cm through the polymer. This will require some degree of scaling to measure the waveguiding transmittance over larger panels of glass. Testing performed includes:
    - Steady-state and time resolved photoluminescence
    - Optical absorption and transmission losses/cm.
    - Quantum yield emission
    - Thermal studies on quenching process
    - Transient absorption
    - Stokes shift analysis

- *LSC Waveguide Fabrication:* Fabrication will depend on the performance and economics of either bulk slab or solution-based deposition and application methods to produce functional thin film coatings.
    - Modeling, realization, characterization, and optimization of planar LSC structures (both slabs and functional films on rigid and flexible substrates).
    - Monte Carlo ray tracing simulations to predict and optimize the performance of different LSC geometrical structures.
    - Evaluate the compatibility between the SiQD and the polymer matrix for slab and film waveguides.
    - Optimize production protocols – slab or thin film
    - Standardization of fabrication procedures and scaling.
    - Color optimization.

  If a hybrid QD polymer thin film is effective, several application methods will be tested: doctor-blade deposition and spray coating. Each method was examined for waveguiding efficiency, ease of use, quality, performance, scalability, and cost of application.

- *LSC + PV Integration:* Assemble a test apparatus to integrate the LSC with a strip of high efficiency solar cells along the edges of the glass and measure the PV performance of different experimental LSC structures. Key questions that need to be answered include:
    - Selection of the ideal PV cells to optimize system efficiency
    - Proper integration to produce an efficient method of coupling light from the LSC structures to the PV cells.

- Overall LSC system efficiency.
- Glass transparency, spectral absorption, and reflectance.
- Design a BIPV test apparatus.

To maximize LSC efficiency, each operative step needs to be optimized. Dedicated efforts will be devoted to optimizing light out-coupling from the LSCs to various types of PV cells, including standard silicon and advanced PVs with spectral response specifically tuned to match the emission profile of the QDs. AQM will use the manufacturing expertise of AWW to assemble a BIPV test apparatus to integrate the optimized LSC modules with the window assembly, PV elements and power inverters. Testing solar to electrical power conversion efficiencies. Productivity and quality will be achieved by an integrated product design, avoiding separate module assembly operations, and designing cell interconnects into the product.

The goal is to achieve a minimum of 5% light to energy conversion and 50 W/m^2 the for BIPV.

- *BIPV Testing:* The optimized LSC modules will be integrated into PV window panels using proper encapsulation and designed frames and electronics to provide a stable power output in real outdoor conditions. Some of the environmental and stress testing of the PV cells according to IEC 61215 protocols was performed in our environmental test chamber to simulate real outdoor conditions.

D. METHODOLOGY

Please provide a narrative describing the methodology and facilities that were used to execute and complete the project. Use subheadings as appropriate.

RESPOND BELOW

The development of the SiQD materials was completed in-house. The initial work was conducted at the University of Alberta. [6]We moved our base of operations to our new facility in the Edmonton Research Park in January 2020. Outside of materials characterization, all experimental work was conducted and analyzed at the AQM facilities.

AQM co-developed a model to realize, characterize, and optimize planar LSC structures with Monte Carlo ray-tracing simulations to predict and optimize the performance of the LSC. In this context, we hired

---

[6] Clark, R.J.; Aghajamali, M.; Gonzalez, C.M.; Hadidi, L.; Islam, M.A.; Javadi, M.; Mobarok, M.H.; Purkait, T.K.; Robidillo, C.J.T.; Sinelnikov, R.; Thiessen, A.N.; Washington, J.; Yu, H.; Veinot, J. G. C. From Hydrogen Silsesquioxane to Functionalized Silicon Nanocrystals. *Chem. Mater.*, **2016**, *29*, 80-89.

Nemsor Technologies Inc. and the University of Alberta, Department of Mechanical Engineering to do the simulation and ray tracing work.

Working with All Weather Windows®, we investigated different types of glass, glass treatments, and various glass coatings that could be used to best assist the waveguiding process and create the most efficient systems. They assisted in assembling the window prototypes for the final tasks of the project. Testing of environmental, mechanical, and electrical standards/protocols will be ongoing as new LSC and BIPV designs are completed.

Please provide a narrative describing the key results using the project's milestones as sub-headings.

- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

RESPOND BELOW

E. PROJECT RESULTS

Milestone 1: SiQDs Development Optical characterization of functionalized SiQDs at ~850 nm. Capacity to produce >100 g/day.

SiQDs of different sizes were synthesized by AQM's patented method. Their surfaces were capped by monomeric moieties of organic groups or polymeric chains of an optically active polymer. While smaller SiQDs show maximum photoluminescent (PL_{max}) emission in the visible region, PL_{max} of bigger size SiQDs were well into the NIR region. The relation between the size of QDs and optical properties (the position and intensity of PL_{max}) was successfully determined.

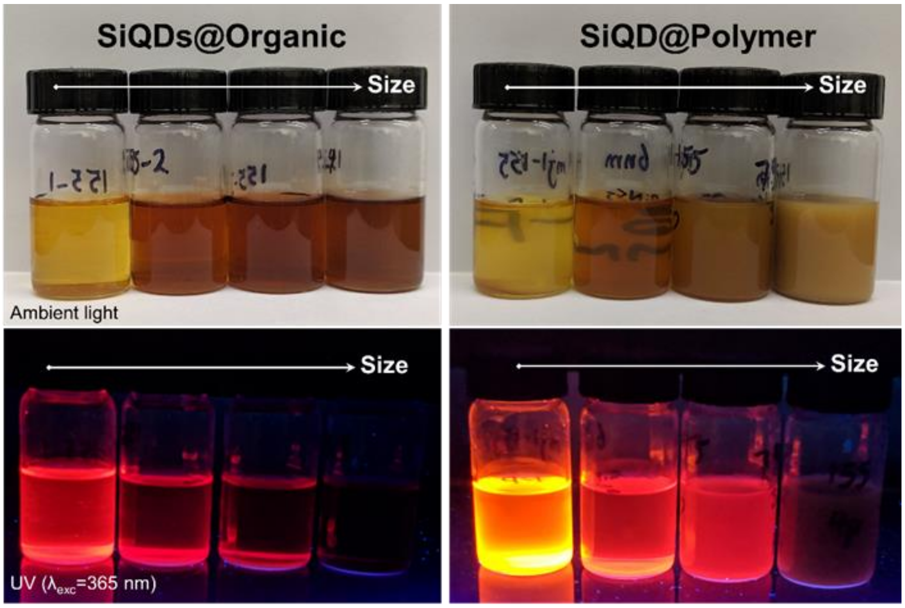

Figure 2. Size Dependent Silicon Quantum Dots with Functionalized Polymer

The appropriate size of SiQD materials that will down convert high energy ultraviolet (UV) light to lower energy photons with emission at ~850 nm was identified as well. Moreover, different sizes/surface-groups of SiQDs were characterized in order to define the optical brightness of each species. A demo of photovoltaic (PV) system coupled with LSC was successfully employed to show the efficacy of SiQDs to be used in LSC systems.

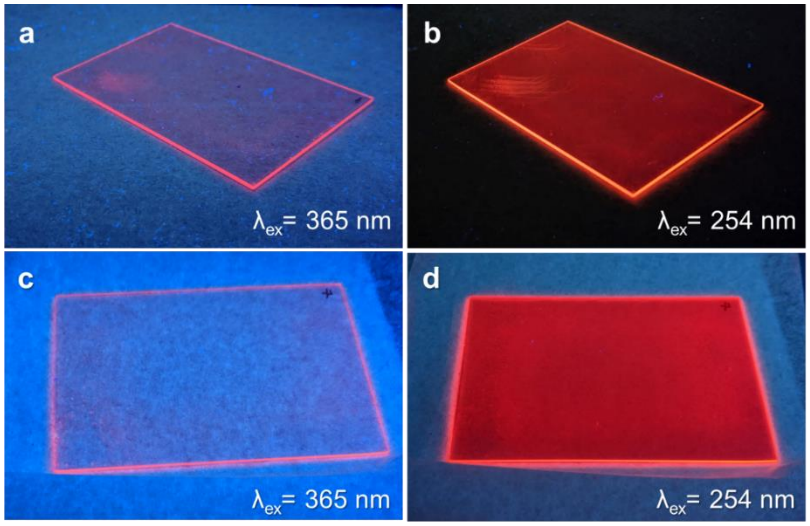

Figure 3. SiQD Coated LSC Under Different Excitation Wavelengths

Neither the U of A nor NRC Nanotechnology Centre had the equipment capable of measuring the NIR quantum yield. Equipment was purchased and the QY measurements were measured and optimized at AQM. Scale-up cost of $5M for 100g/day production of material is not yet market justified.

Milestone 2: Polymer Functionalization of SiQDs Polymer functionalized SiQDs with >70% QY at ~850 nm demonstrating waveguiding on a 30 x 30 cm glass.

SiQDs with 66% QY were achieved, however, polymer functionalized SiQDs with 30-45% QY at ~850 nm could only be reached as the best polymer for the LSC coating altered the QY. A new SiQD@co-polymer was developed to modify functionalization and solution viscosity in order to bring stability and adherence to the glass. Dip coated glass is shown in Figure 4.

Our focus was on evaluating different coating methodologies to make a uniformly coated LSC waveguide. We have previously tried spray coating of SiQDs@Polymer samples using an air-blade as well as an ultra-sonic spray. We also tried other coating approaches such as dip-coating and drop-casting. Both spray coating and drop-casting showed promising results as the SiQDs coatings from this method were uniform and almost defect-free. Apart from this, a demo of c-Si as well as organic PV system coupled with an LSC was successfully designed and built by All Weather Windows® to show the efficacy of the SiQDs to be used in LSC systems.

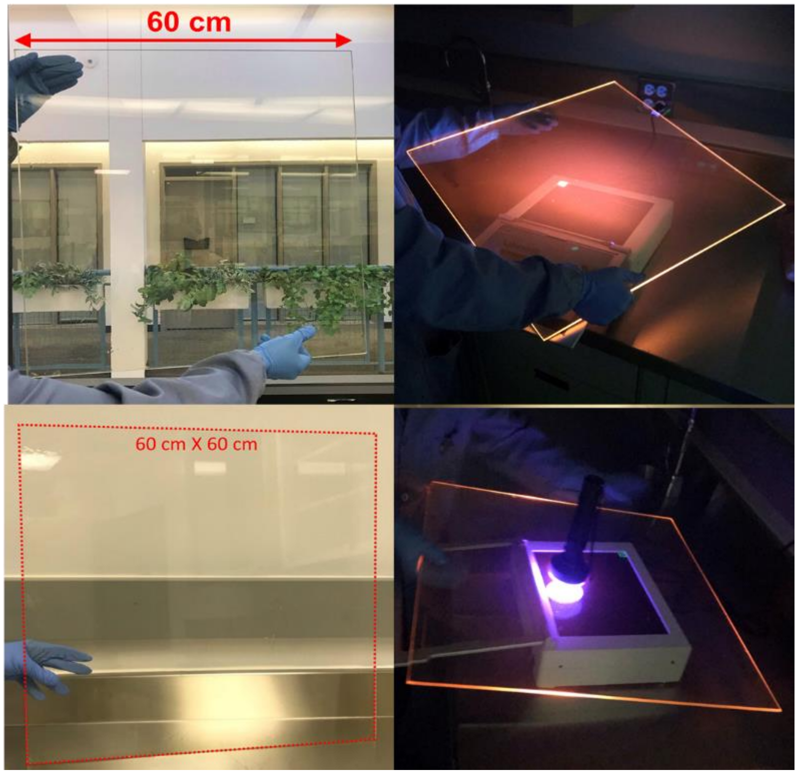

Figure 4. Large scale SiQD Coated Glass

Milestone 3: Fabrication of LSC waveguide Prototypes and fabrication protocols for a scaled 60 x 60 cm glass and film LSC with low absorption losses. Recommendations on the preferred methods of fabrication based on cost, performance, and efficiency.

- An LSC prototype assembly in the testing phase is shown in Figure 5.
- Spray coating was deemed the best option, and the parameters are being optimized to maximize the application process.
- Film application to the glass required optimization for uniformity, transparency, and film stability. Window frames from All Weather Windows® have been received and testing has started.

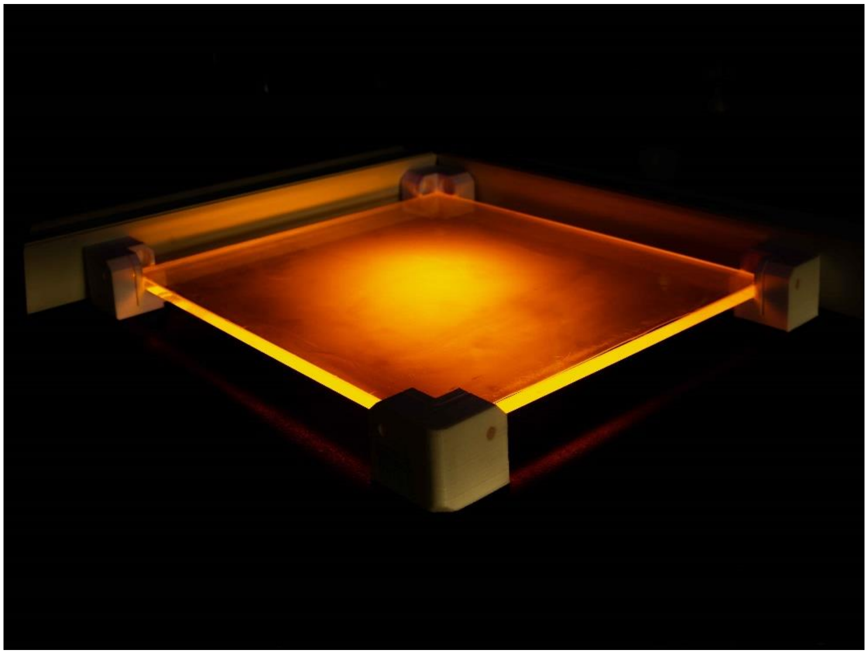

Figure 5. Luminescent solar concentrator assembly

Figure 6. Luminescent solar concentrator undergoing tests.

Milestone 4: LSC + PV integration with a scaled 100 x 100 cm glass and/or film LSC integrated with PV cells. To achieve a minimum of 5% light to energy conversion for BIPV and 50 W/m2 output.

- The goal was to achieve a minimum of 5% light to energy conversion for BIPV, we were able to achieve 1.1% PCE and 12 to 27 W/m^2 depending on coating thickness, sun orientation and time of year.

The focus was on optimizing different coating methodologies to make a uniformly coated LSC waveguide. A new copolymer was developed that showed promise to adhere to the glass surface. A SiQD@co-polymer nanomaterial was developed. The resulting uniform coating adhered to the glass without any peeling, discoloration, and minimal haze. Work continued the integration of c-Si as well as organic PV systems coupled with an LSC. All Weather Windows® designed and built several window frames to show the efficacy of the SiQDs to be used in LSC systems. A LSC with coated glass was assembled into a window frame and demonstrated electrical power output.

Figure 7. BIPV Assembly

Milestone 5: BPIV Passing of environmental, mechanical, and electrical standards and protocols.

A new design for the window frame is currently being fabricated to replace the original frame. Due to the limitations found with the original frame design, and the experimental evidence collected, a new frame has been designed to show enhanced features. With the new frame, we will determine the features and outputs that are generated. Concurrently, the glass will be subjected to all the pertinent environmental testing. Based on deliverables,

- Testing has shown that AQM's best functionalized SiQD quantum yield was between 55 to 66% varying somewhat from batch to batch. Polymer functionalized SiQDs showed a QY of 40-53%.
- Spray coating of the copolymer@SiQDs onto the glass showed both excellent adhesion and transparency.
- We conducted stability tests under weather conditions in our environmental chamber. We tested to see if the films would flow when they are hung in vertical direction. The samples were kept in an environmental chamber for 7 days with a specific temperature and relative humidity profile

for every 24 hours. After 7 days we found that the polymer did not melt and drop, which means they have stable attachment with the glass.

- Tests showed a visible light transmittance of 60 to70%. There was still some issue of polymer film being layered, which can be addressed by optimizing the path distance of nozzle and wt% of copolymer in solution. Also, there are still small imperfections on the glass due to uneven spray coating. This can be addressed with a better-quality spray coater.
- Currently, we have not found a higher quality solar cell product that could be implemented. If found, it would significantly boost the power conversion efficiency (PCE).
- A LSC was coupled with a c-Si PV assembly with a 15 x 15 cm^2 glass with a SiQDs film thickness of 0.3-0.5 mm. In testing under sunlight, the PCE was measured to be 1.1%. In the current design of LSC, when we measure PCE, the solar cells are not attached to glass by an index matching adhesive. They are separated by a few mm (1 to 5 mm) gap. This gap is probably allowing scattered light to pass through and reducing efficiency. A redesign of the LSC with an index matching adhesive needs to be tried and compared to the early design.
- Overall, we are making progress on all the LSC attributes. As mentioned above, there are still engineering and developmental issues to be resolved before we can do pilot trials with All Weather Windows.

Project Specific Metrics Summary

Objectives were defined in detail in Section C. The outcomes for those objectives are listed below.

Objective	**Outcome**
Near-IR QD Scaled Development	The scale-up of the SiQDs is still in the planning stages (blueprints and equipment cost identified) as we are waiting for a market demand.
Polymer Functionalized Quantum Dots	Polymer functionalized SiQDs with 30-45% QY at ~850 nm was achieved.
LSC Waveguide Fabrication	Spray coating was deemed the best option, and the parameters are being optimized to maximize the application process.
LSC + PV Integration	The key issue was the efficiency of the solar cells was not as advertised. The best solar cell manufacturer we could find is no longer in business. Some design changes to attach the LSC more efficiently to the solar cell is needed.
BIPV Testing	In the current version of BIPV, we were able to achieve a PCE of 1.1% and between 12and 27 W/m2.

F. KEY LEARNINGS

Please provide a narrative that discusses the key learnings from the project.

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes.

RESPOND BELOW

Milestone 1: Our project taught us to design our silicon quantum dots to design the wavelength shift for optimal LSC performance and QD size for proper use in an LSC. Also, we improved the brightness and the quantum yield of our materials. Further, we learned to modify these materials to properly mix with various polymers. Without proper functionalization, we saw agglomeration and uneven mixing. However, polymer functionalized SiQDs always show a drop in QY which challenged us to provide the brightest SiQDs.

Milestone 2: In order to coat the glass, we had to evaluate different coating methodologies to make a uniformly coated LSC waveguide. We identified that the optimal application of the material is by ultra-sonic spray coating device from All Weather Windows®. Further we needed to develop a new co-polymer that could be applied to the glass and properly adhere. The formulation of our new compound also had to be adapted for ultra-sonic spray application. This developed expertise has been invaluable as we engage with other clients.

Milestone 3*:* Our challenge was to uniformly coat the LSC with a designer SiQDs@co-Polymer that would adhere to the glass without any peeling, discoloration, minimal haze, and maximum transparency. We initially tried to use solar simulators to accurately measure the amount of sunlight reaching the LSC. We determined that a full spectrum solar simulator that included the UV portion of the spectrum was not available on the market. As such, we had to combine two light sources (UV source and existing solar simulators) to get some approximation of the solar spectrum. The best source was actually ordinary sunlight, but this varied during the day or season.

Milestone 4: A major issue that we found was sourcing solar cells that would integrate with our LSC and BIPV. The flexible organic solar cells were great for integration, but their solar conversion efficiency was too low to be useful. Other c-Si solar cells were brittle and had to be delicately connected into the BIPV. We did source one product that had the right configuration but through a number of tests with solar simulators and in sunlight, we determined that the solar cells were not as good as advertised. In fact, they were only 50% as efficient as advertised. We may require custom designed solar cells to maximize the potential of the LSC prototype. To date, no such manufacturer has been found. We also determined that the design of the LSC and window frame were crucial in improving BIPV performance. All Weather

Windows® designed and built several window frames to show the efficacy of the SiQDs to be used in LSC systems.

Milestone 5: A LSC with quantum dot coated glass was assembled into a window frame and demonstrated electrical power output. The LSC glass was subjected to realistic environmental testing including temperature and humidity demonstrating stability of our proprietary co-polymer under adverse conditions. Another factor that had to be considered was window transparency coupled with all the other ideal specifications. This was achieved by careful selection of the QDs themselves.

Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate.

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Energy Metrics:** Describe how the project outcomes impact the Clean Energy Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** List of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

RESPOND BELOW

G. OUTCOMES AND IMPACTS

Project Outcomes

The project enabled AQM to push the limits of silicon QD fabrication techniques and blending with polymers. Outcomes are described above. We are optimizing all the components of the system to increase performance. There are three key factors that will increase performance of the LSC +BIPV to make it useful for commercialization. 1.) We need to steadily increase our SiQD QY yield from its current 40% to 70+%. 2.) We believe that a re-design of the BIPV will increase performance and overall PCE. 3.) Lastly, more efficient, and properly designed solar cells will make a big difference in over PCE. Until we can find such a solar cell, we will only be able to achieve half our desired and practical goal for commercialization.

This project began before the definition of Clean Energy and Program Specific Metrics. Therefore, the assessment will be based on the metrics that were defined in the agreement. Since those metrics are described in the Project Success Metrics, a limited discussion will occur in the following sections.

Clean Energy Metrics

Based on what we have accomplished so far, the energy performance metrics will need to be revised as only 1.1% power conversion versus the 5% target. The reduced performance may require a change in the final product application. We have discussed with AWW the application of using the acquired LSC energy to open and close windows without the need for external wiring to a power source.

Program Specific Metrics

Not defined in the original agreement.

Project Outputs

No publications, or presentations were held during the project as travel and conferences were cancelled for a lengthy period during the pandemic. The Monte Carlo simulations were published as part of a thesis by a student of Mechanical Engineering at the University of Alberta. As this is a commercial venture, proprietary knowledge will be kept as trade secrets.

H. BENEFITS

Please provide a narrative outline the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, etc.) compared to the industry benchmark. Discuss benefits, impacts and/or trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the province. Discuss the research infrastructure used or developed to complete the project.

RESPOND BELOW

Economic

The project benefits were primarily job creation and some retention during the pandemic. We added and retained four jobs during the course of the project and pandemic. The knowledge gained during the period has been applied to other company activities and projects with other customers. Improvements in SiQD synthesis and polymer blending have added significant expertise to the company's overall IP portfolio. This expertise has enabled AQM to secure several new projects with multinational companies in the solar and cosmetics industries. Both applications will rely on new custom polymer functionalized SiQDs. Should we be successful with these product integrations, it will create 20 new jobs in manufacturing and result in large scale production of SiQDs supplying kilograms/month. The majority of AQM's sales (98%) is exported outside Canada.

Environmental

As the project has not yet been commercialized, we cannot comment on the potential environmental impact.

Social

Since the project started, the company has tripled in size and AQM has become a world leader in silicon-based nanomaterials that are having impacts in numerous industrial sectors. AQM has developed a global reputation for advanced materials design and integration. We are becoming a sought-after company to work for and have built excellent relations with the Universities of Alberta, Calgary, and NAIT.

Building Innovation Capacity

During the course of the project, AQM trained 7 new staff members. Our growth has attracted several HQP to the province. As a result of the project, we acquired both new and used equipment including a spray coater system developed by AWW which has been used in a variety of other applications. We have engaged with four research groups at the University of Alberta and two with the University of Calgary and collaborative R&D projects to investigate and commercialize new innovation. Our growing activities with the UofA NanoFAB support this important piece of infrastructure.

Please provide a narrative outlining the next steps and recommendations for further development of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken over the next two years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

RESPOND BELOW

I. RECOMMENDATIONS AND NEXT STEPS

AQM expects to continue refining the technology to the point that the power efficiency is high enough to be implemented into a window assembly. Our immediate plan with AWW is to accumulate and store energy from the LSC that can be used to power a small motor that will open and close windows automatically.

J. KNOWLEDGE DISSEMINATION

Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry.

RESPOND BELOW

The project used a Monte Carlo simulation to model the basic components of our LSC. This resulted in the publishing of a M.Sc. thesis, *Simulation of a Luminescent Solar Concentrator,* by Don Jehan Jayamaha at the Department of Mechanical Engineering at the University of Alberta in 2023.

Development of the material synthesis resulted in new discoveries for surface functionalized silicon quantum dots. We intend to present our findings at a suitable international quantum dot conference.

Please provide a narrative outlining the project conclusions.

- Ensure this summarizes the project objective, key components, results, learnings, outcomes, benefits and next steps.

RESPOND BELOW

K. CONCLUSIONS

The project was to develop Luminescent Solar Concentrators (LSCs) for Building Integrated Photovoltaics. The objectives for the project included five integrated tasks to develop LSCs for Building Integrated Photovoltaics (BIPV). These tasks included the development of near-IR emitting silicon quantum dots (SiQDs), a polymer functionalization of SiQDs, assembly of protypes for LSC waveguiding, coupling our LSC prototype with a photovoltaic (PV) system, and finally, fabricating a functional BIPV system.

In Task one, we achieved SiQD sizes (ranging from 3-10 nm) with variable photoluminescence (PL) properties (visible to the near-IR range). The appropriate size of SiQD materials that will convert high energy ultraviolet (UV) light to lower energy photons with emission at ~850 nm was identified.

In Task two we functionalized the SiQDs to SiQDs@co-Polymer, that have a 40-53% PLQY, enhanced stability and surface compatibility.

The third Task was to design and develop usable protypes for LSC waveguiding. Extensive experimental investigation was dedicated to uniformly coating SiQDs on LSC glass. Using the ultrasonic automated spray setup from All-Weather Windows®, evidence determined the addition of a secondary solvent improves the solution adhesion to the glass, the clarity, and uniformity of the material application had significantly improved. In addition, simulation tests indicated that our experimental work, once optimized, will be able to reach the desired outcomes for our LSC design.

We demonstrated in the fourth Task that our SiQDs can be excited with sunlight to generate an emission spectrum. Preliminary environmental experiments using window test frames and unoptimized SiQDs@Polymer coatings, performed positively as evidenced by waveguiding on the polymer coating and glass. We are hopeful that better performing solar cells will be available in the future that can be integrated into our BIPV to improve performance. Unfortunately, this technology is outside our capability. Currently, new model window test frames are being fabricated, new SiQDs@co-Polymer pre-coating techniques are being explored, and the project is moving towards the final task and making a commercial BIPV.

Lastly, we performed environmental testing on our LSC glass to determine performance in adverse weather conditions. To date, we are confident that our system will measure up to the standards required for the Canadian climate.