EXPERIMENTAL INVESTIGATION AND IMPLEMENTATION OF A MULTIPLE-INLET BIPV/T SYSTEM IN A CURTAIN WALL

Olesia Kruglov, Efstratios Rounis, Andreas Athienitis, Hua Ge

ABSTRACT

Building-integrated photovoltaic/thermal (BIPV/T) technologies are becoming a competitive alternative to traditional claddings by producing electrical and thermal energy in addition to comprising the external skin of the building. The heat generated by the photovoltaic (PV) panels and collected by the air flowing in open loop air-based BIPV/T systems can be used in various low temperature applications. However, due to a lack of constructability and performance standardization, these technologies have yet to become part of the mainstream building envelope design and construction.

This paper provides an overview of recent advancements in air-based BIPV/T systems, in order to assess architectural, structural and performance considerations for systems intended for full envelope integration and large scale applications. A BIPV/T prototype design was developed and built based on these considerations, adopting a conventional high-performance curtain wall framing system. Several design variables were investigated for thermal enhancement, such as variable flow rates, the use of multiple inlets for lower and more uniform PV temperatures, and different transparencies of PV modules for increased solar absorption.

A series of preliminary tests was conducted to assess the BIPV/T prototype's electrical and thermal performance, as well as its function as a building envelope assembly. Issues of constructability, material compatibility, maintenance and accessibility were addressed, and finally, guidelines for a BIPV/T performance standard have been proposed. Results from the preliminary testing showed that the use of multiple inlets may increase the thermal output by up to 18%, decrease the peak PV temperatures by up 3°C, and marginally increase the electrical output.

INTRODUCTION

PV Integration with Buildings

The building sector is currently responsible for more than 30% of the global energy consumption. Approximately half of this consumption is dedicated for space heating and is provided primarily by fossil fuels (Energy & Transformations, 2017). To meet an emissions trajectory that would limit the global temperature increase to 2°C by 2025, also known as the 2°C Scenario or 2DS, the International Energy Agency (IEA) suggests a 32% increase in heat generation from renewable sources, which can be largely

achieved with solar thermal heating.

Direct implementation of renewable energy generation technologies in buildings is increasing as the building sector moves away from fossil fuel use (Energy & Transformations, 2017). Systems that convert energy from the sun into electricity (photovoltaics, or PV) as well as heat (solar thermal technologies) may have widespread applications on buildings. Current practices for PV technologies on buildings include primarily racked systems, as well as integration with the building itself (BIPV). Solar thermal technologies include collectors on roofs and unglazed transpired collector (UTC) walls.

One concept combining the generation of electricity and useful heat is the photovoltaic/thermal system (PV/T), which is similar to a flat plate solar collector, the difference being is that the absorber is either replaced by or enhanced with PV cells. PV/T systems were originally developed in the 1970s (Wolf, 1976: Florshuetz, 1979), the focus being on the thermal part, since the efficiency of the PV cells was still considerably low (~6%) and these systems were intended for small scale residential applications.

In the following decades, there has been a lot of research on ways to enhance the thermal output of PV/T systems including studies on optimal geometric features and flow rates (Bambrook & Sproul, 2012; Kaiser, Zamora, Mazo´n, Garci´a, & Vera, 2014), the use of added glazing and double pass channels (Baljit, Chan, & Sopian, 2016; Hegazy, 2000; Tiwari, Sodha, Chandra, & Joshi, 2006), as well as the use of added elements inside the coolant channel to enhance heat transfer to the coolant (Hussain et al., 2015; Kumar & Rosen, 2011; Tonui & Tripanagnostopoulos, 2006; T. Yang & Athienitis, 2014) among others.

Among the various types of PV/T systems, the most common are as follows:

1) Water-based systems: These systems use water as the fluid medium to transfer heat from the PVs. They have higher heat exchange efficiencies due to the thermal properties of water, and are best suited for climates with high solar irradiation levels and ambient temperatures.
2) Concentrator systems: Reflectors are used to increase the radiation intensity on the PV cells. While less area is needed for PV coverage, the high temperatures with the collector reduce PV efficiency. These systems are intended for high temperature (more than 100ºC) applications and usually require a tracking system.
3) Air-based systems: Using air as the fluid medium, these systems are better suited for cold climates where ambient temperatures can be quite low. There are two types of air-bases systems:
    a) *Passive air systems,* which utilize buoyancy or stack effect for natural air flow
    b) *Active air systems,* which include mechanically assisted air flow, can be open-loop or closed-loop

A development of the PV/T system is the building integrated photovoltaic/thermal (BIPV/T) system. The benefits of integrating a BIPV/T system with the building envelope include increased cost-effectiveness of the installation, replacement of common building materials and an overall better architectural result (T. Yang & Athienitis, 2016). When a PV receives energy from the sun in the form of radiation, it converts 5 – 23% of it directly to electricity and reflects another portion of it, while the remaining 50% or so turns into heat. This excess heat leads to degradation of the PV module, decreasing cell efficiency and imposing thermal stresses (Chow 2010). PV panels should maintain low operating temperatures, prioritizing the high quality energy generation of electricity (Tripanagnostopoulos, 2006). PV/T systems collect the heat

generated by the PV cells, maintaining them at relatively low temperatures. Using a fluid medium, the heat can then be transferred as energy for various applications.

For large-scale building applications, air-based systems are advantageous for multiple reasons. They are lightweight, do not have the risk of leakage, and thus require less maintenance. The downside to using air is its low heat exchange efficiency. Natural convection is often not sufficient for the cooling of integrated PV panels. For BIPV/T, fan-assisted flow may provide adequate PV cooling, as well as the option to collect part of the excess heat for further use. Thermal enhancements may further reduce the PV temperatures and increase the systems thermal performance, with the exception of techniques that reduce thermal losses to the ambient, i.e. the use of a glazing over the PV. Figure 1 shows the concept of an air-based, multiple-inlet BIPV/T façade.

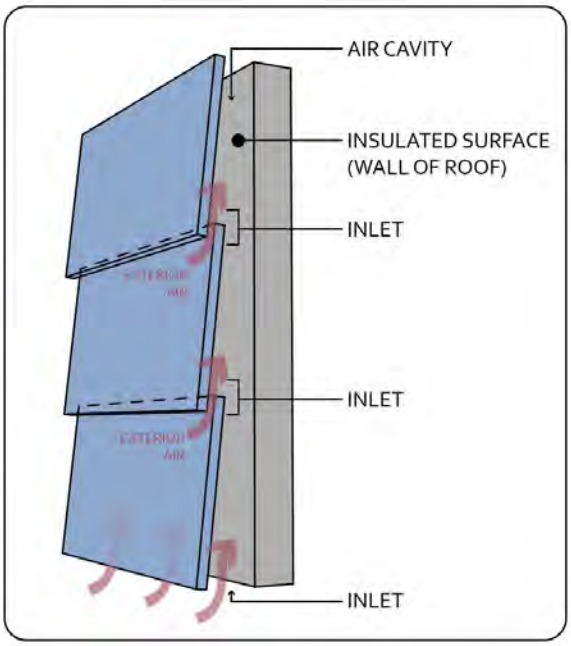

Figure 1: BIPV/T concept with multiple air inlets

Two recently built projects showcase the air-based BIPV/T system (Figure 2). The BIPV/T façade at the penthouse level of the John Molson School of Business is a custom design in response to architectural requirements for visible uniformity (Athienitis et al, 2010). The PV panels have black framing and were dimensioned to conform to the existing curtain wall configuration. This system includes UTC panels behind the PVs, but is not a full integration of technologies and envelope. In the Varennes Library, designed as a net-zero energy building, the BIPV/T cavity is created by adding the BIPV over a fully functional roof.

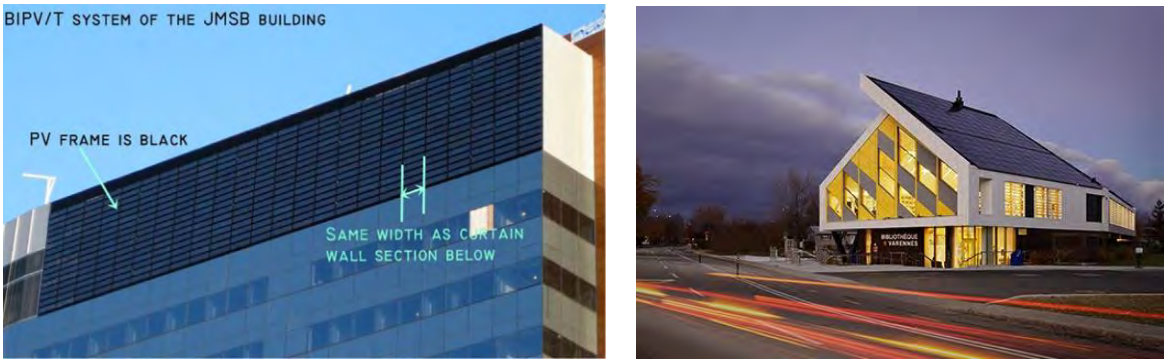

Figure 2: BIPV/T facade on the JMSB building at Concordia (left) and BIPV/T roof on the Varennes Public Library (right)

Despite development of various system improvements and a handful of physical demonstrations, there are many current barriers which prevent widespread industry application of BIPV/Ts. Such barriers include inconsistent integration into building design, unclear performance assessment & predictions, cost-benefit analysis, a lack of BIPV/T-specific standards and codes, and constructability issues (R. J. Yang, 2015).

The objective of this paper is to present the design and development of a BIPV/T cladding system based on an optimal design for electrical and thermal performance while also fulfilling requirements for a complete and modular building envelope system. A prototype was fabricated, based on a holistic approach for a BIPV/T system, and was tested at the Solar Simulator and Environmental Chamber (SSEC) testing facility at Concordia University. The system was designed to facilitate integration and assembly as a curtain wall, a very common and often preferred choice for commercial building enclosures. Performance enhancements for the BIPV/T cladding, construction limitations, and aesthetic effects were key drivers throughout the design iterations. Collaboration with a regional curtain wall fabricator allowed for adjustments throughout the design and production processes as improvements and constraints were discovered. Finally, a set of characterization tests were carried out. Future goals are to extract patterns from the results for predictive modeling and construct a set of base typologies for various façade applications.

BIPV/T DESIGN REQUIREMENTS

BIPV/T Design

There are several considerations for designing a BIPV/T system, which are derived from requirements both from energy production and façade design point of view. The structural, architectural, constructability and durability requirements affect the PV system layout, sizing and connections while PV system creates limitations for the façade as well. Listed below are the main factors that should be considered in the BIPV/T design process.

Electrical and Thermal Performance

For a BIPV/T system, the electrical efficiency of the system is of primary importance. This is because electrical output produces a higher quality energy than the thermal output. Thermal efficiency is also important and can be enhanced and optimized with methods to increase thermal extraction. Parameters such

as building orientation and wall area geometries are less flexible and will affect BIPV/T layout and sizing and system shading, determining the electrical output. Various PV technologies, such as mono-crystalline silicon or poly-crystalline silicon, will also have an impact on electrical efficiency.

Cooling of the PV through natural ventilation is typically inefficient as it only occurs through buoyancy or wind, while mechanical cooling with the use of a fan to draw air in must consider the net electrical efficiency after fan energy use is considered. For this, fan optimizations which involve calculating the fan speed and air pressure drop can be employed.

The thermal performance of the system can be further enhanced by various techniques, such as double glazing, use of fins, and other methods discussed in the introduction. However, these optimization and enhancement techniques should be chosen based on the acceptable upper threshold for PV surface temperatures, system durability and taking into account the intended purpose of the system, which may be a heat exchanger, a heat pump, direct integration of the pre-heated air to the air conditioning system in the winter months, or for domestic hot water heating during warm summer months.

Envelope Functionality

Common building typologies and established building envelope techniques guide the BIPV/T design from an architectural standpoint. It is important to consider that as a building material, the PV system must be considered for primary functions of the building envelope including dead, live and other loads, compatibility with other façade materials, thermal insulation performance, air and water resistance, fire safety characteristics, and soundproofing. The insulation of the air cavity of the BIPV/T system should be adjusted to meet thermal and code requirements such as assembly test NFPA 285. Due to the size and continuity of the air cavity of this type of system, non-combustible insulation such as stone wool or mineral wool can be used, as well as fire stops at floor edges. Other aspects, such as water management, drainage, and insect and bird protection which are especially important to a rainscreen façade, must work in parallel with any electrical/thermal optimizations designed for the air channel.

For the purpose of conventional façade constructability, the installation sequencing and accessibility for maintenance after the system is in place are important. In terms of constraints from the industry, the design is susceptible to PV and PV framing technology limitations, manufacturing availability, and architectural as well as aesthetic aspects (color, texture, finish, visual conformance to other façade appearances) that come to the forefront during design development phases of projects.

Façades

A curtain wall (CW) framing assembly is one of the better solutions for designing large scale, air-based BIPV/T systems, but it is important to consider the types of CW systems, depending on the uniqueness of the project. The two types of systems discussed are stick-built and unitized.

The stick-built system is a common method for CW assembly, in which assembly occurs in the field. Parts can be individually packaged and delivered, and resulting in a lower shipping cost. Less specialized training is required, since parts are not custom and the installers are more familiar with generic systems. Material distribution on site is easier, and construction sequencing is more flexible. However, there are also several

downsides to this type of installation. There is less quality control, since field installation of sealants and other materials is subject to outdoor conditions, also limiting timeframe of construction throughout the year. There is generally a longer installation time and some costs are associated with an increase of labor intensity. There is less chance for custom shape integration in the design, limiting designers' choices. In-plane movement of joints is more likely to occur during and after installation.

Figure 3 shows a basic stick-built installation sequence for a curtain wall. The sequence starts with the placement of the vertical framing, followed by the horizontal framing to complete the structural components. The profile of the horizontal framing would have to be more shallow than the vertical to ensure an uninterrupted air channel. Following, the back-pan and insulation would be installed, creating a continuous inner surface for the air channel. Finally, the glazing is placed at the outer face of the system. For a BIPV/T system, PV panels would replace the glazing layer, and the interior channel would be dimensioned for sufficient air flow behind the PV panels.

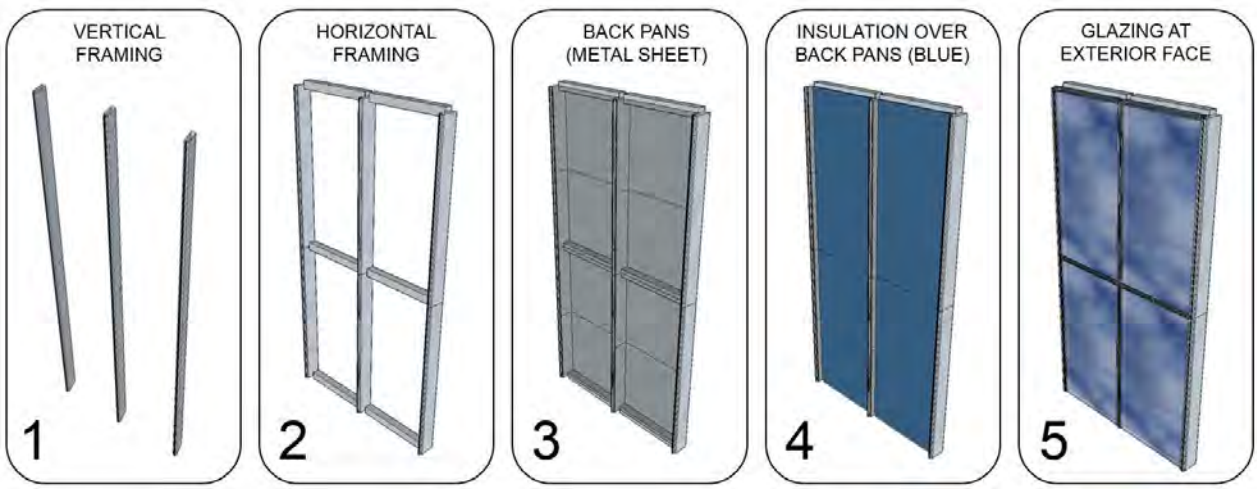

Figure 3: Curtain wall facade installation sequence

For a BIPV/T system, the transition from a stick-built design to a unitized design can be relatively easy. Unitized systems are generally considered more expensive and therefore less common applications than stick-built systems, but they have their own advantages. Most of the assembly occurs in the shop, which increases quality control while decreasing the chance of defective parts. Once these panels are shipped to the site, there is a much faster erection and enclosure phase. The design allows for more customizable extrusions as well as accommodation of in-plane movements. The disadvantages to this type of system include higher shipping costs, a much more rigid construction sequence, extra training of the installers for the custom parts, and a larger error in tolerance during the final assembly due to the design. Although the particular BIPV/T design mentioned in this paper was constructed using the stick-built approach, it is just as easy to incorporate the PV panels and insulation into a unitized system as most of the components are interchangeable (Figure 4).

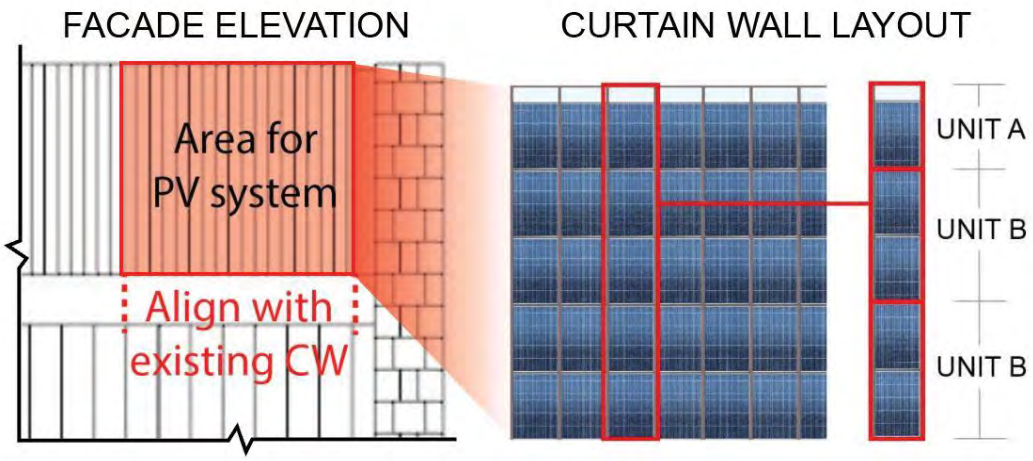

Figure 4: Existing façade requirements (left) and sample layout of a unitized system for the façade (right)

Structural framing significantly affects the design of the curtain wall. Sizing and quality of the floor slabs, as well as dimensions and spacing of the beams will affect whether the system may be hung or placed on top of the slab. If the system is unitized, there will be a size limitation to the vertical span of each unit. Due to the weight of BIPV panels, it is also important to consider whether the system will be captured on all four sides, or if two sides will be glazed in with silicone sealant.

Retrofits

With the percentage of new building construction lowering in relation to the existing building stock, retrofits are becoming an attractive option for many property owners, both commercial and residential. BIPV/T systems can be designed for retrofits, especially with CW assembly components. The option for overcladding or recladding allows for commonly used construction practices, and gives the possibility to turn semi-conditioned spaces or unused spaces into fully enclosed conditioned spaces, with the insulating benefit of BIPV/T systems.

Roof Applications

Curtain wall BIPV/T systems also have the potential to be applied to low-slope roofs as new roofing systems, or as retrofits. Although a low slope keeps the traditional flat roof look, a slope close to latitude is preferred for optimal electrical and thermal performance. For the 2017 Solar Decathlon China competition, a team of students and professors from Concordia University and McGill University conceptualized a residential home with a BIPV/T roof system, the design of which was based on building energy needs (Figure 5). It utilizes a stick-built CW framing system and allows the incorporation of a skylight in the middle of the roof.

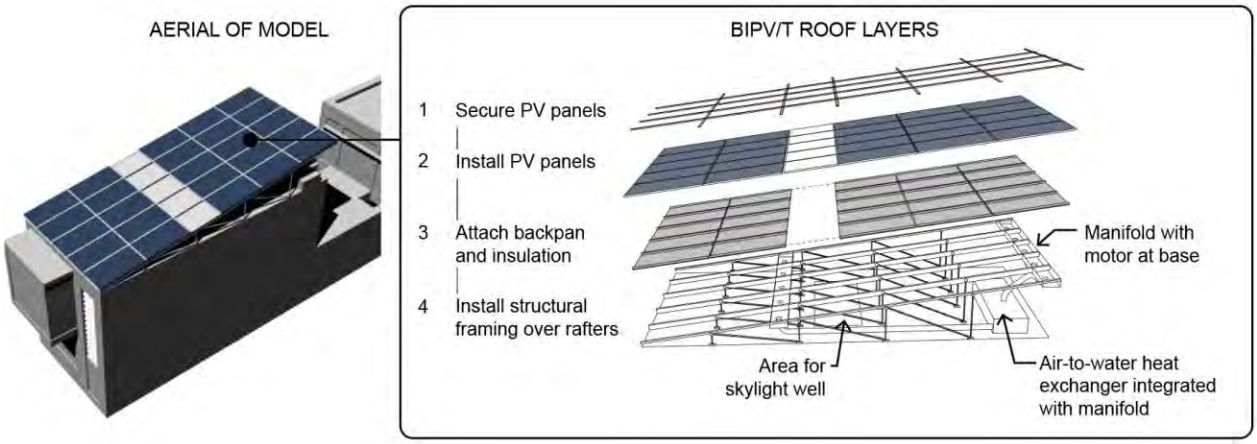

Figure 5: Solar Decathlon roof system design

CURTAIN WALL BIPV/T PROTOTYPE

Concept and Development

The design of the BIPV/T prototype described in this paper is based on the design considerations mentioned in the previous section for a CW façade application. Emphasis was placed on the facilitation of the assembly, and a simple air channel configuration. The system is multiple-inlet, and the PV panels serve as the rainscreen layer of the enclosure. Figure 6 shows the layers and components of the design. The backpan is a dark surface, such as a sheet of aluminum, which acts as an air and water barrier and also absorbs any radiation transmitted between the silicon cells, if the PV panel is semi-transparent. Semi-transparent photovoltaics (STPV) are modules which use a clear front and back sheet, usually a type of plastic or glass, and have silicon cells spaced apart enough to transmit light through the clear portion. The insulation, intended to create a near adiabatic boundary for the air channel, can also be selected to match the building code requirements for thermal resistance, which may affect the depth of the framing.

In order to be able to test the prototype for thermal and electrical efficiency, some changes were made from the original design. While the original design was a 3-panel, floor-to-ceiling modular unit, the prototype constructed for testing was smaller due to laboratory size limitations.

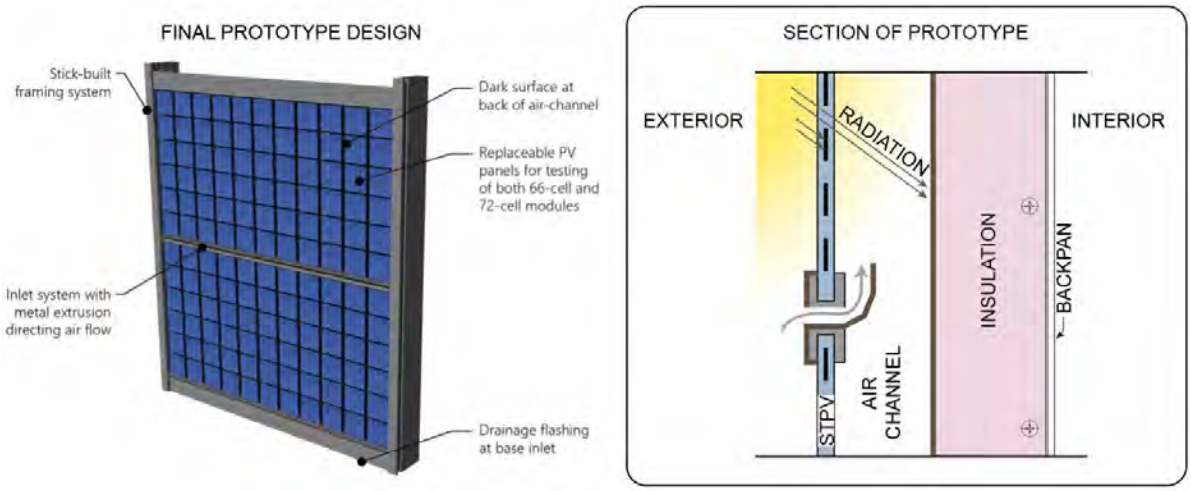

Figure 6: Features of final prototype design

The prototype contains two inlets, one at the base allowing for free flow of air almost the full depth of the channel, and one at the center between the two panels, to reduce the surface temperature of the upper panel by adding a cool stream of air to what is already flowing inside. This is intended to boost the heat extraction from the upper PV panel by introducing a second intake of fresh air and breaking the thermal boundary layer and ultimately enhance the electrical and thermal performance. The performance of multiple-inlet BIPV/T systems has been investigated by Yang and Athienitis (2014) and Rounis et al (2016). To improve the air flow entering at the intermediate inlet, as well as prevent rainwater from entering, a metal extrusion was placed along the inlet width, directing the air directly behind the PV panels for better heat transfer (Figure 7).

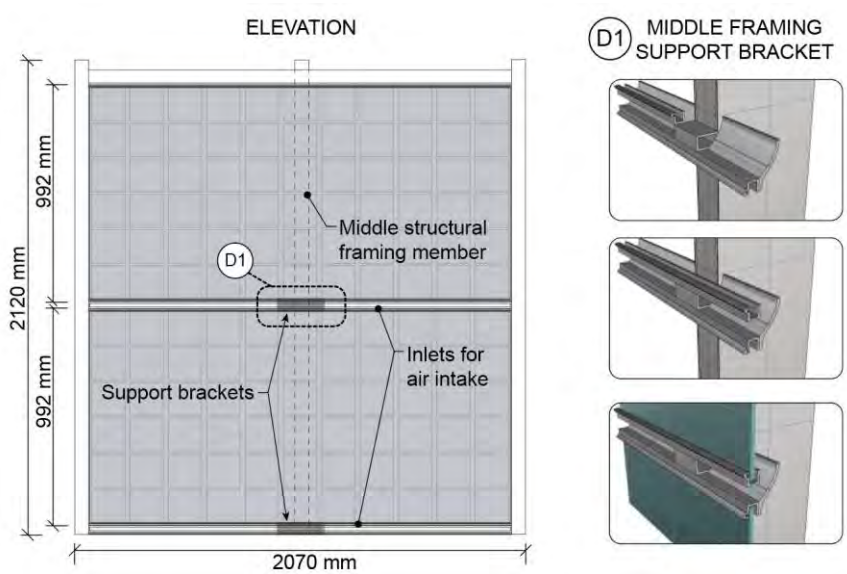

Figure 7: Architectural drawings and air inlet renders

Prototype Construction

Once the architectural drawings for the prototype were finalized, the framing was fabricated and partially assembled at the shop of a local curtain wall manufacturer. Figure 8 shows, from left to right, the prototype

assembled and with PV panels in place, the location where the CW framing was cut away to accommodate the junction boxes, openings in the top horizontal framing for the air flow manifold, and a sheet metal flashing at the base for water drainage.

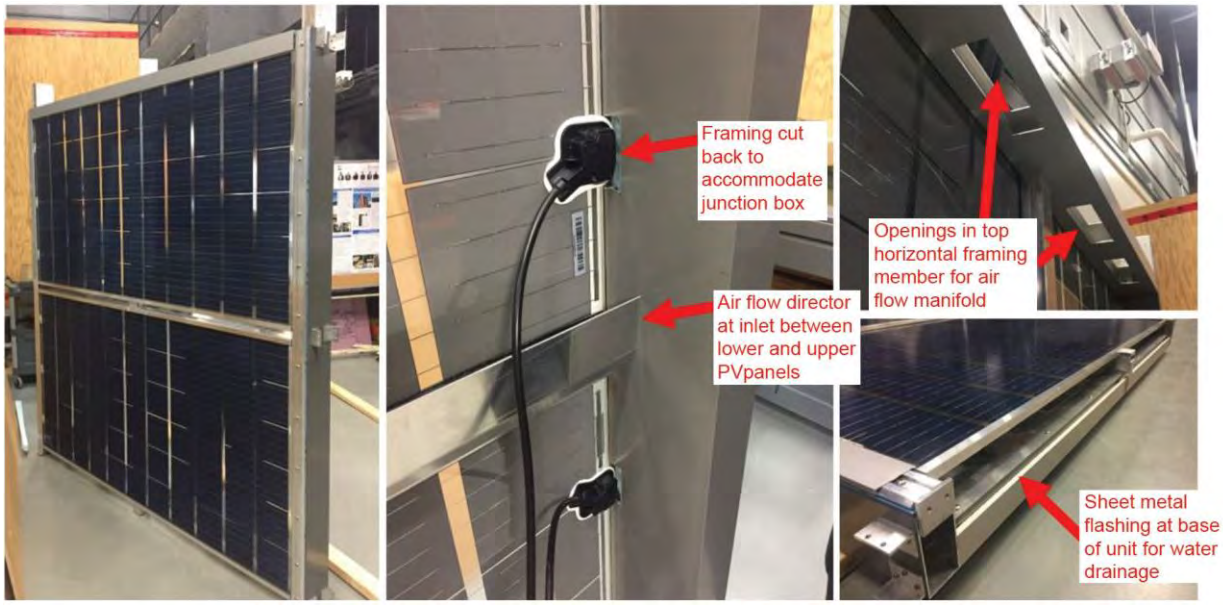

Figure 8: Details of constructed prototype

Although the prototype had certain adjustments for indoor laboratory testing, a number of resolutions were noted that would be required for a final product design. This includes a modified structural design based on system dimensions, Wire management at the junction box, sealing of any additional penetrations and joints related to the PV wiring, type of air channel insulation and coating if aluminum backpans are not possible, and manifold location, orientation and penetration through the envelope.

Experimental Setup

The curtain wall BIPV/T prototype testing was carried out at the Solar Simulator and Environmental Chamber laboratory of Concordia University in Montreal, Canada. The Solar Simulator consists of eight metal halide lamps that emulate the sunlight, creating a spectrum that complies with the ISO 9806 (ISO 2013). A ventilated artificial sky, located in front of the lamps, helps remove the infrared radiation created by the lamps. The platform upon which the specimens are set, as well as the lamp field, can rotate from 0° (horizontal) to 90° (vertical). The tests for the curtain wall BIPV/T prototype were all carried out at the vertical position (Figure 9). A fan positioned at the rear end of the platform is used to replicate the effect of wind and an air collector test stand unit is used for air collection from the air channel with flow rates adjustable up to 600 kg/h. The room temperature of the facility is regulated at 21°C±1°C.

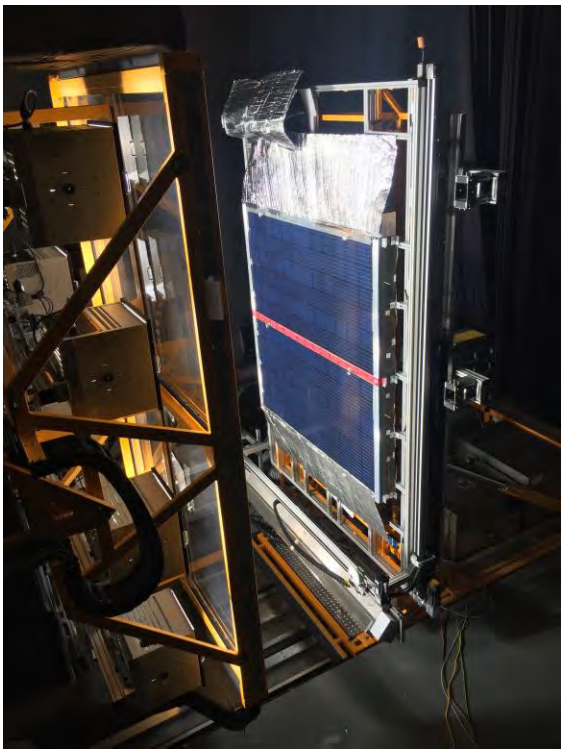

Figure 9: Vertical position of prototype during testing

The prototype was tested using two separate sets of glass-on-glass semi-transparent, PV modules custom made by Canadian Solar, with two different transparencies: 66-cell modules and 72-cell modules (Figure 10) and nominal output of 280 W and 320 W respectively. Each set of modules was tested under three irradiation levels and three mass flow rates, however this study includes only the results that correspond closer to the nominal operating cell temperature conditions (NOCT), namely: 839 W/m^2 solar irradiation, with a uniformity of approximately 94%, 21ºC±1ºC ambient temperature and an average of 1.1 m/s exterior wind. The channel flow rates were set at 0.11 kg/s, 0,14 kg/s and 0.17 kg/s (respective average channel air velocities are 0.5 m/s, 0.62 m/s, 0.74 m/s). Lower flow rates were not used as they would result in average air velocities of less than 0.5 m/s inside the air channel which resemble the levels of natural convection.

Furthermore, two configurations were used, one with a single intake of air located at the bottom of the prototype and one with a second inlet between the two PV modules, in order to investigate the effect of a second intake of air in the electrical and thermal performance of the prototype, as well as the maximum PV temperatures.

The prototype's dimensions are 2.07 meters in width, 2.12 meters in height, and it covers a total area of 4.39 m^2. It must be noted that the initial design included a total of three modules, corresponding to a story-high system. However, due to limitations regarding size and irradiation uniformity, the final dimensions were reduced and the prototype represents part of the actual collector.

A total of 97 thermocouples were used to monitor the temperatures of the PV surfaces, the air channel and the black absorber sheet covering the insulation (Figure 10).

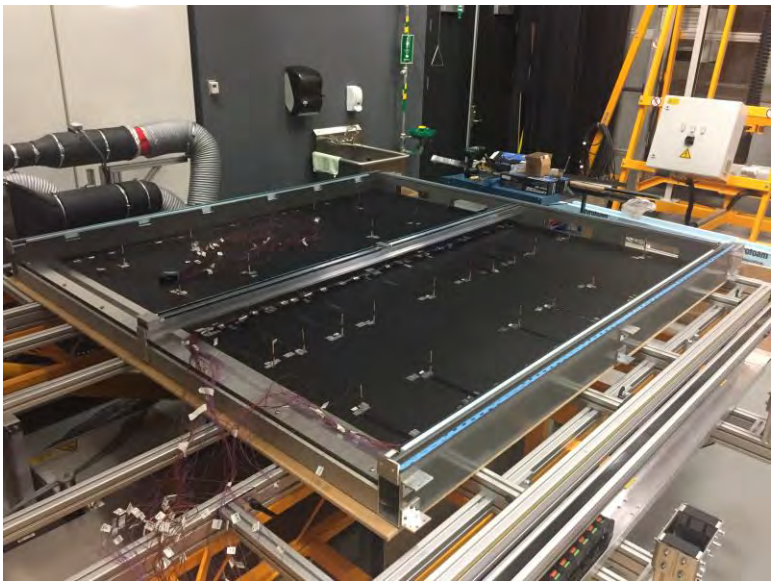

Figure 10: Thermocouple setup inside of BIPV/T air cavity

Initial characterization testing of varying irradiation levels and mass flow rates for single inlet and double inlet configurations is complete. Testing which has not commenced includes:

- Installation of fins inside of the air channel
- Varying the air channel depth without affecting the full system thickness
- Adding the prototype to a complete curtain wall enclosure of a test hut in the Environmental Chamber (Figure 11).

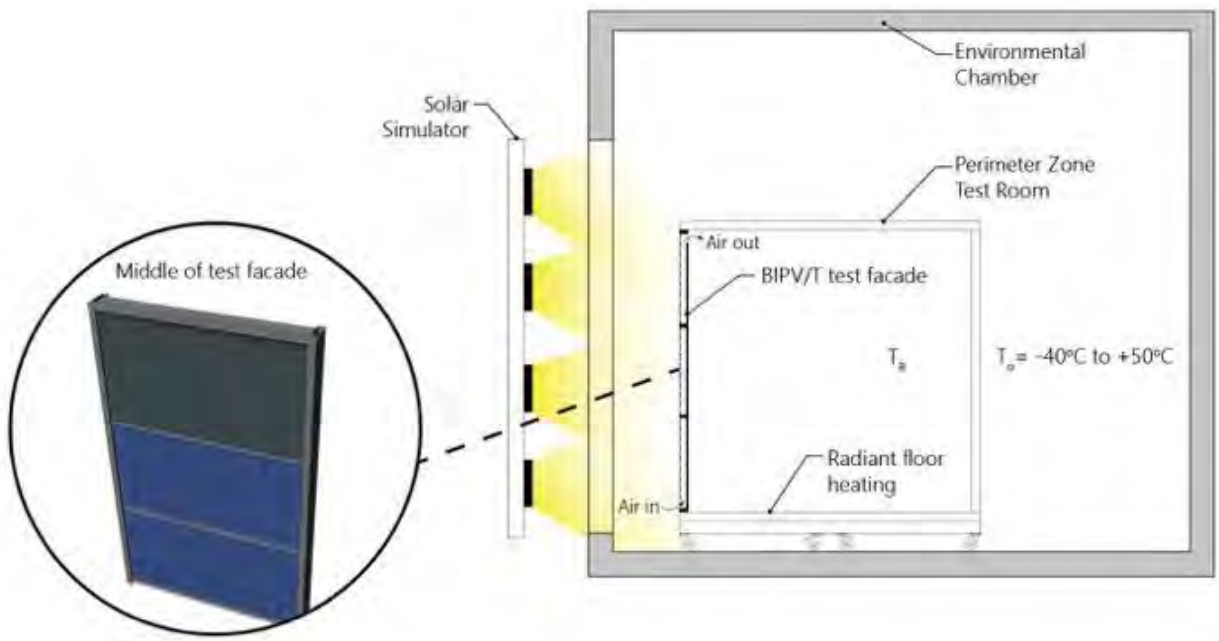

Figure 11: Future testing as part of an enclosed room

Solar Simulator Testing Results

Preliminary results for the NOCT testing conditions showed combined electrical and thermal efficiencies of up to 38.9% and 43.8% for the single and the double inlet configurations respectively. The double-inlet configurations performed best at all times, with 2%-5% higher thermal efficiencies, 3°C – 4°C lower maximum PV temperatures, as well as marginally higher electrical efficiencies.

Depending on the flow rate, the temperature rise inside the air channel varied from 6°C to 8.5°C for a 2 m long air channel, and it was approximately 1°C higher for the cases of the double-inlet configurations. The 66 cell panels had a slightly higher thermal efficiency due to the higher transparency, compared with the 72-cell modules. This thermal gain, however, was at a cost of the electrical efficiency.

It should be mentioned that the combined efficiencies mentioned previously, were calculated assigning the same value for electricity, which is high grade energy, and heat, which is low grade energy. Athienitis et al (2011) has argued that in assessing the overall performance, or the equivalent thermal efficiency, of a hybrid PV/T system, the value of electricity is four times higher than that of heat, based on the coefficient of performance (COP) of a heat pump.

The charts in Figure 12 summarize the prototype's performance at NOCT conditions with a channel flowrate of 0.14 m/s. The electrical efficiency of the 72-cell configuration is higher than the 66-cell configuration due to a larger coverage of the surface with solar cells, but has a slightly reduced thermal efficiency due to overall higher PV surface temperatures. In both cases, it is evident that the addition of a second inlet improves the combined performance of the system. However, if the prototype was not limited in size to just two panels, the results would likely show more drastic changes between the single inlet and

multiple inlet configurations for taller systems.

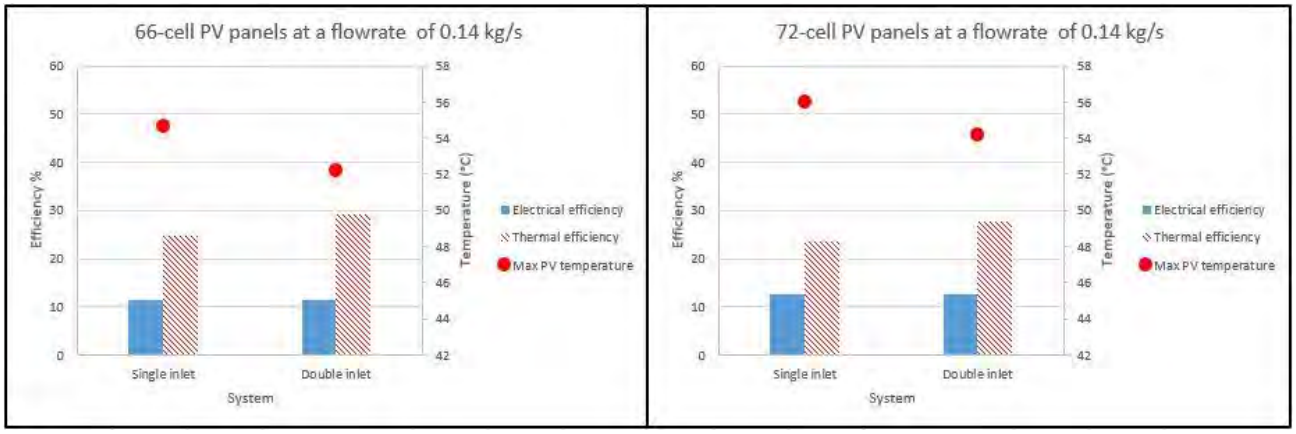

Figure 12: Results for 66-cell configuration (left) and 72-cell configuration (right) prototype testing at NOCT conditions

DEVELOPING A BIPV/T PERFORMANCE STANDARD

One of the biggest challenges to BIPV/T production is the lack of a unified performance standard. There are currently standards for electric performance of PV panels, air and liquid solar/thermal collector performance, even BIPV performance, but no standard exists for the performance of a PV/T system. The following table lists some of the existing standards related to PV and BIPV technologies.

Table 1: Standards for solar collectors and PV

PV standards	
EN 61215	Crystalline Silicon Terrestrial PV Modules
EN 61646	Thin-film Terrestrial PV Modules
EN 61730	Photovoltaic Module Safety Qualification
UL 1703	Flat-Plate Photovoltaic Modules and Panels
UL 4703	Outline for Photovoltaic Wire
BIPV standards	
AC 365	BIPV roof covering systems
EN 50583-1	Photovoltaics in Buildings: BIPV modules
EN 50583-2	Photovoltaics in Buildings: BIPV modules
Solar thermal standards	
ISO 9806	Solar thermal collectors – test methods

Building on some of the existing standards, such as the more recent EN 50583, adding requirements from building envelope testing standards (for air infiltration, water penetration, and thermal performance) and extracting useful correlations from the experimental data, a set of guidelines can be developed for a BIPV/T standard.

It is important to note that the design and optimization of the system's thermal performance should not be arbitrary and should consider the intended use of the preheated air (heat pump boost, direct preheated fresh air supply, drying, desiccant cooling etc.), which would dictate the requirements for flow rate and outlet air

temperature. These requirements, along with the upper limits for maximum PV temperatures, as well as the pumping energy consumption will provide the frame for the performance design of the system.

CONCLUSION

This study presents the design considerations for open-loop, air-based BIPV/T systems intended for full integration with the building envelope. The requirements for structural, architectural and energy performance, which were the motivation behind the design, have been addressed.

- A BIPV/T prototype was developed and built based on a typical curtain wall design, focusing on common building practices and previous lack of true integration between façade and PV/T system design. Based on the development process and collaboration with a CW fabricator, further practical issues of materiality and constructability have been addressed.

- The prototype was tested under NOCT conditions at an indoors solar simulator facility. The testing included a single and a double inlet configuration. The results showed a highly efficient BIPV/T envelope system with combined electrical and thermal efficiencies in the range of 40%. The double-inlet system performed better than single in terms of electrical and thermal efficiency, as well as maximum PV temperatures, corroborating the results of previous studies such as Bloem (2008) and Vats & Tiwari (2012).

- Guidelines for the development of a BIPV/T energy performance standard were suggested.

Initial testing indicated that thermal output increased by up to 18% with the addition of a second inlet in the prototype, while peak PV temperatures decreased by up to 3°C. Electrical output was marginally increased in the multiple inlet configuration (as opposed to the single-inlet system). These differences are expected to be greater in large scale applications, which is the intent of application for this system design.

FUTURE WORK

Future work in this area includes testing for electrical and thermal efficiency with adjustments to the prototype which could affect the performance. Such adjustments include:

1) Meshes at the inlets, which would be applied in the field for bird and insect protection
2) Positioning of the manifold in vertical and horizontal configurations. This takes into consideration the limitations of floor height and space availability.
3) Insulation of the framing. There may be a lack of this in field installation and it's important to consider practicality of large scale curtain wall applications.

Testing of the prototype for water management is important to complete the performance assessment in terms of the enclosure performance. A rain penetration test per ASTM E331, with diagnostic testing to determine any problematic areas, should be performed as an initial step.

Finally, further analysis of the data resulting from the electrical and thermal performance testing can be

incorporated into a parametric modeling program for architects to be able to use this in conjunction with physical modeling in programs for early design stage analysis of building performance.

ACKNOWLEDGEMENTS

The authors would like to thank Samuel Doyon-Bissonnette for the technical support in the curtain wall design and in the construction of the prototype.

REFERENCES

Athienitis, A. K., Bambara, J., O'Neill, B. and Faille, J. (2011). "A prototype photovoltaic/thermal system integrated with transpired collector". *Solar Energy*, 85(1), 139-153.

Baljit, S. S. S., Chan, H., & Sopian, K. (2016). Review of building integrated applications of photovoltaic and solar thermal systems. *Journal of Cleaner Production*, *137*, 677–689. http://doi.org/10.1016/j.jclepro.2016.07.150

Bambrook, S. M., & Sproul, A. B. (2012). Maximising the energy output of a PVT air system. *Solar Energy*, *86*(6), 1857–1871. http://doi.org/10.1016/j.solener.2012.02.038

Energy, I., & Transformations, S. (2017). Tracking Clean Energy Progress 2017 Tracking Clean Energy Progress 2017.

Hegazy, A. A. (2000). Comparative study of the performances of four photovoltaic / thermal solar air collectors. *Energy Conversion and Management*, *41*.

Hussain, F., Othman, M. Y. H., Yatim, B., Ruslan, H., Sopian, K., Anuar, Z., & Khairuddin, S. (2015). An improved design of photovoltaic/thermal solar collector. *Solar Energy*, *122*, 885–891. http://doi.org/10.1016/j.solener.2015.10.008

Kaiser, A. S., Zamora, B., Mazo´n, R., Garci´a, J. R., & Vera, F. (2014). Experimental study of cooling BIPV modules by forced convection in the air channel. *Applied Energy*, *135*, 88–97. http://doi.org/10.1016/j.apenergy.2014.08.079

Kapsis K. and Athienitis, A. K. (2015). "A study of the potential benefits of semi-transparent photovoltaics in commercial buildings". *Solar Energy*, Vol. 115: 120-132.

Kumar, R., & Rosen, M. A. (2011). Performance evaluation of a double pass PV/T solar air heater with and without fins. *Applied Thermal Engineering*, *31*(8–9), 1402–1410. http://doi.org/10.1016/j.applthermaleng.2010.12.037

Rounis, E.D. Athienitis A.K. and Stathopoulos, T. (2016). "Multiple-inlet building integrated photovoltaic/thermal system modelling under varying wind and temperature conditions". *Solar Energy*, Vol. 139: 157 – 170.

Tiwari, A., Sodha, M. S., Chandra, A., & Joshi, J. C. (2006). Performance evaluation of photovoltaic thermal solar air collector for composite climate of India. *Solar Energy Materials and Solar Cells*, *90*(2), 175–189. http://doi.org/10.1016/j.solmat.2005.03.002

Tonui, J. K., & Tripanagnostopoulos, Y. (2006). Improved PV/T solar collectors with heat extraction by forced or natural air circulation. *International Journal of Hydrogen Energy*, *31*(15), 2137–2146. http://doi.org/10.1016/j.ijhydene.2006.02.009

Yang, R. J. (2015). Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): Hardware and software strategies. *Automation in Construction*, *51*(C), 92–102. http://doi.org/10.1016/j.autcon.2014.12.005

Yang, T., & Athienitis, A. K. (2014). A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets. *Solar Energy*, *104*, 82–92. http://doi.org/10.1016/j.solener.2014.01.049

Yang, T., & Athienitis, A. K. (2016). A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) syste1ms. *Renewable and Sustainable Energy Reviews*, *66*, 886–912. http://doi.org/10.1016/j.rser.2016.07.011