AIR-BASED BIPV/T FOR LOW-ARCTIC APPLICATIONS

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Abstract

The Arctic communities of Canada are almost completely dependent on fossil fuels for their energy needs. This dependence can lead to negative environmental consequences, such as fuel spills and harmful emissions as well as vulnerabilities during emergency situations. Alternative energy options are required in order to have a sustainable future for this region. One such promising system is the building integrated photovoltaic/thermal collector (BIPV/T), where not only electricity is generated but valuable heat is recovered and can be used for all seasons of the year in the Arctic. In this study a simulation model of the BIPV/T was created using design weather data for Iqaluit, Canada as the input to test the electricity generation and heat recovery for different configurations to maximize the energy performance for the area. It was seen that the best performing month was April, with outlet temperature increases of approximately 18°C, and daily heat recovery and electricity generation over 6.2 kWh and 8.7kWh respectively. Based on these initial simulations an experimental prototype has been designed and fabricated to test thermal enhancements in a solar simulator laboratory. Upon experimental testing, improvements are to be recommend for a field prototype to be deployed in a low-Arctic community of Canada.

Keywords: BIPV/T, fossil fuel reduction, Arctic renewable energy

1. Introduction

Canada has close to three hundred remote communities, as seen in Fig.1 (Hayne et al., 2023), that are almost totally dependant on fossil fuels for their electricity and heating needs. Electricity is generated in these locations from local microgrid diesel fired thermal power plants. In order to maximize the efficiency of the electricity produced all heating needs must be met from heating oil fired burners in each building. While well established and fairly dependable if properly maintained, there are many negative environmental consequences from fossil fuel energy systems (Taillard et al., 2022).

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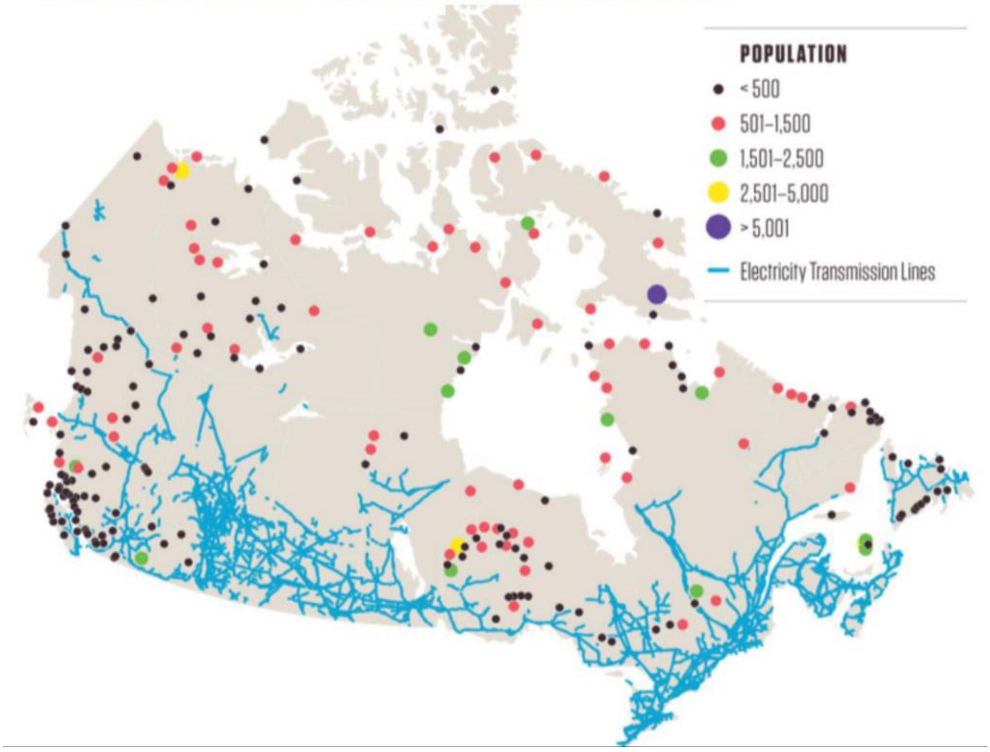


Fig.:1 Canada's Diesel Dependant Communities (Hayne et al., 2023)

On top of CO_2 emissions, fuel spills and leaks are major issues. Leaks inside buildings from poorly maintained heating equipment can lead to strong odors and vapors that significantly affect the indoor air quality and safety of the occupants (Paquet et al., 2021). Since heating oil is a light weight hydrocarbon it can easily be dispersed from the initial leakage area and spread throughout the building materials, and leak into the ground (Canadian Council of Ministers of the Environment, 2008), depriving soils of water and oxygen as well as vital nutrients (Mitter et al., 2021).

(a) Heating oil leakage from boiler (Photo taken by author)

(b) Heating oil leak from storage tank (Photo taken by Edua Jones)

Fig. 2: Heating oil leakage

The northern villages of Canada have several engineering challenges that must be taken into account when designing buildings for the region. As presented by (Baril et al., 2023) some of the main issues are the extreme cold climate, the remoteness of area causing long lead times for goods to be delivered, and shortage of skilled labor. Keeping these issues in mind on top of the need to reduce the fossil fuel usage, solar energy is seen as a viable option to the fossil fuel based energy systems. Several photovoltaic projects have taken place in the recent years to generate clean electricity, helping to avoid the extremely high electricity costs for the off-grid communities in the remote Arctic regions of Canada, such as the 940kW solar farm in small Arctic village of

Old Crow (Arctic Economic Council, 2022) and the 3.5MW solar power plant at the Diavik Mine in Canada's Northwest Territories (Rio Tinto, 2024). Both projects use traditional ground mounted PV arrays and are able to generate approximately 25% percentage of their energy needs, however large portions of lands must be developed for the PV structure and access roads. Other systems take advantage of the already developed land, by applying the PV systems to existing buildings (BAPV), such as the 100kW façade applied PV array on the arena in the northern village of Kuujjuaq (Tarquti, 2024). This system helps reduce the environmental impact on the land and delicate ecosystem as well as minimizing electrical cable and other material needs. Improving on the BAPV is the building integrated PV system (BIPV) that uses the PV system as an architectural element of the building serving such purposes as the rainscreen and UV barriers of the cladding or roofing materials, or incorporated into fenestration systems, such the BIPV roof of the Varennes Library in Quebec, Canada (Sigounis et al., 2023).

A higher level of integration is the building integrated photovoltaic/thermal collector (BIPV/T) in which heat is actively recovered from the PV panels; a cross section of an air-based BIPV/T system is shown in Fig.3. In the extreme cold regions of Canada's north over 80% of the energy costs are for heating purposes. The usage of BIPV/Ts are an effective way to maximize the energy benefits for the region and are deemed suitable for several reasons. This system serves multiple purposes, not only generating electricity but also recovering useful heat, cooling the PV modules, increasing PV efficiency and replacing the building cladding or roofing materials, acting as the rain and UV barriers. BIPV/T system typically have two types of heat transfer fluids, either liquid based or air based (Yang & Athienitis, 2016), (Dimitrios Rounis et al., 2022). While a liquid-based system can take advantage of the higher specific heat of the liquid to improve heat transfer, air as the heat transfer fluid eliminates the risk of damage from leaks that could occur when using a liquid-based system, reducing the maintenance requirements and improving the ease of construction. Air based systems can easily be integrated with a building's heating, ventilation and air conditioning system (HVAC) as seen in the successful projects in Montreal, Canada, such as the BIPV/T system at Concordia University which is used to preheat the fresh air for classrooms (Athienitis et al., 2011), as well as a portion of the roof at the Varennes Library used to pre-heat the air of an energy recovery ventilator (ERV) as well as an air to water heat pump (Amara et al., 2020).

In order to reduce heat losses through the building envelope in the extreme cold climate of the Canadian Arctic it is important to reduce the unintentional air infiltration and exfiltration to a minimum. Fresh air must then be provided by the use of a heat recovery ventilator (HRV) or energy recovery ventilator (ERV). However, when inlet temperatures drop below -5ºC to -10ºC frosting of the air exchange core occurs, resulting in a stoppage of fresh air during system defrost (Beattie et al., 2018). Simulation studies conducted in extreme cold climates concluded that pre-heated fresh air using a BIPV/T was seen to be useful to prevent frosting of a heat recovery ventilator (HRV) (Li et al., 2021), (Baril et al., 2021) or to improve the coefficient of performance (COP) of a heat pump (Ma et al., 2021). The focus of this project is to maximize the energy performance of a BIPV/T system for demonstration house in the low Arctic communities of northern Canada, (Berquist et al., 2021), as part of a greater project focused on renewable energy microgrid integration for remote off-grid cabins in Nunavut, Canada (CINUK, 2024).

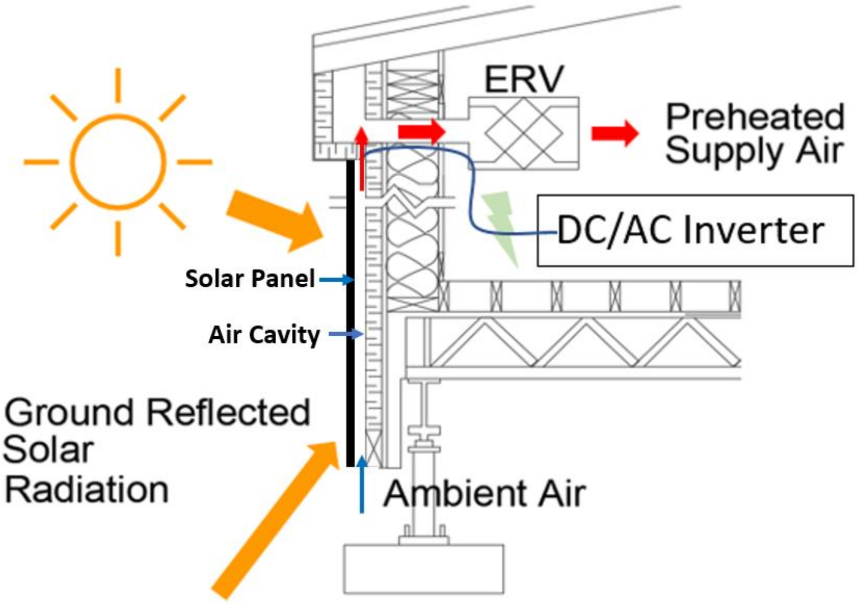


Fig.3: BIPV/T system cross section

2. Methodology

The first step in the BIPV/T design was a parametric study using a thermal network model of the system similar to the model created by (Candanedo et al., 2011) using local weather data. The cross-sectional thermal network of the BIPV/T cavity is shown in Fig. 4. By setting up an energy balance of the thermal resistive network at the key nodes of the PV panel, cavity air and cavity back surface, a system of equations was obtained. The equations were solved using an explicit finite difference control volume method with Canadian Weather Year for Energy Calculations (CWEC) monthly average hourly weather data for the city of Iqaluit, Nunavut, Canada, 63°N. The model was calibrated and validated using experimental data from (Yang & Athienitis, 2014).

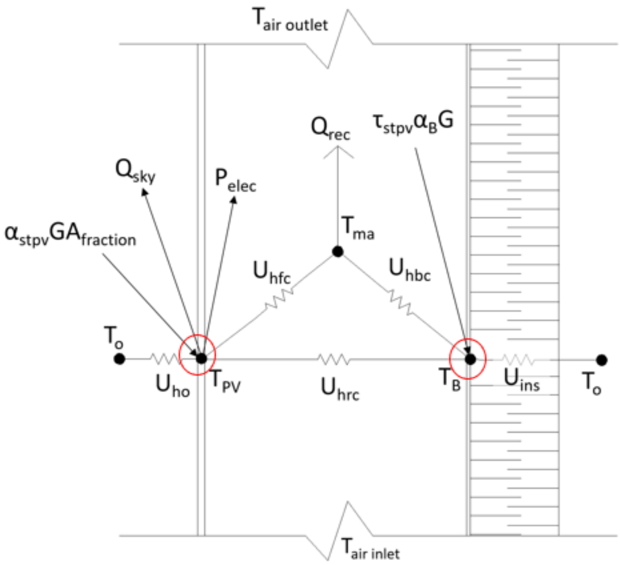


Fig. 4: BIPV/T thermal network

Due to the low solar altitude of Iqaluit , Canada a façade integration was chosen instead of the low sloped roof to maximize the solar irradiance received on PV panels and to take advantage of the ground snow reflectance, and to better match the energy generation with the building's loads throughout the year. A roof integrated system could be advantageous if the building such as a hunting cabin is intended to be used primarily in the late spring and summer. Therefore, it is important to determine the intended usage and occupant schedule of the building and design the BIPV/T accordingly.

$$T_{air\ outlet} = \frac{T_{pv}+T_B}{2} + \left(T_{air\ inlet} - \frac{T_{pv}+T_B}{2}\right) * e^{\frac{-2L_{cv}}{A}} \quad \text{(eq.1)}$$

$$A = \frac{M*C_{p\_air}*\rho_{air}}{W_{ch}*\frac{(hb+hf)}{2}} \quad \text{(eq. 2)}$$

$$T_B = \frac{U_{hbc}T_{ma} + U_{hrc}T_{PV} + U_{ins}T_O + A_{CV} * \alpha_B * G * \tau_{STPVG}}{U_{hbc} + U_{hrc} + U_{ins}} \quad \text{(eq.3)}$$

$$T_{pv} = \frac{T_o U_{ho} + A_{CV} * \alpha_{STPV} * G * A_{fraction} - P_{elec} - q_{sky} * A_{CV} + T_{ma}U_{hf} + T_B U_{hr}}{U_{hr} + U_{ho} + U_{hf}} \quad \text{(eq.4)}$$

$$Q_{rec} = \dot{m} * C_{p\_air} * (T_{outlet} - T_O) \quad \text{(eq.5)}$$

$$P_{elec} = \eta_{pv} * \alpha_{pv} * G * A_{pv} \quad \text{(eq.6)}$$

$$Q_{sky} = e_1 * \sigma * (T_{PV} + 273.15)^4 - \left(T_{sky} + 273.15\right)^4 \quad \text{(eq.7)}$$

Semi-transparent photovoltaic (STPV) modules with a transparent glass between the solar cells, were selected to allow for a portion of the irradiance to reach the back cavity surface, reducing heat losses from the PV surface and increasing heat recovery. A packing factor of 0.9 is used. The PV properties are listed in Table 1 (Prism Solar, 2023) along with the assumed BIPV/T material properties listed in Table 2.

Table 1: PV Specifications (Prism Solar, 2023)

Model	**Prism Solar BI60-381BSTC**
Type	Mono-crystalline
Exterior Glass Dimensions	985 X 1696mm (1.67m^2) X 6.4mm
Module Efficiency	18.1%
Power Temperature Coefficient	-0.376%/C
STC Temperature	25°C
STC Power	300W

Table 2: Parameters assumed for BIPV/T

BIPV/T
STPV Absorptance=0.85
Back cavity surface absorptance= 0.9
Packing factor of STPV=0.893
Emissivity of Glass=0.9
Emissivity of Insulation= 0.6

3. Results

The airflow through the BIPV/T is assumed to be via a residential HRV with a range of volumetric air flow of 15.5L/s to 40.5L/s. Major outputs from the simulation were the BIPV/T outlet air temperature, the heat recovered and the electricity generation. As shown in eq. 1, eq. 2, and Fig. 5, the peak daily outlet temperature for April, follows an exponential decay trend dependent on the cavity length. Since a typical single-story house has a usable façade height of approximately 2 m to 3m it can be seen that the outlet temperature does not approach its peak for either the high or low flow rates at these heights. The asymptote can be seen in Fig. 5 to occur between cavity heights of 8m to 13m, therefore, a C-shaped cavity was designed, as seen in Fig 6, which increases the cavity length to approximately 10m.

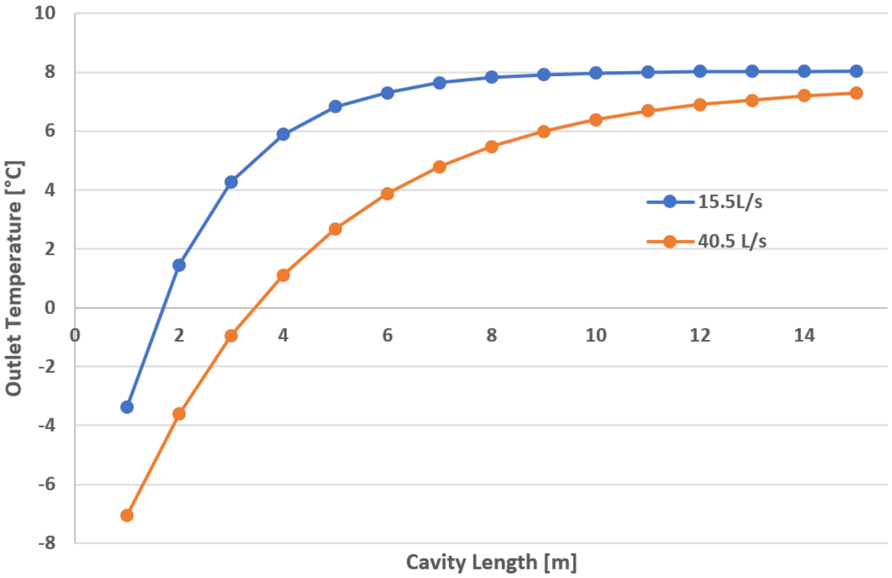


Fig. 5: BIPV/T Peak daily outlet temperature in April vs cavity length for Iqaluit, Canada

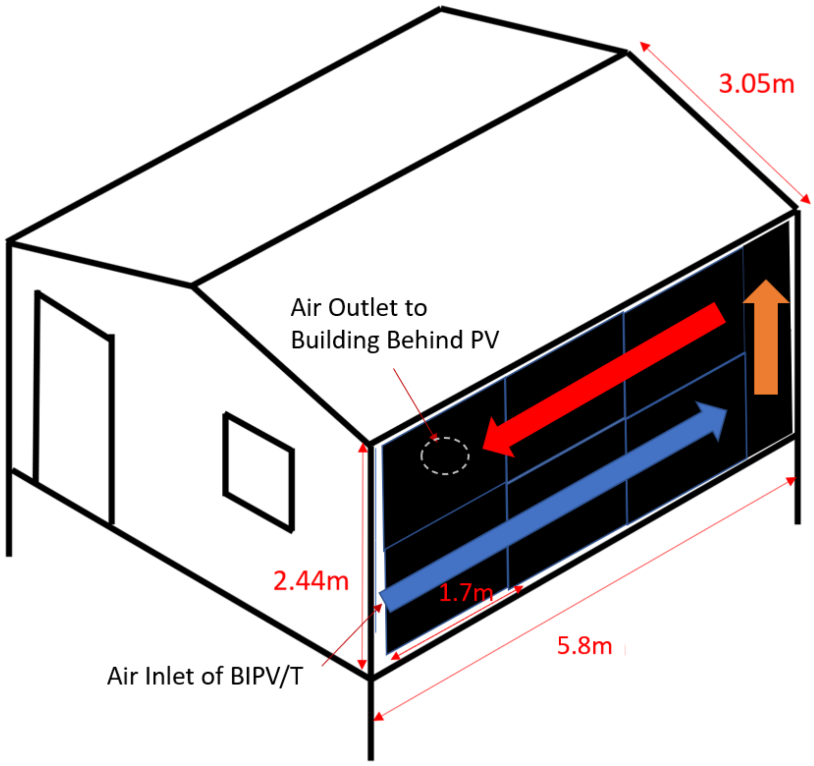


Fig. 6 C-Shaped BIPV/T

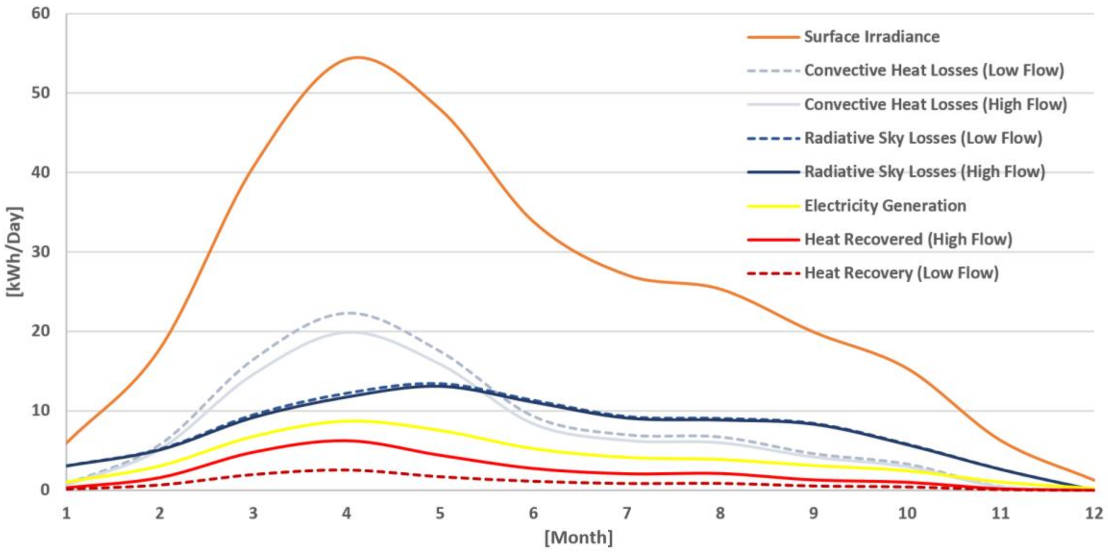


Fig.7: Solar energy conversion for 15.5L/s and 40.5L/s air flows using 10m cavity length

The surface solar irradiance is either reflected, converted to electricity, heat, or transmitted. The breakdown of the surface irradiance for the high air flow of 40.5 L/s and the low air flow of 15.5L/s is shown in Fig.7. Several strategies are available to decrease heat losses to the environment, such as increasing the cavity air flow rate, thus recovering more of the heat. As shown in Fig.7, as the air flow rate is increased from 15.5L/s to 40.5L/s, the convective and radiative losses are reduced and the heat recovered is increased. However, the increase of airflow rate reduces the air temperature rise through BIPV/T. As shown in Fig.8, the highest daily outlet temperature increases occur in April with a temperature increase of over 18°C at the low flow rate of 15.5L/s, while a delta T close to 14°C at the highest flow rate of 40.5L/s.

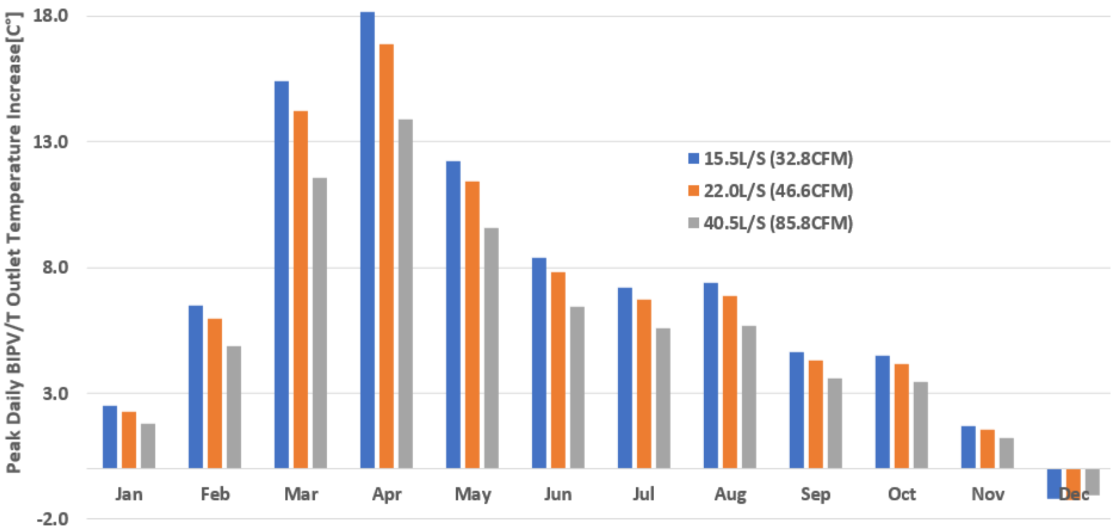
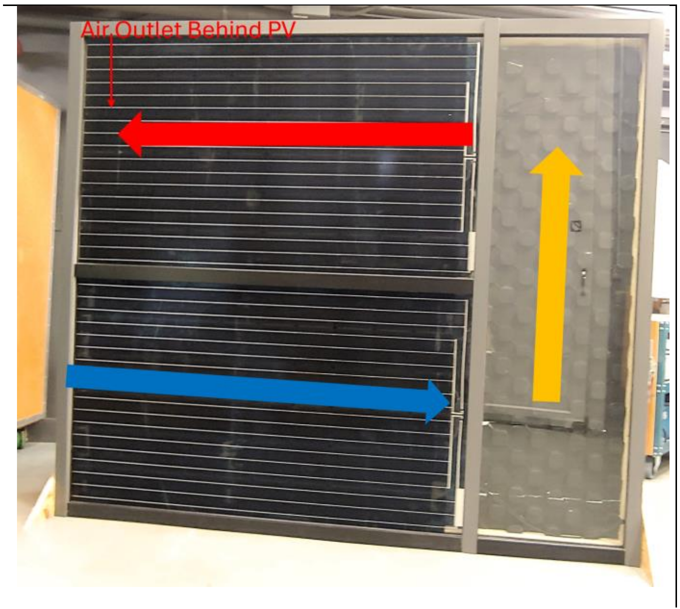


Fig.8 Daily peak BIPV/T outlet air temperatures increase

However more strategies are needed to increase the heat recovery, such as increasing the convective heat transfer from the back cavity surface U_{hbc}. As studied by (Nghana et al., 2023) it was seen that adding transverse ribs to the air cavity helped increase the air turbulence thus increasing the convective heat transfer from the cavity surfaces to the air, reducing the PV temperature, increase PV efficiency. To study the thermal enhancements for a BIPV/T, an experimental prototype has been designed (shown in Fig.9), similar to the curtain wall BIPV/T system developed by (Rounis et al., 2021), and will be tested in a solar simulator and environmental chamber lab (Fig.10), with the objective to validate the simulation model for the C- shaped cavity as well as testing the heat transfer enhancements such as alternative cavity back surfaces to increase convective heat transfer U_{hbc} by increasing the air turbulence from the cavity back surface. Other experimental objectives include testing of air flow control strategies to maximize heat recovery when applicable, and improving durability of the design to withstand the harsh Arctic environment. Upon completion of these objectives a field prototype will be fabricated and shipped to a northern village for installation on a demonstration house for continuous field monitoring to evaluate the performance of the system throughout all seasons of the year.

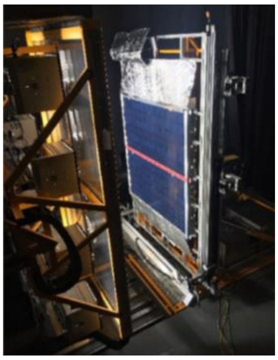
(a) Back Cavity Surface



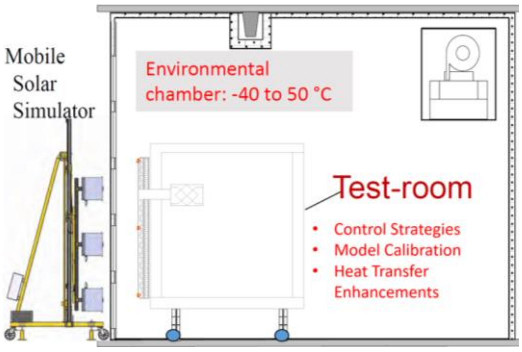
(b) Integrated STPV and flow path

Fig. 9 BIPV/T Prototype

(a) Solar simulator test bed



(b) Mobile solar simulator lamp field



(c) Environmental chamber experimental set up

Fig.10: Concordia's Solar Simulator and Environmental Chamber Lab

4. Discussion

The average monthly peak daily outlet temperatures can be seen in Figure 11. The peak values are seen to occur in July and August when the outdoor air temperatures are the highest with values over 16°C at the lowest flow rate. As these average peak annual values are well under the typical room set point temperature of 20-22°C, the pre-heated air from the BIPV/T can be assumed to be of value almost all year round without risk of over heating the indoor space. However for periods of time when outlet temperature values are greater than 20°C are encountered then a control strategy can be implemented to increase the air flow rate, thus decreasing the outlet temperature and recovering additional heat while there is no need for HRV defrosting. Another option is the integration of the BIPV/T with an air to water heat pump, which allows for coupling with the building's hydronic heating system and leads to the possibility of thermal storage. By controlling the airflow rate the optimal balance between outlet temperature and heat recovery can be used to boost the coefficient of performance (COP) of the heat pump and facilitates thermal storge of excess heat in water tanks or thermal mass.

Other unique thermal enhancement opportunities in the extreme cold Arctic climate is the addition of low-emissivity coatings to the inside of the outer glass surface to reduce the radiative heat losses, as well as the possibility to add an additional glazing cover to reduce the convective wind losses. While an increase in PV temperature can reduce the PV efficiency and lifespan of the module, the cold outdoor temperatures reduces the risk of over heating and when used with airflow control the air speed can be modulated to maximize the balance between PV generation and heat recovery, resulting in a increased electrical and thermal efficiency.

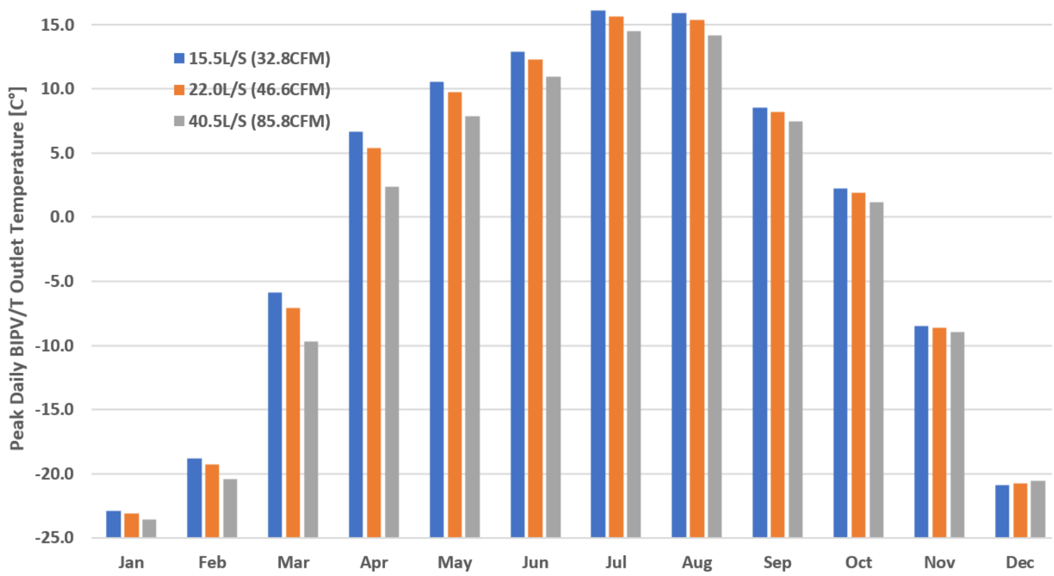


Fig. 11 Daily peak BIPV/T outlet temperature

5. Conclusions

An air-based BIPV/T system design project for a low-Arctic residential application has been started. From initial simulation modelling, the 2.4m air cavity length using the one story demonstration house needed to be increased to maximize the outlet air temperature, therefore an alternative C-Shaped channel design was chosen to increase the cavity length to 11m. The increased cavity length resulted in outlet temperature increases up to 18°C in April and more than 6.2kWh of heat recovery per day and approximately 1436kWh/year of electricity and 814kWh/year of heat. An experimental prototype has been designed and fabricated to be tested in a solar simulator and environmental lab to validate the simulation model as well as to test heat transfer improvements, using an alternative back cavity surface material to increase turbulence and convective heat transfer for improved thermal efficiencies, as well as to test air flow control strategies to prepare for a field monitoring project in a low-Arctic community of Canada.

6. Nomenclature

α_{STPV} –Absorptance of STPV
α_B –Absorptance of cavity back surface
$A_{fraction}$-Surface area of PV, m^2
Cp_{air} -Specific heat of air, kJ/kgK
hb-Cavity back convective heat transfer coefficient, W/(m^{2}K)
G – Incident irradiance, W/m^2
L_{cv}-Length of control volume, m
M – Volumetric flow rate, m^3/s
ρ_{air} -Density of air, kg/m^3
P_{elec}-Electrical energy generated, W
Q_{rec}-Heat recovered, W/m^2
T_{ma}-Cavity air mass temperature, °C
T_O - Outdoor Dry Bulb Temperature, °C
$T_{Air\ Inlet}$ – BIPV/T Inlet Temperature, °C
$T_{Air\ Outlet}$ – BIPV/T Outlet Temperature, °C
T_{pv}-PV Module temperature, °C
Uhf-Cavity front convective heat transfer coefficent, W/(m^{2}K)
Uhb-Cavity back convective heat transfer conductivity, W/(m^{2}K)
Uhf- Cavity front convective heat transfer conductivity, W/(m^{2}K)

Q_{sky}-Heat losses to sky, W/m^2
τ_{STPV} –Transmittance of STPV
T_B- Cavity back surface temperature, °C
Uho- Exterior convective heat transfer conductivity, W/(m^{2}K)
$Uhrc$- Cavity radiative heat transfer conductivity, W/(m^{2}K)
U_{ins}-Wall thermal conductivity, W/(m^{2}K)
W_{ch}-Width of cavity, m

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