Integration of Building Integrated Photovoltaic/Thermal (BIPV/T) System with Heat Recovery Ventilators for Improved Performance under Extreme Cold Climates

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Abstract. The reliable operation of Heat Recovery Ventilator (HRV) is critical for maintaining a healthy indoor environment to remove contaminants and moisture, however, it remains a challenge in the Northern Canada due to the frequent frosting under the extreme cold conditions. The heat generated by a building-integrated photovoltaic/thermal (BIPV/T) system can be used to pre-heat the incoming fresh air in HRV in order to reduce its defrost cycle, therefore, improving the reliability of HRV to provide adequate ventilation required. In this case, the BIPV/T needs to be designed for higher air temperature rise, which may not be optimum for the thermal energy and PV power generation. Therefore, system integration and optimization for coupling BIVP/T with HRVs is required. Depending on the level of thermal energy available and the outlet air temperature from the BIPV/T system, a control strategy needs to be developed to optimize the operation of HRVs. This paper presents the analysis of four different BIPV/T configurations and their integration with HRVs for a 120 m^2 house located in Iqaluit, NU, Canada through modelling. Results show that the outlet air of a BIPV/T façade installation can be 14.8 °C higher than outdoor air on a clear sky winter day and that the defrost cycle can be reduced by 13%, up to 619 hours annually.

Keywords: Building integrated photovoltaics/thermal (BIPV/T); heat recovery ventilator (HRV); System integration; Defrost cycle; Extreme cold climate; Canadian Northern region.

1 Introduction

Extreme weather (temperatures below -40 °C, snow storms, hail, etc.), high dependence on fossil fuels and high electricity cost (10 times higher than the Canadian average) constitute not only obstacles but also opportunities for Northern Canada housing, creating a push towards the increase of building efficiency and the exploitation of renewable source of energy [1]. Among the different sustainable housing practices, the implementation of BIPV/T systems is promising because it introduces an envelope concept that simultaneously generates electricity and recovers thermal energy, transforming the building skin into an active system [1]. The heat recovered from the photovoltaic (PV) panels can be used for pre-heating the supply inlet air of a HRV, a device that not only reduces the energy required for heating but also offers health benefits for the building occupants. Thus, the coupling of the two systems can help prevent frost formation, a major problem for HRVs in cold climates. The formation of frost in HRV reduces the efficiency of the system and can provoke damage or system failure, if it is not controlled [2]. As a consequence of the coupling, the reliability of the system, which is critical to maintain a healthy indoor environment through the removal of moisture and contaminants, can be improved. The aim of this paper is to study different integration scenarios of BIPV/T systems with HRV. Four different configurations are analysed for a 120 m^2 house located in Iqaluit, NU, Canada through a MATLAB model and compared in order to determine the reduction of defrost cycle and the energy generation of each scenario.

1.1 Building integrated photovoltaics/thermal (BIPV/T)

A BIPV/T system is a photovoltaic system that is incorporated in the envelope of a building and produces both electricity and thermal energy recovering heat from the PV panels [3]. The system is not only a simple addition to the building but also an active part of its envelope, changing the various loads (heating, cooling and lighting), that can be coupled with other energy systems such as a heat recovery ventilator or a heat pump [4]. The PV panels form the exterior layer/cladding of the walls or roof and as such also act as a rainscreen managing various environmental loads.

1.2 Heat recovery ventilator (HRV)

Air-to-air heat exchangers used as HRVs are devices that exchange sensible heat between two air-steams [5,6]. Their main use in residential or commercial building is the pre-heating/cooling of supply air. Major advantages of HRVs include not only energy saving and reduction of fossil fuel consumption but also removal of indoor air contaminants and prevention of respiratory disorders [2]. However, problems in their operation can occur if implemented in cold climates. At low outdoor air temperatures, frost formation within the exchanger core starts due to the condensation of water-vapour in the exhaust air [7]. As a consequence, the efficiency of the system is reduced and, if no measures are implemented to stop the phenomenon, failure and/or damage can occur [2]. Different techniques are implemented to solve this problem; such as defrost methods like recirculation of exhaust air or supply fan shutoff, or frost control methods like the pre-heating of cold supply air before its entering the exchanger core. The last strategy can significantly affect the system efficiency and be very expensive due to the use of fossil fuel, but, at the same time, it offers a good possibility of integration with BIPV/T [5-8].

1.3 Integration of BIPV/T with HRV

The integration and optimization of these two technologies is a recent topic of research, especially for cold climates. An interesting study was conducted by Natural Resources Canada - CanmetENERGY. In this paper, Maayan Tardif et al. [9] studied the performance of different heat management strategies in an all-electric Canadian home located in Montréal, QC, in which one of the scenarios used the preheated air from a roof BIPV/T system as supply inlet air of a HRV. This case consisted of a 12.75 m^2 installation on 40° slope south-facing roof. The annual electric energy consumption for heating and domestic hot water was 12338 kWh for the base case with electric furnace (no BIPV/T and HRV). During the heating season and whenever solar radiation was above 50 W/m^2, pre-heated air was fed to the HRV; on the other hand, when solar radiation was not available and during the non-heating season, outdoor air was used as inlet of the HRV. Results showed a promising maximum increase in pre-heated air temperature of 21 °C, however, the reduction of heating and domestic hot water energy consumption was only 1%, as a result of the small amount of energy recovered due to the low availability of solar radiation during the heating season.

2 Methodology

Different configurations of the BIPV/T system in terms of tilt angle of the surface and air speed in the cavity behind the PV panels are considered. The first scenario (Scenario Façade 90) is a south-facing façade installation of PV panels (90° from the horizontal). The second (Scenario Roof 10), third (Scenario Roof 20), and fourth (Scenario Roof 30) scenarios model a south-facing roof installation of the system with roof tilt angle among the most common roof inclination for Northern Canada (namely 10°, 20°, and 30°) [1]. For every single configuration, a one-year simulation with hourly weather data at different air speeds (from 0.5 to 2.5 m/s) is performed using a code implemented in MATLAB. After the sensitivity analysis, the air speed that maximizes the integration with the heat recovery ventilator system is chosen and the main results are presented and compared. In the last part of the paper, the main findings are summarized and conclusions are drawn.

2.1 Location

The selected location for the simulation is Iqaluit (63.75° N, 68.55° W) in the Nunavut territory. It was chosen for the simulation because it represents an example of the challenges related to housing in extreme cold climates and for the availability of reliable weather data for a Typical Meteorological Year (TMY) [10]. Table 1 shows the typical climatic parameters for the location, while daily average, maximum and minimum temperatures over 30 years in °C are presented in Table 2 [11]. The outdoor temperature and the Global Horizontal Radiation (GHR) for an average day[1] and a clear sky day[2] of summer and winter are shown in Fig. 1 (left) and Fig. 1 (right), respectively.

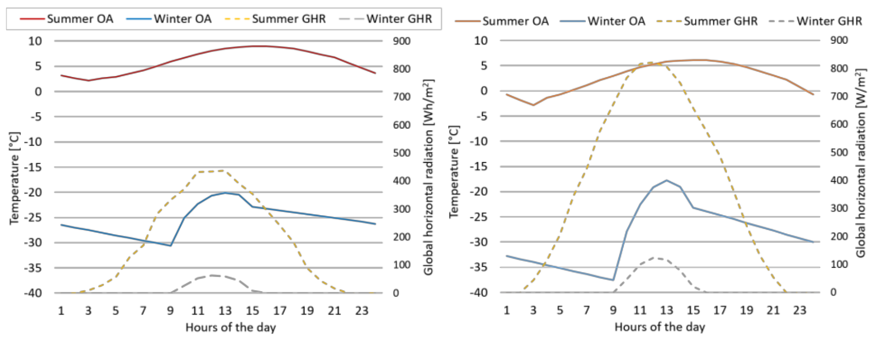
Table 1. Typical climatic parameters for Iqaluit [11]

Heating degree days (HDD 18)	10117.4 days
Cooling degree days (CDD 18)	0 days
Annual beam (direct normal) radiation	1421.5 kWh/m^2
Annual diffuse radiation	426.0 kWh/m^2
Annual days with daily GHR below 200 Wh/m^2	60 days

Table 2. Monthly temperature of Iqaluit [11]

Temperature	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average [°C]	-26,6	-28	-23,7	-14,8	-4,4	3,6	7,7	6,8	2,2	-4,9	-12,8	-22,7
Maximum [°C]	-22,5	-23,8	-18,8	-9,9	-0,9	6,8	11,6	10,3	4,7	-2	-8,9	-18,5
Minimum [°C]	-30,6	-32,2	-28,6	-19,6	-7,8	0,3	3,7	3,3	-0,4	-7,7	-16,7	-26,9

1. An average day is estimated by calculating the mean of the weather parameters of the days of the seasonal typical week indicated in the TMY data. For Iqaluit, the typical summer week is July 13 to July 19, and the typical winter week is January 20 to January 26 [10].
2. January 29 and June 16 of a TMY were chosen as representative clear sky days, due to their low value of daily average sky cover, a value of 1.63 and 0.58, respectively [10].



(a) Average day (b) Clear sky day

Fig. 1. Representative weather data for Iqaluit [10,11]

2.2 House model

The building considered is a 12 m by 10 m house with attic and a floor height of 3.43 m representing a low-energy house built in this region (see Fig. 2) [12]. The external envelope is an R-45 (8.0 m^2K/W) Structural Insulated Panel (SIP) wall, a pre-fabricated high-performance envelope system, whereas the ceiling envelope is R-70 (12.4 m^2K/W). The indoor conditions are 22 °C and 30% of relative humidity and the fresh air intake necessary to satisfy Indoor Air Quality (IAQ) is 0.035 m^3/s as defined by ANSI/ASHRAE Standard 62.2-2016 [5,13].

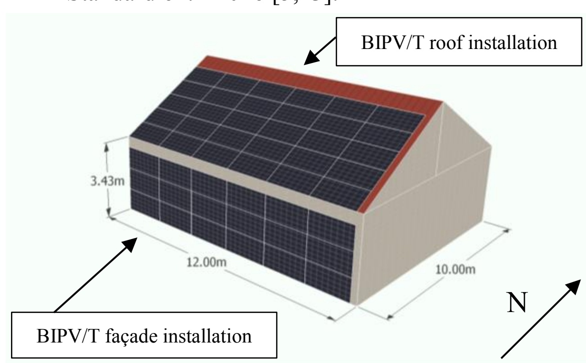


Fig. 2. 3D model of the house

As a benchmark for the energy consumption of the house, the E/2 Northern Sustainable House (NSH) is considered, which is a 127.8 m^2 one-storey household with three bedrooms, designed and built by the Nunavut Housing Corporation under the NSH initiative of Canada Mortgage and Housing Corporation (CMHC), due to its representative role for the energy-efficient and cultural appropriate housing models for Northern Canada [14]. The household has an annual consumption of 9180 kWh of electricity and 20556 kWh of heating oil. The main energy-performance related details of the house are presented in [14].

2.3 BIPV/T model

The system is an air-based open-loop BIPV/T, which uses Canadian Solar poly-Si modules with efficiency of 16.16% and nominal power of 310 W at standard conditions [15]. It is mechanically ventilated by a fan in order to provide a constant air flow as modelled in Yang [16]. Its consumption varies from approximately 5 kWh/y at 0.5 m/s to approximately 500 kWh/y at 2.5 m/s with a 20% efficiency [3]. The reduction of collected energy due to snow cover on a roof tilted at an angle below 60° is neglected.

Performance parameters. The annual electricity production of the BIPV/T system is calculated using Equation 1:

$$E_{PV} = \sum_{i=1}^{8760} S_i \alpha_w \eta_{PV_i} A_w - E_{fan_i} \tag{1}$$

where S_i is the hourly solar radiation received on the surface in kWh/m^2, α_w is the absorptivity of the BIPV cladding, η_{PV_i} is the hourly PV module efficiency, A_w is the surface area in m^2, and E_{fan_i} is the hourly electricity fan consumption in kWh. The heat gained by the air during its passage through the cavity is:

$$Q_{air} = \sum_{i=1}^{8760} \dot{m}_\iota c_{air} (T_{outlet,a_i} - T_{o,i}) \tag{2}$$

where $\dot{m}_\iota$ is the hourly mass flow rate in kg/s, c_{air} is the specific heat of air in kJ/kgK, T_{outlet,a_i} is the hourly temperature of air at the outlet of the cavity in °C calculated with the model presented in Kayello et al. [12], and T_{o_i} is the hourly outdoor temperature in °C. The electrical and thermal efficiency of the system are [17]

$$\eta_{el} = \frac{E_{PV}}{SA_w} \tag{3}$$

$$\eta_{thermal} = \frac{Q_{air}}{SA_w} \tag{4}$$

where S is the annual solar irradiance on the surface in kWh/m^2. The combined efficiency is as follows [17]:

$$\eta_{combined} = \frac{E_{PV}+Q_{air}}{SA_w} \tag{5}$$

The electricity savings are calculated with the following equation

$$E_{savings} = \frac{E_{PV}}{E_{E/2\,NSH}} 100 \tag{6}$$

$$HO_{savings} = \frac{Q_{air}}{Q_{E/2\,NSH}} 100 \tag{7}$$

where $E_{E/2\,NSH}$ and $Q_{E/2\,NSH}$ are the electricity and heating oil consumption in kWh of the E/2 NSH house, respectively.

2.4 HRV

The heat recovery ventilator uses outdoor air either directly or pre-heated by the BIPV/T system depending on the temperature. The operating strategy is summarized in Table 3. When Pre-heated Air (PA) temperature is lower than Outdoor Air (OA) temperature, HRV draws outdoor air directly. When the PA temperature is higher than OA temperature but lower than 25 °C, the air from the BIPV/T system is utilized in the HRV. When the PA temperature is higher than 25 °C and there is heating demand from the house, BIPV/T outlet air can be supplied directly to the house for Direct Space Heating (DSH) while indoor air can be exhausted directly without heat recovery. When the PA temperature is higher than 25 °C while there is no heating demand from the house, the thermal energy generated by BIPV/T can be used for other applications such as pre-heating domestic hot water or exhausted while the OA will be used in HRV.

Table 3. HRV control strategy

$T_{outlet,a} < T_o$	$\Rightarrow$	OA to HRV and PA to other purposes
$T_{outlet,a} \geq T_o$	$\Rightarrow$	$T_{outlet,a} \leq 25\,°C$ $\Rightarrow$ PA to HRV $T_{outlet,a} > 25\,°C$ during heating season $\Rightarrow$ PA to DSH $T_{outlet,a} > 25\,°C$ during non-heating season $\Rightarrow$ OA to HRV

Note that the air entering the HRV is a portion of the outlet air of the BIPV/T system, as the HRV provides solely the flow rate required for an adequate IAQ, and, thus, the surface area of the PV modules required for HRV purposes is smaller and defined as:

$$A_{HRV} = h_{PV} \times \frac{\dot{V}_{IAQ}}{l \times V_{air}} \tag{8}$$

where h_{PV} is the height of the PV installation in m, $\dot{V}_{IAQ}$ is the IAQ air flow rate in m^3/s, l is the width of the air cavity in m, and V_{air} is the air speed in the cavity in m/s.

An important parameter to be considered is the frosting limit, which is defined as the lowest inlet supply air temperature that does not lead to frost formation. A typical value is -5 °C for relative humidity levels of typical indoor air in sensible heat exchanger cores as experimentally verified in [2,5,7,18], hence in cold climate it is necessary to implement a defrost mechanism in order to avoid the frost formation on the surfaces of the heat-exchanger core [19].

Performance parameters. The following parameters are used to evaluate the integration of the BIPV/T with HRV:

- frost risk (FR) time t_{FR}: number of hours when OA temperature is lower or equal to the frosting limit;
- frost control (FC) time t_{FC}: number of hours when PA temperature is higher than the frosting limit while the OA temperature is below or equal to the frosting limit;
- pre-heated air time t_{PA}: number of hours when PA is used as supply inlet air of the HRV (PA mode);
- outdoor air time t_{OA}: number of hours when OA is used as supply inlet air of the HRV (OA mode);
- direct space heating time t_{DSH}: number of hours when PA is used for direct space heating (DSH mode).

3 Simulation

Input data are divided into fixed parameters, which are constant in every scenario, and variable parameters, which represent the key variables to be used for identifying the best configuration of the system and are changed in different cases. The variable parameters include the tilt angle of the surface β_c and the air speed in the cavity v_{air}. An overview of the scenarios is shown in Table 4.

Table 4. Overview of the scenarios

Scenario	Tilt angle	Number of PV modules	Surface area	Area sufficient for HRV	Air speed in BIPV/T cavity
Façade 90	90°	18	34.54 m^2	From 8.25 m^2 to 1.65 m^2	From 0.5 m/s (0.15 m^3/s) to 2.5 m/s (0.73 m^3/s)
Roof 10	10°	30	57.56 m^2	From 13.75 m^2 to 2.75 m^2	
Roof 20	20°	30	57.56 m^2	From 13.75 m^2 to 2.75 m^2	
Roof 30	30°	30	57.56 m^2	From 13.75 m^2 to 2.75 m^2	

3.1 Sensitivity analysis

The electricity and thermal energy generation[3] per installed m^2 are presented in Fig. 3 (left) and Fig. 3 (right), respectively. It can be seen that Scenario Façade 90 has the best energy production performance, followed by Scenario Roof 30, Roof 20, and Roof 10, due to better exploitation of low radiation period for closeness to the optimal tilt angle of the location (the latitude). The four scenarios have a similar trend for electricity reaching a peak between 0.75 and 1.25 m/s and then decreasing of approximately 3.5% as the fan consumption rises with the increase of velocity, while for thermal energy there is an upward trend with an increase approximately 200% due to higher air mass flow rate.

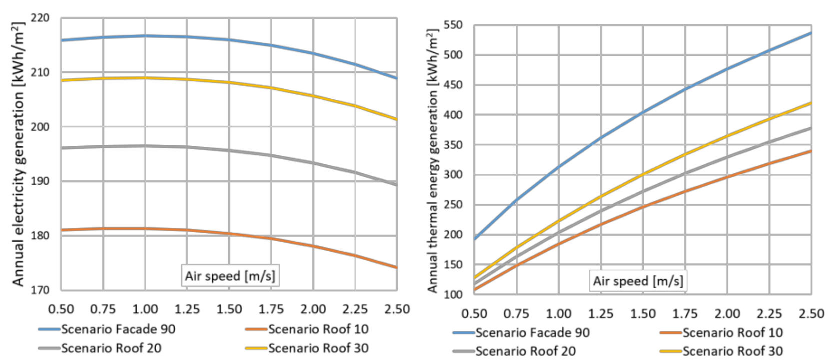


Fig. 3. Sensitivity analysis: annual electricity (left) and thermal energy (right) generation per installed m^2

As for the integration with HRV, the frost control time hours fall while the speed of the air in the cavity rises as shown in Fig. 4 (left). Scenario Façade 90 reaches 619 hours at 0.5m/s and then is the second best until the air speed is just below 1.25 m/s when it is overcome by Scenario Roof 20. This is because the air is pre-heated in the façade installation for a shorter distance compared to the roof scenarios, thereby an

[3] In this paper, electricity generation includes also the fan electricity consumption, thus, it is a net electricity production. However, in general electricity generation does not consider the consumption of the fan.

increasing air speed gains lower thermal energy. The performance of Scenario Façade 90 is worse compared to the remaining scenarios, as it declines significantly faster than the others (37.80%), while the three roof scenarios have an approximately constant downward trend (decrease between 27.76% and 30.83%). Higher roof inclination has greater number of frost control hours.

The maximum difference in temperature between OA and PA for an average summer and winter day are shown in Fig. 4 (centre) and Fig. 4 (right), respectively. It can be seen that in the two seasons and for every scenario the maximum temperature difference decreases as the air speed rises. This is due to a higher air mass flow rate of air passing through the cavity. The façade installation performs better in winter when the sun is low on the horizon with a maximum increase of 6.58 °C whereas the 30° slope roof configuration has the best performance in summer with a 15.34 °C temperature rise.

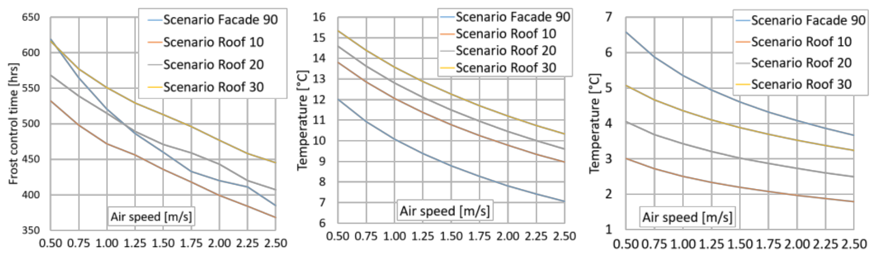


Fig. 4. Sensitivity analysis: frost control time (left) and maximum temperature difference between OA and PA for an average summer (centre) and winter (right) day.

4 Results

The results of the simulation with an air speed of 0.5 m/s, which maximizes the frost control time and, therefore, the integration with HRV, are summarized in Table 5.

Table 5. Main results of the simulation

Scenario	Facade 90	Roof 10	Roof 20	Roof 30
Annual electricity production [kWh]	7454.49	10422.56	11289.25	12002.86
Annual electricity production [kWh/m^2]	215.83	181.06	196.11	208.51
Electricity savings [%]	81.20%	113.54%	122.98%	130.75%
Annual thermal energy production [kWh]	6647.72	6214.23	6806.17	7388.97
Annual thermal energy production [kWh/m^2]	192.47	107.95	118.23	128.36
Heating oil savings [%]	32.34%	30.23%	33.11%	35.95%
Electrical efficiency [%]	16.08%	16.11%	16.05%	15.99%
Thermal efficiency [%]	14.34%	9.61%	9.68%	9.84%
Combined efficiency [%]	30.42%	25.72%	25.72%	25.83%
Maximum BIPV/T cladding temperature [°C]	51.05	50.14	52.83	55.04
Frost risk time [hrs]	4763	4763	4763	4763
Frost control time [hrs]	619	532	568	616
Pre-heated air time [hrs]	8568	8543	8492	8427
Outdoor air time [hrs]	0	0	0	0
DSH time [hrs]	192	217	268	333
FC time relative to FR time [%]	13.00%	11.17%	11.93%	12.93%

4.1 General results

It can be seen that, while the electricity production increases from 7454.49 kWh (81.20% of the electricity requirement of the household) in Scenario Façade 90 to 12002.86 kWh (130.75% of the building's need) in Scenario Roof 30, the heat generation decreases from 6647.72 kWh in the façade installation to 6214.23 kWh in the 10° tilt angle roof configuration but it increases from Scenario Roof 20 (6806.17 kWh) to Scenario Roof 30 (7388.97 kWh). This different patterns are because façade and roof scenarios differ in both surface areas, air path length, and amount of solar radiation. When the energy production is analysed per installed m^2, both the electricity and thermal output follow the same trend: Façade 90 is the highest followed by Roof 30, Roof 20 and Roof 10. The thermal output is 192.47 kWh/m^2 for façade 90, 128.36 kWh/m^2 for roof 30, 118.23 kWh/m^2 for roof 20 and 107.95 kWh/m^2 for roof 10. The electricity output for is 215.83 kWh/m^2 for façade 90, 208.51 kWh/m^2 for Roof 30, 196.11 kWh/m^2 for Roof 20 and 181.06 kWh/m^2 for Roof 10.

Thermal efficiency is 5% higher in Scenario Façade 90 than in the roof configurations (between 9.61% and 9.84%) whereas electrical efficiency remains approximately constant among the different scenarios (approximately 16.05%). As the variation in thermal efficiency is higher than the variation of the electrical efficiency, combined efficiency follows the same trend of thermal efficiency.

4.2 Integration with HRV

Fig. 5 shows the frost control time and frost control time relative to the frost risk time. Outdoor temperature is below -5 °C for 4763 hours, which corresponds to the 54.37% of the year. The coupling of BIPV/T with HRV reduces the formation of frost in all four scenarios. The maximum reduction of frost condition is achieved by Scenario Façade 90 with a decrease of 13.00%, followed by Scenario Roof 30, Scenario Roof 20, and Scenario Roof 10 in this order. As a consequence, the HRV system avoids entering the defrost cycle for 619 hours with Scenario Façade 90, for 532 hours with Scenario Roof 10, for 568 hours with Scenario Roof 20, and 616 hours with Scenario Roof 30 compared to a system without BIPV/T air preheating.

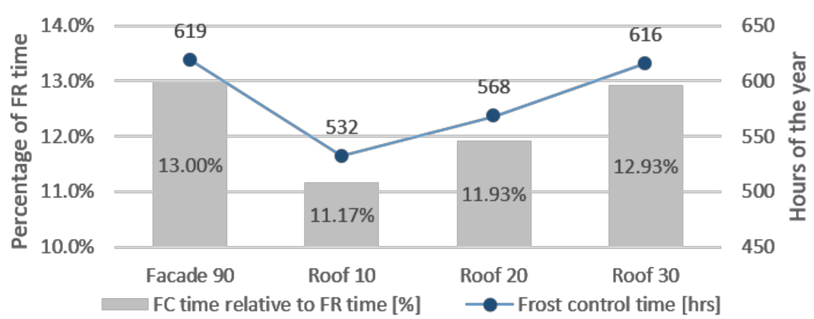


Fig. 5. Frost control time and frost control time relative to frost risk time

Fig. 6 (top) shows the daily trend of outdoor temperature and air outlet temperature for an average summer day and an average winter day. In summer, Scenario Roof 30 presents the best performance with a maximum increase in temperature of 15.34 °C, followed by Scenario Roof 20 and Roof 10 with 14.59 °C and 13.81 °C, respectively, while Scenario Façade 90 increases the temperature of 12.01 °C. However, in winter, Scenario Façade 90 produces an increase of 6.57 °C, which is a temperature rise higher than the one achieved in Scenario Roof 10 (3.01 °C), in Scenario Roof 20 (4.04 °C), and in Scenario 4 (5.07 °C). On a clear sky day, the same trend of performance is seen but the increase in temperature is higher as shown in Fig. 6 (bottom). In summer, PA is 24.84 °C hotter than OA for Scenario Roof 30, 22.91 °C for Scenario Roof 20, 20.76 °C for Scenario Roof 10, and 19.76 °C for Scenario Façade 90. On the other hand, in winter the façade installation produces air 14.81 °C hotter than the ambient, while the increase in temperature of PA is 5.74 °C for Scenario Roof 10, 8.34 °C for Scenario Roof 20, and 10.91 °C for Scenario Roof 30.

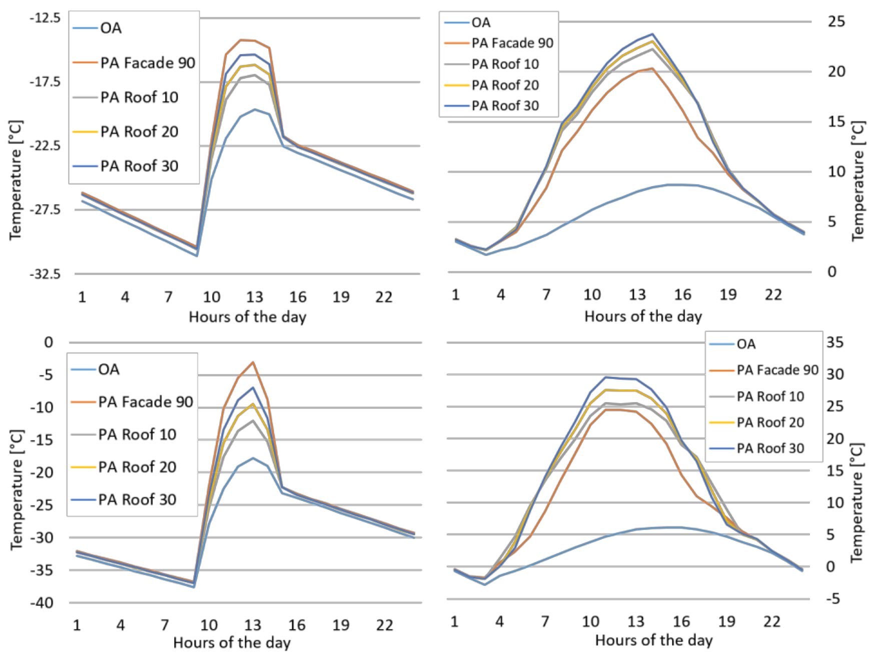


Fig. 6. PA and OA temperatures of a typical winter (top left) and summer (top right) day, and of a winter clear sky (bottom left) and summer clear sky (bottom right) day

5 Conclusion

Four different configurations of a BIPV/T system with HRV have been examined for a 120 m^2 house in Iqaluit, NU, Canada. Annual simulations were performed to analyse the configurations of the system with different tilt angles of the surface and air speeds in the cavity. The sensitivity analysis revealed that the cavity air speed that maximizes the electricity production does not optimize the integration with HRV. Indeed, an air speed of 0.5 m/s achieves the highest frost control time whereas the scenarios reach the peak of the electricity production with velocity between 0.75 and

1.25 m/s. For this reason, the 0.5 m/s air speed was chosen for the further analysis of the systems. Results show that, even if Scenario Façade 90 has the smallest PV installation area, the façade installation is able to generate more energy during the winter months and, therefore, to optimize the integration with HRV in the period when it is more needed, achieving a maximum temperature increase between PA and OA of 6.57 °C and of 14.81 °C during an average and clear sky winter day, respectively. As a consequence, the pre-heated air from the façade installation of the PV modules reaches a temperature above the frosting limit for 619 hours, therefore, reducing the need of defrost cycle by 13% and it achieves a heating oil saving of 32.34% compared to a system without BIPV/T pre-heating. This paper shows that the integration of BIPV/T with HRV is useful to improve the performance of a heat recovery ventilator in cold climates reducing the time needed for defrost cycles, especially if the PV modules are installed on the south-facing façade of a building. Future work should focus on the analysis of the energy consumption of HRV and investigate the energy benefit provided by the integration with BIPV/T.

References

1. Chen, Y.: Design and Evaluation of Facade-Integrated Solar Technologies Suitable for High-Latitude Applications. Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Canada (2012)
2. Beattie, C., Fazio, P., Zmeureanu, R., Rao, J.: A preliminary study of the performance of sensible and latent heat exchanger cores at the frosting limit for use in Arctic housing. Energy Procedia 78, 2596-2601 (2015)
3. Candanedo Ibarra, L.: Modelling and Evaluation of the Performance of Building-Integrated Open Loop Air-based Photovoltaic/Thermal Systems. Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Canada (2010)
4. Yang, T., Athienitis, A.: A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. Renewable and Sustainable Energy Reviews 66, 886-912 (2016)
5. Beattie, C.: Experimental study of air-to-air heat/energy exchangers for use in Arctic housing. Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Canada (2017)
6. Phillips, E., Chant, R., Fisher, D., Bradley, V.: Comparison of freezing control strategies for residential air-to-air heat recovery ventilators. ASHRAE transactions 95(2), 484-490 (1989)
7. Kragh, J., Rose, J., Svendsen, S.: Mechanical ventilation with heat recovery in cold climates. In : 7th Symposium on Building Physics in Nordic Countries, Reykjavik, vol. 1 (2005)
8. Rafati Nasr, M., Fauchoux, M.-, Besant, R., Simonson, C.: A review of frosting air-to-air energy exchangers. Renewable and Sustainable Energy Reviews 30, 538-554 (2014)

9. Maayan Tardif, J., Tamasauskas, J., Delisle, V., Kegel, M.: Performance of Air Based BIPV/T Heat Management Strategies in a Canadian Home. Procedia Environmental Sciences 38, 140-147 (2017)
10. Government of Canada: Engineering Climate Datasets. (Accessed 2017) Available at: HYPERLINK "http://climate.weather.gc.ca" http://climate.weather.gc.ca
11. Government of Canada: Canadian Climate Normals 1971-2000 Station Data: Iqaluit A. In: Government of Canada. (Accessed June 01, 2017) Available at: HYPERLINK "http://climate.weather.gc.ca" http://climate.weather.gc.ca
12. Kayello, A., Ge, H., Athienitis, A.: Attic Ventilation in Northern Canadian Climates. In : 15th Canadian Conference on Building Science and Technology, Vancouver, British Columbia, Canada, pp.1-16 (2017)
13. ASHRAE: Ventilation and Acceptable Indoor Air Quality in Residential Buildings., Atlanta (2016)
14. Canada Mortgage and Housing Corporation (CMHC): Arviat E/2 Northern Sustainable House Energy Consumption Performance Assessment., Ottawa (2015)
15. Canadian Solar Inc.: Max Power CS6X-310 | 315 | 320P. (Accessed September 2017)
16. Yang, T.: A Numerical and Experimental Investigation of Enhanced Open-Loop Air-Based Building-integrated Photovoltaic/Thermal (BIPV/T) Systems. Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Canada (2015)
17. Athienitis, A., Bambara, J., O'Neill, B., Faille, J.: A prototype photovoltaic/thermal system integrated with transpired collector. Solar Energy 85(2011), 139-153 (2010)
18. Fisk, W., Chant, R., Archer, K., Hekmet, D., Offerman III, F., S., P.: Onset of freezing in residential air-to-iar heat exchangers. ASHRAE Trans 91(Part 1B), 145-158 (1985)
19. Natural Resources Canada: Heat Recovery Ventilators. Office of Energy Efficiency, Natural Resources Canada, Ottawa, Canada (2012)
20. Athienitis, A.: Energy Analysis of Airflow Window with Roller Blind or Semitransparent PV Panel. Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Canada (2015)