Building Integrated Photovoltaic/Thermal (BIPV/T) (Air Based) System and its Potential in Building Facades Application in Toronto, Canada

Abstract

In this study, a series of simulations have been undertaken on Matlab to determine the hourly solar radiation on a vertically inclined surface in south, east and west orientations in Toronto. Temperature, electricity and COP computations for different array sizes of BIPV/T modules applied on the building orientations have been calculated on Matlab for typical winter days. Based on the highest design heating load of a four-storey commercial building, the compressor power and electricity generated to offset the power for one floor and the whole building have been assessed. The results show that a 12x6 BIPV/T array on the south façade in combination with a 12x4 BIPV/T array on the east and west facades can completely meet the compressor power demand for one floor between 10:00am and 5:00pm on a typical March day. The same system meets a half of the compressor power at 1:00pm for the whole building.

Introduction

Over the past few years, a high global economic growth intertwined with a rising population have contributed significantly to the fast pace of climate change and dwindling of fossil fuel reserves seen today (IPCC, 2019). In the backdrop of this changing energy landscape, mitigation efforts worldwide have looked at phasing out the reliance on traditional forms of energy sources such as coal, oil and natural gas in the different sectors of the economy. Studies have shown that a continued supply of energy to meet consumption, particularly in the OECD countries, results in sustaining continued economic growth (Aali-Bujari et al., 2017).

In contemporary times, there has been a special focus on enhancing energy efficiency in Canada's commercial building sector (Carlson & Pressnail, 2018). Despite the sector constituting only about 8% of the total primary energy consumption, it has experienced about a 34% increase in energy use from 1990 to 2016 (Natural Resources Canada, 2019). There has been a rising focus on solar energy recently due to development of technologies that can be used for the purpose of heating and electricity generation in buildings (Jagoda et al., 2011).

Background

Photovoltaics that are integrated in a building can be either applied on top of the building and be known as Building Applied Photovoltaics or are part of the envelope and be known as Building Integrated Photovoltaics (Frontini et al., 2012, p. 83). In addition to harnessing solar energy passively through adjusting building form and orientation, its active use typically encapsulates the application of appropriate technologies such as photovoltaics (PV) and solar collectors on building facades (Demain et al., 2013). Therefore, it is important that the implementation of these technologies is based on a "quantitative assessment of solar radiation incident on inclined surfaces" (Demain et al., 2013, p. 710). The effectiveness of solar technologies depends also on the overlying climatic conditions, as well as the latitude of the region where they are situated (Duffie & Beckman, 2013).

Hailu and Fung (2019) investigated different radiation models, i.e., isotropic and anisotropic models for the determination the solar radiation intensities on inclined PV panels at different tilt angles and orientations. The objective of this Greater Toronto Area-based study was to determine the optimum tilt angle of PV panels that could be possibly implemented when they are introduced on the rooftops of residential buildings. The study also explored the variation in outlet air temperature based on the variation of the PV orientation. Hailu and Fung (2019) used daily radiation data pertaining to the 12 months for the computations. The study found that the optimum angle for maximum solar radiation exposure varies throughout the year, whereby it is less in summer months, but rises from the spring to winter seasons. For the winter months, the optimum tilt angles were determined to be 63°-68° in the isotropic models, whereas they were found to be 66°-69° in the anisotropic models (Hailu & Fung, 2019).

In 2014, Hachem, Athienitis, & Fazio investigated the energy generation on multi-storey buildings spanning from three floors to twelve floors based in Montreal, Canada. The study examined different scenarios under which onsite electricity generation capacity of a multi-storey building could be augmented. Hachem et al. (2014) pointed out that the ratio of roof area to the total floor area decreases with a rise in the number of building storeys. On the other hand, the ratio of the building façade area to the gross floor area increases concurrently. The study findings were fundamentally that if 60% of the south façade and 80% of the east and west sides, in addition to a gable roof, are covered by BIPV panels, about 50% of the energy demand of a 12-storey building can be met. Furthermore, through appropriate strategies involving BIPV installation on the façades, the peak electricity generation could be spread for a couple of hours, thereby reducing the reliance on grid electricity.

Photovoltaics alone form part of standalone systems that are typically erected on rooftops or on open fields. However, photovoltaics can be combined with an in-built thermal energy extracting mechanisms, thus transforming them into hybrid photovoltaic-thermal systems (Tripanagnostopoulos et al., 2002). Similarly, a novel development in this field has involved harnessing heat energy from the BIPV modules, whereby this system is referred to as the BIPV/Thermal (or BIPV/T) systems. BIPV/T systems can be categorized as either air based or water based, and are so characterized due to the circulating fluid cooling the modules (Yang & Athienitis, 2016).

A BIPV/T unit essentially constitutes glass cover, PV cells, PV back surface, an air channel, and an insulating layer. At the different layers of the BIPV/T, heat transfer mechanisms such as convection, conduction and radiation need to be accounted for and represented in energy balance equations. Based on the constituent layers of a BIPV/T system, there is variation in the magnitude of heat flux going across. Therefore, for BIPV/T systems having transparent or opaque covers, the energy balance equations across each layer would need to reflect the radiative heat flux component (Agrawal & Tiwari, 2010; Hailu & Fung, 2019; Kamel & Fung, 2014b). Therefore, in addition to acting as an effective exterior cladding and a weather barrier, they provide the dual benefit of electricity generation and possible source for heated air used in conjunction with ASHPs for indoor heating purposes (Roberts & Guariento, 2009). In the process of converting solar radiation into electricity, photovoltaic panels also absorb thermal energy, whereby the accumulation of heat can reduce their performance. Based on the configuration of photovoltaics, the cell temperature varies and thus the power output (Skoplaki & Palyvos, 2009).

Kim, Park, and Kim (2014) undertook an experimental study on a photovoltaic thermal collector that was placed outdoors and tested under the standard conditions of 22°C. The findings underpinned a close connection between the temperature of the PV cell and solar radiation, whereby the two form directly proportional relationship. On the other hand, a higher temperature can reduce electrical efficiency. In relation to this, the study involved steady-state testing that served to examine the impact of PV operating temperatures on the electrical and thermal efficiencies of hybrid photovoltaic-thermal systems.

Kamel (2015) also examined the impact of varying duct depths (38mm, 51mm, 63mm and 76mm) and total mass flow of air (0.6kg/s, 1.2kg/s and 2kg/s) through different array configurations and sizes, whereby it was found that the maximum thermal energy was recovered when the duct depth was 38mm and mass flow of air was 2 kg/s. Increasing mass flow of air with decreasing duct dept was seen to increase the electricity generation too, however this was limited by the number of panels in an array (Kamel, 2015). Similarly, for the same mass flow rate, the results of the study indicated that the overall efficiency decreased as the array size increased.

The COP of ASHP drops during winter months, as it is affected by air entering the system at low ambient temperatures. Therefore, in addition to maintaining an optimum level of electricity generation, a few studies have looked at coupling photovoltaics with Air Source Heat Pumps (ASHP) (Vuong et al., 2015). The fundamental concept behind this arrangement relies on the removal of excess absorbed heat via an airflow behind the PV panels, such that this heat is drawn into the ASHP, thereby improving its Coefficient of Performance (COP) of the ASHP. This combined system maximises the functional operation of both the photovoltaics and the ASHP (Kamel, 2015). Past studies on the combined BIPV/T and ASHP system have involved simulations on software programs such as TRNSYS, MATLAB and EnergyPlus. Variables such as BIPV/T module tilt angle, rate of air mass flow, outlet air temperature, duct depth, optical properties of cover and orientation have been identified to impact the efficiency of the BIPV/T and ASHP system. Similarly, information regarding the geographical latitude, solar radiation and weather conditions also have a bearing on the overall performance (Hailu & Fung, 2019; Kamel & Fung, 2014a). The literature review on the subject, however, points to a vast majority of studies pivoting predominantly on the performance assessment of a BIPV/T and ASHP system in a residential setting.

In this study monthly averages of actual weather data would be utilized to determine the solar irradiation on the vertical building surfaces. Previous studies have also not looked at a Matlab-based simulation of vertically positioned Building Integration Photovoltaic panels coupled with an Air Source Heat Pump (ASHP) on a four-storey commercial building in Toronto.

Research objective

Therefore, the objective of this paper is to simulate a model of BIPV/T with an ASHP system in a commercial office building using MATLAB. As Canada is in the north hemisphere, facades orientated towards the south get the highest solar radiation intensity. The system would, however, be integrated on all façade orientations, i.e., north, south, east and west orientations, whereby it is hypothesized that the 90° inclination of the BIPV/T panels and the incident solar radiation would have an impact on the overall energy performance of the building. This would help in determining if energy generation on say the east or west facades could be used to meet energy demand in the morning or evening. Similarly, the study aims to investigate the contribution of electricity generation and thermal collection from all the considered orientations on the performance of the ASHP. The overarching goal is to determine the magnitude in the reduction in reliance on the grid during the winter months, when a BIPV/T system is installed on building facades.

Methodology

The study investigated the application of BIPV/T panels orientated towards the south, east and west directions in a mid-rise commercial building, wherein this system was additionally coupled with an ASHP. Several scenarios were tested, whereby the BIPV/T panels were arranged in different series and row configurations. The study methodology is outlined in Figure 1. It is to be noted that the investigation has been based for typical winter days (i.e., January, February, March, November and December) and a four-storey commercial building has been examined.

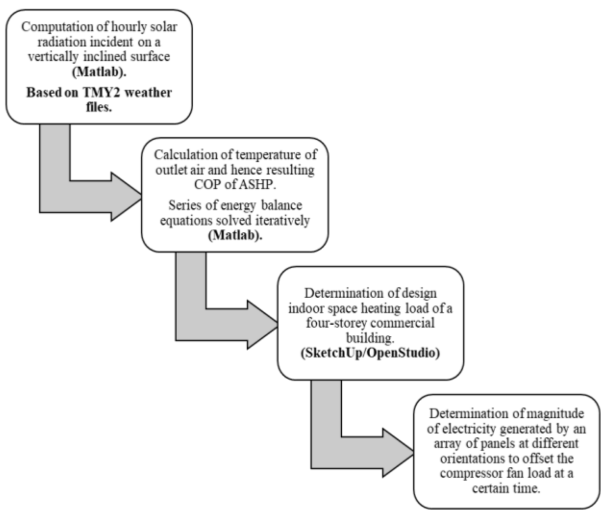

Figure 1: The methodological sequence adopted in this study

Hourly solar radiation calculations

The study closely followed the methodological sequence that the Hailu and Fung (2019) study outlined, whereby the calculations for the average monthly hourly solar radiation incident on an inclined surface was performed on R2019b (MathWorks®). For this purpose, TMY2 weather files were obtained from the weather database present in the TRNSYS software. The location selected for the computations was Toronto, which is situated at a latitude of 43.7ºN latitude. Three different scenarios for solar radiation incident on a vertically inclined surface (inclination angle, $\beta = 90^{o}$) orientated towards the south, east and west were simulated. The hourly solar radiation computed was then averaged on a month by month basis, such that the final computations represented monthly average hourly solar radiation intensities on the inclined surface under consideration. In order to determine the hourly radiation profile on the south, east and west orientations of the building, different scenarios of array configurations of BIPV/Ts were analysed.

Hailu and Fung (2019) looked at photovoltaic tilt angle and orientation when placed on the rooftop of a GTA based building. The global solar radiation incident on an inclined plane surface, $H_{\beta T}$, is a function of the associated direct beam, diffuse and reflected radiation components (see (1) (Demain et al., 2013; Li et al., 2008; Ulgen, 2006; D. Yang, 2016):

$$H_{\beta T} = H_{\beta B} + H_{\beta D} + H_{\beta R} \qquad (1)$$

The direct beam radiation is a function of the average global radiation and diffuse radiation (acting on a horizontal plane) in addition to the ratio between the perpendicular components of the solar radiation incident on an inclined and horizontal surface (see (2) (Hailu & Fung, 2019; Ulgen, 2006) :

$$H_{\beta B} = (H_G - H_D)R_b \qquad (2)$$

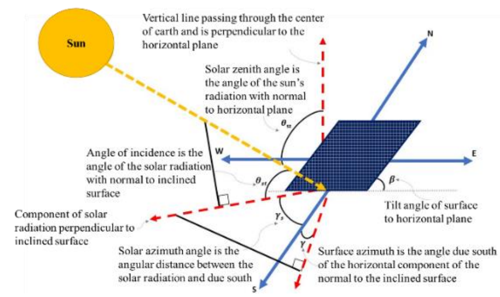

Figure 2:Solar geometry indicating the angles for incidence, zenith, tilt, surface azimuth, solar azimuth and the orientations.

Energy balance equations for the BIPV/T panels

The sequence of calculations for ascertaining the temperatures across BIPV/T panels were performed in Matlab R2019b (MathWorks®). Data pertaining to the dry bulb temperature and wind speed were extracted from the TMY2 weather file for the computations at this stage. The methodological sequence for this part of the study closely followed the approach adopted by Kamel (2015) and Vuong (2017) in their theses. Additionally, the input parameters were based on those that were used in the Kamel (2015) on BIPV/T panels, with the exception of a few changes in some variables. As aforementioned, the BIPV/T panels were arranged in different array configurations (namely 12x1, 12x2, 12x3, 12x4, 12x6 in the south, east and west orientations), whereby the mass flow of air flowing through each row varied as the array size increased. For these set of calculations, it was assumed that the inlet temperature of air entering each successive panel was the outlet temperature of the preceding one (Kamel, 2015). For the purpose of simplifying the modelling process, this study investigated panels stacked vertically one after the other, whereby there were three panels per floor. In this study, the reference building height is 12m and this essentially dictates the final outlet temperature of air leaving the topmost PV panel. Therefore, an iterative approach was adopted in solving the energy balance equations for each panel, in order to determine the temperature of the outlet air with increasing height. It is important to mention that the BIPV/T panels considered in this study are opaque, whereby the energy balance equations for this type of photovoltaics, does not included the component of solar radiation entering the air duct via gaps in between PV cells. Higher thermal efficiency is expected if transparent backing PV is used (Kamel and Fung, 2015). Furthermore, the total mass flow entering an array is 1.2 kg/s, whereby the row mass flow rate changes as the total mass flow is further divided based on the number of rows in an array.

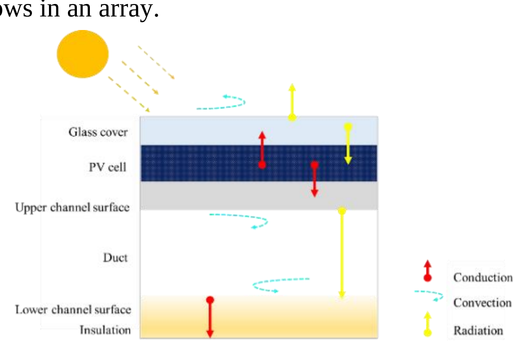

Figure 3: The heat transfer mechanisms across the BIPV/T layers (conduction, convection and radiation)

The energy balance equations pertaining to the different layers that are constituent of the BIPV/T module are fundamentally based on the conductive, convective and radiative components as indicated in Figure 3 (Kamel, 2015; Vuong, 2017).

Simulation of a commercial building

A four-storey commercial building was modelled on SketchUp Make 2017, followed by energy simulations that were performed on the Open Studio Version 2.9 software. The building was considered as a block with dimensions measuring 20m x 10m x 12m.The climate file for the simulations was the Toronto CWEC weather file that was obtained from the EnergyPlus weather resource database, wherein the climate zone assigned to Toronto in this case was ASHRAE 169-2006 Climate Zone 5A. For this exercise, it was assumed that all floors of the building followed the 'ASHRAE 189.1-2009 – CZ5- Open office classification'. Similarly, schedule sets, loads and building characteristics were accounted for in the energy modelling process.

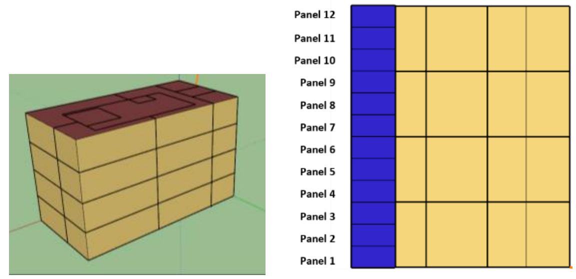

Figure 4: (Left) The mid-rise commercial building modelled on SketchUp Make 2017/Open Studio (Right) The vertical arrangement of panels along the height of the four-storey building

Modelling the Air Source Heat Pump

Based on the magnitude of the peak heating demand acquired from the energy simulations of the commercial building, an appropriately sized Air Source Heat Pump was selected to meet the heating needs. The Air Source Heat Pump in this study was the Mitsubishi heat pump with a model of PUZ-HA36 and an outdoor air flow rate of 3530 CFM. The relationship between the heat pump COP with the temperature is given as follows (Kamel & Fung, 2014b):

$$COP_{heat\ pump} = 0.1158 * Ambient\ temperature(T) + 3.7258$$

Results

Solar radiation on an inclined surface

In Toronto, the maximum solar radiation intensity is observed to occur on the south façade, followed by the west and finally the east facades. The winter months having the highest solar radiation intensity is March (~0.37 kWh/m^2) and the lowest solar radiation intensity is December (0.21 kWh/m^2). The duration of solar irradiation is also longer in March (about 12 hours) compared to December (about 8 hours) (see Figure 5 to Figure 11).

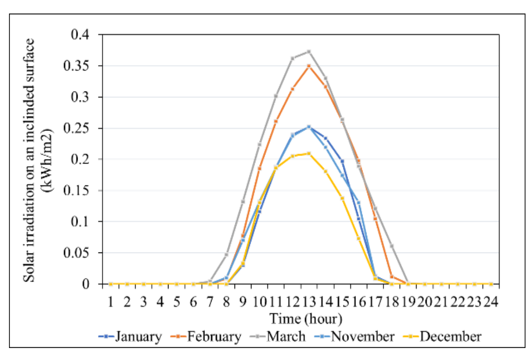

Figure 5: The total hourly radiation (kWh/m^2) on an inclined surface, β=90° present on the south facing façades

during typical Winter days in Toronto

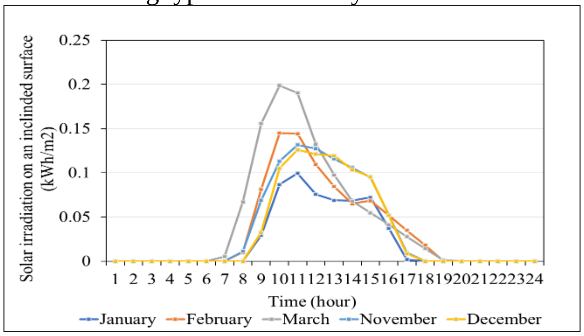

Figure 6: The total hourly radiation (kWh/m^2) on an inclined surface, β=90º present on the east facing façades during typical Winter days in Toronto

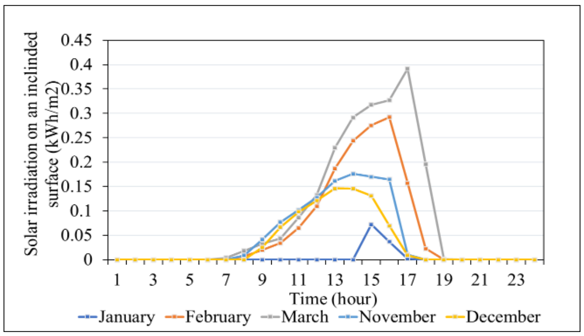

Figure 7: The total hourly radiation (kWh/m^2) on an inclined surface, β=90º present on the west facing façades during typical Winter days in Toronto

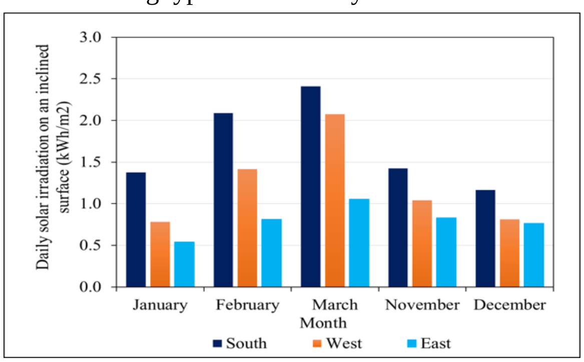

Figure 8: The monthly variation of the total daily radiation (kWh/m^2)

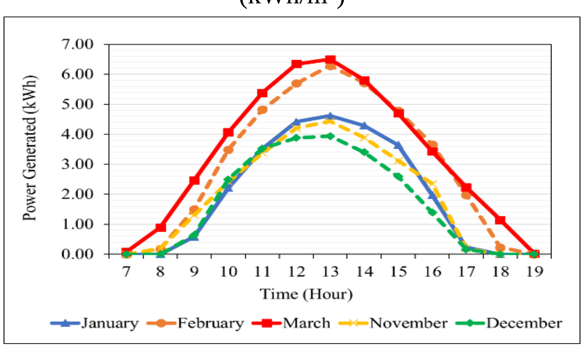

Figure 9: The PV electricity (kWh) generated on the south façade with a 12x6 array

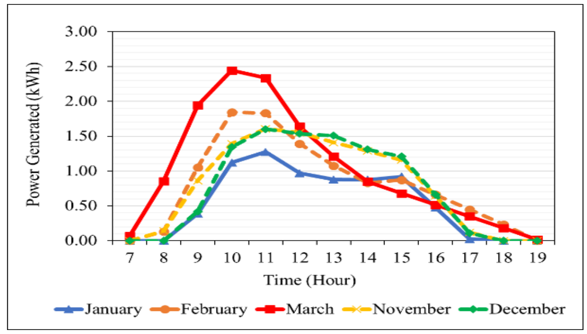

Figure 10: The PV electricity (kWh) generated on the east façade with a 12x4 array

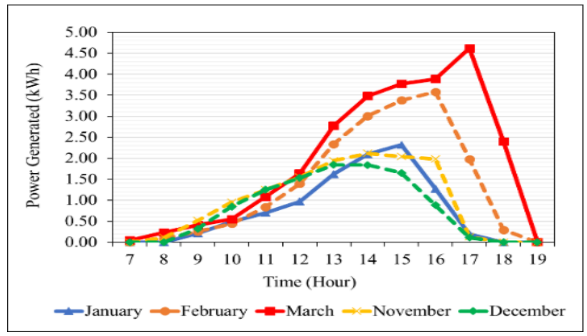

Figure 11: The PV electricity (kWh) generated on the west façade with a 12x4 array

PV power

There is great variation in the PV temperature and efficiencies across the day. Similarly, as expected, the highest PV temperature (and subsequently lowest PV efficiency) occurs on a typical March day at around 1:00pm. On the other hand, the highest power generated is in March due to larger magnitude of solar radiation that surfaces are exposed to (~6 kWh at 1:00pm for a typical March day). Similarly, it is seen that the south façades generate greater magnitude of power (~4 kWh at 1:00pm for a typical January day) (see Figure 12 to Figure 14).

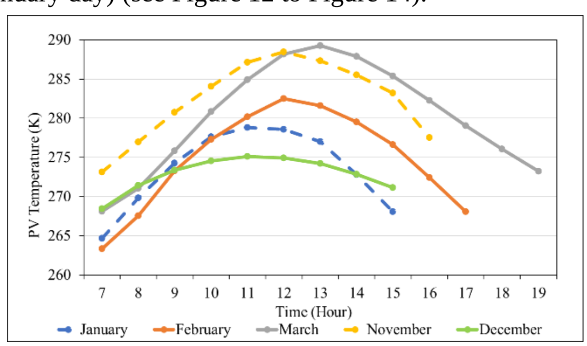

Figure 12: Hourly PV temperature variations for typical Winter days (BIPV/T Panel no. 12 in a south orientated 12x6 array configuration).

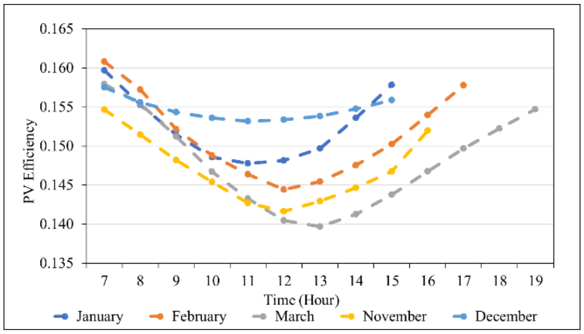

Figure 13: Hourly PV efficiency variations for typical Winter days (BIPV/T Panel no. 12 in a south orientated 12x6 array configuration).

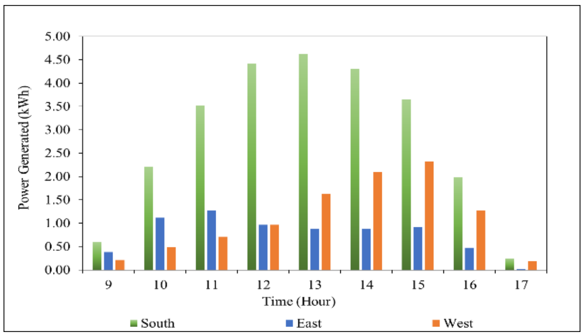

Figure 14: A profile of the hourly power generated by a 12x6 array in the south orientation and 12x4 array in the east and west orientations for a typical January day

Outlet air temperature and COP

The outlet air at the fourth-floor level is higher than the air that entered at ground floor level (ambient temperature). Due to a higher magnitude of solar radiation on the south-facing surface at noon, the outlet temperature can be about 10K higher than that at 9am (for a typical January day). This results in a higher COP especially at noon when it can rise from 2.5 to about 4.51 (for a typical January day). The highest COP occurs in March, also corresponding to higher solar irradiation on south facing surfaces and higher temperatures.

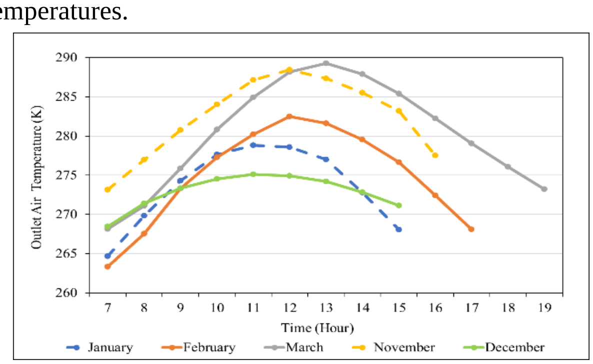

Figure 15: Hourly outlet air temperature variations for typical Winter days (BIPV/T Panel no. 12 in a south orientated 12x6 array configuration).

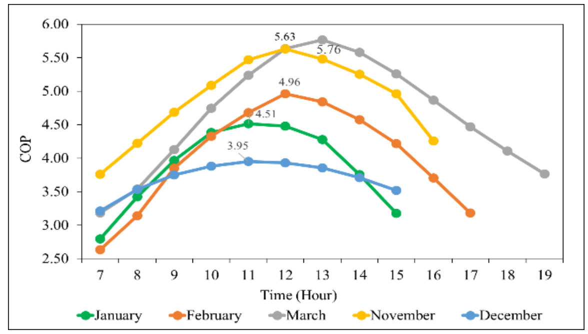

Figure 16: The hourly variation of COP for typical Winter days

As expected, the outlet air temperature is the highest (~290K) in a typical March day due to the higher ambient temperatures compared to say January. The highest COP (5.76) is therefore at around 1:00pm in a typical March day.

Design heating load for the four-storey building

The design heating load for one typical zone and the whole building indicated in Table 1.

Table 1: The design heating load for one typical zone (floor) and the whole building

	One typical floor	Whole building
Design Heating Load (kWh)	22	88.4

The offset of compressor power 12x6 array on the south orientation for a typical January day

The vertically positioned south-facing BIPV/T panels improve the COP of the air that is entering into the ASHP. Due to this improvement, the power required to run the ASHP compressor reduces. Similarly, electricity is also generated on the panels arranged on the south, east and west facades. Figure 17 to Figure 22 show the magnitude of hourly electricity that can be offset both by COP improvement and electricity generation on the facades (for a typical January day).

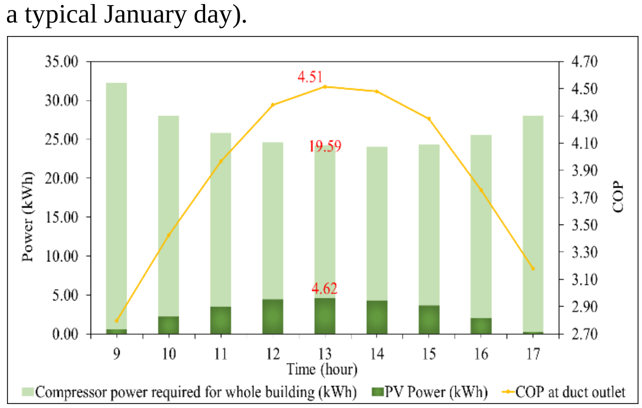

Figure 17: The offset of compressor power via PV for the whole building for a typical January day (south orientated façade)

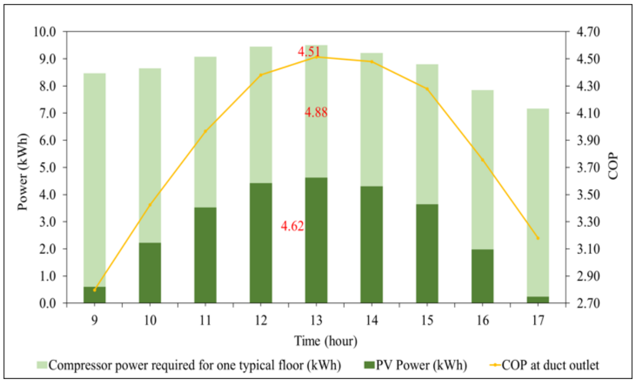

Figure 18: The offset of compressor power via PV generation for one typical floor for a typical January day (south orientated façade).

Deficit of compressor power due to a combination of the 12x6 arrays on the south and 12x4 arrays on the east and west orientated facades for a typical January day

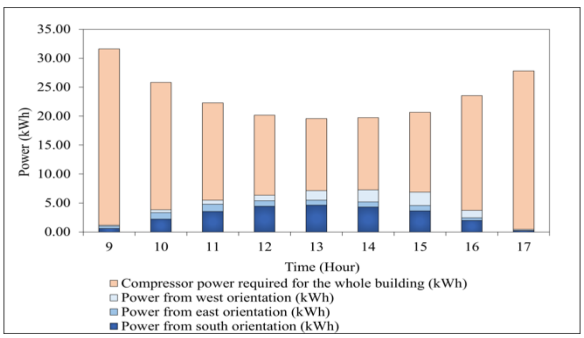

Figure 19: The offset of compressor power combining the PV electricity generated from the south, east and west orientations

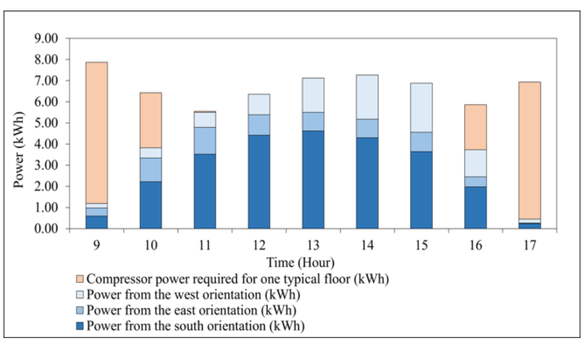

Figure 20: The offset of compressor power for one typical floor (a typical January day)

Deficit of compressor power due to a combination of 12x6 arrays on the south and 12x4 arrays on the east and west orientated facades for typical Winter days

Time (Hour)	Typical Winter day				
	January	February	March	November	December
7			98%		
8		99%	86%	98%	
9	96%	90%	71%	87%	95%
10	85%	75%	63%	75%	81%
11	75%	63%	58%	64%	73%
12	68%	55%	57%	55%	69%
13	64%	46%	55%	**50%**	67%
14	63%	48%	55%	55%	71%
15	67%	53%	57%	62%	76%
16	84%	62%	60%	72%	88%
17	98%	81%	60%	98%	98%
18		97%	77%		
19			100%		

Figure 21: The deficit of compressor power needed to run the compressor for the whole building during a typical Winter day

Time (Hour)	Typical Winter day				
	January	February	March	November	December
7			97%		
8		95%	68%	92%	
9	85%	60%	10%	48%	80%
10	41%	0%	0%	0%	25%
11	0%	0%	0%	0%	0%
12	0%	0%	0%	0%	0%
13	0%	0%	0%	0%	0%
14	0%	0%	0%	0%	0%
15	0%	0%	0%	0%	4%
16	36%	0%	0%	0%	51%
17	93%	26%	0%	91%	94%
18		89%	30%		
19			99%		

Figure 22: The deficit of compressor power needed to run the compressor for one floor during a typical Winter day

Discussion

An analysis on the solar radiation incident on vertical facades facing the south, east and west orientations was performed. There was great variation in the magnitude of irradiance from the east and west orientations, owing plausibly to the weather data (TMY2) that was used in this study. According to Dean (2010), the TMY2 weather file, which contains hourly data for a duration of a year, pertains to a wide range of weather variables such as global solar irradiance, diffuse irradiance, dry bulb temperature, wind speed, etc. of a location. Irrespective of the fact that TMY2 weather files are based on 30 years of past data of the location, the methodological approach by which different variables have been sifted out to represent typical weather patterns, presents an inherent doubt in its accuracy (Dean, 2010).

The computations in this study have been done for a typical Winter day as the combined BIPV/T and ASHP system is envisaged to work optimally under the overlying climatic conditions of this period. The trends in variation of variables such as electrical efficiencies, outlet temperature and ASHP

COP was in conformance to what is expected considering the time day, façade orientation and the month. The array size implemented for the east and west orientations have been restricted by the length of those sides, i.e., 10m. It was observed that starting with a total mass flow rate of 1.2kg/s, an increasing array size (more rows of BIPV/T modules), the mass flow of air passing through each row decreased. Therefore, the selection of an appropriate array size of BIPV/T modules hinged on the row mass flow rate not to drop below an acceptable threshold of 0.2kg/s to 1.2 kg/s.

With decreasing mass flow rates, the temperature of air at the outlet also augmented. Moreover, the 12x6 array on the south side contributed to a COP of about 5.76 (for a typical March day), whereas the COP is lower in the east and west orientations due to a lower temperature of outlet air. As the magnitude of solar radiation incident on these orientations is lower compared to the south orientation, the air that moves along the BIPV/T modules does not heat up to the same extent as they do on the south façade. Similarly, the power generated on the east and west façade orientations is lower too. The compressor power for one typical floor can be offset by PV electricity generation cumulatively by all three facades for a duration of maximum seven hours (between 10:00am to 5:00pm) for a typical March day. On the other hand, for the whole building, a half of the compressor power can be met by PV electricity generated by all facades 1:00pm in a typical November day. Therefore, the study found that an arrangement of a 12x6 array of BIPV/T modules on the south side and 12x4 arrays on the east and west facades as the optimal arrangement for a four-storey building of this morphology.

It is noteworthy that to ascertain the maximum benefit from a BIPV/T system installed on facades, it was assumed that the building in this study was windowless. In future work, to account for a more realistic building that has windows, transparent or semi-transparent BIPV/T modules would be investigated for the combined electricity, thermal, and daylight benefits. Additionally, the economic benefit of the recommended system is analogized to the duration during which there is a reduction in reliance on the electricity grid in Winter months.

Conclusions and future work

The study provides an insight into the effectiveness of a combined BIPV/T and ASHP system in offsetting the energy load during a typical winter day for a commercial building located in Toronto. The simulated conditions for a typical day in January was chosen, as the highest heating demand occurs in this month. The system was able to significantly offset the compressor power at specific durations of the day. This presents an opportunity for a full-scale envelope retrofit with BIPV/T modules. South façade area can be modified to enhance solar radiation exposure. Improved curtain wall systems that enhance façade performance could be explored to investigate greater energy production. Additionally, a full-scale application of BIPV/T modules can be implemented all over the south, east and west façade orientations to ascertain how much energy can be generated on site and offset the demand. In order to enhance the COP, solar glazed collector could be introduced in succession to BIPV/T modules to heat up the air as it moves along the cavity out of the outlet into the ASHP.

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