Feasibility of Building Integrated Photovoltaic-Thermal Collector (BIPV/T) with Two-stage Variable Capacity Air Source Heat Pump in Toronto Area (GTA), Canada

CCTC 2013 Paper Number 1569671063

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Abstract

In this feasibility study, analyses have been conducted to estimate the potential benefits of integrating photovoltaic thermal collector (BIPV/T) with air source heat pump. A mathematical model has been developed to predict the electrical output and the useful thermal energy obtained from the PV/T system during the heating season. The effect of the air mass flow rate, the duct depth and the PV/T system configuration (number of PV/T systems in rows N_R and series N_S) on thermal energy production, electrical energy production, heat pump coefficient of performance (COP) and the electricity consumed by the heat pump has been investigated. It is found that the COP could be increased from 2.74 to 3.45. The results show that the heat pump electricity consumption for heating purpose was reduced by 20.2% with combining PV/T systems with air source heat pump. For the same total number of PV/T systems used in one array, it is better to have N_S greater than N_R in order to produce more thermal energy. This consideration has slight effect on the total electricity production.

Keywords: heat pump, photovoltaic, thermal energy, electrical energy, solar, coefficient of performance

Résumé

Dans cette étude de faisabilité, des analyses ont été menées pour estimer les avantages potentiels de la combinaison d'un capteur thermique photovoltaïque (PVIB/T – système photovoltaïque et thermique intégré au bâtiment) avec une thermopompe utilisant l'air comme source de chaleur. Un modèle mathématique a été conçu pour estimer l'électricité et l'énergie thermique utile générées par le système PV/T durant la saison du chauffage. L'étude a évalué les effets du débit massique d'air, de la profondeur du conduit et de la configuration du système PV/T (nombre de rangées, N_R, composées d'une série de N_S panneaux PV/T) sur la production d'énergie thermique et d'énergie électrique, sur le coefficient de performance (COP) et sur l'électricité consommée par la thermopompe. L'étude révèle que le COP s'est accru, passant de 2,74 à 3,45. Les résultats montrent également que la consommation d'électricité de la thermopompe aux fins de chauffage a été réduite de 20,2 % en combinant le système PV/T à la thermopompe utilisant l'air comme source. Pour le même nombre total de panneaux PV/T utilisés dans une même configuration, il est préférable d'avoir une série plus nombreuse de N_S panneaux, sur un nombre moindre de rangées N_R, pour produire davantage d'énergie thermique. Cette configuration a un léger effet sur la production totale d'électricité.

Mots-clés : thermopompe, photovoltaïque, énergie thermique, énergie électrique, solaire, coefficient de performance

1. Introduction

Challenges and problems have been occurred for heating systems using single stage air-source heat pump (ASHP) in cold climates like Canada; especially when outdoor temperatures decrease below 0°C. One of the main problems for air-source heat pumps at very low ambient temperatures is the decrease of heat output and coefficient of performance (COP). Research has shown that a two-stage ASHP could perform better in harsh weather. Bertsch and Groll [1] showed that the functionally of such a system was able to operate at temperature between -30°C and 10°C, resulting in a (COP) of 2.1 at -30°C. Umezu and Suma [2] have shown that energy saving up to 15% could be achieved using a two stage variable capacity compressor. This performance can be further enhanced by low grade thermal energy fed into the ASHP. This can be achieved by warm air generated in the building integrated photovoltaic/thermal (BIPV/T) collector fed into the ASHP for heating production. Integrating solar heating technology with heat pumps could maximize the utilization of solar energy; overcoming the irregular intensity of solar irradiance, and enhance the COP of the heat pump. At the same time, the amount of electricity demand can be generated by PV module from the BIPV/T system.

The earliest efforts to utilize solar energy to boost performance of heat pump started by Sporne and Ambrose in 1955 [3] and [4]. On cold days, the performance of the heat pump decreases. Also, the solar system collects energy in low temperature. Consequently, it may not work efficiently in direct heating. This energy could be used as a source to the heat pump in Winter. In other words, the solar collector system provides energy with temperature above the ambient temperature, leading improvement of COP. Integrated solar energy system with a heat pump is an interesting field of research as it provides energy saving [5]. Candanedo and Athienitis [6] have shown out that the typical range of air temperature leaving the BIPV/T is 0 - 20°C which depends on several factors such as flow rate, outdoor temperature and solar radiation. The exit temperature of the BIPV/T system is low in order to be applied directly but it could be used as the source of a heat pump.

2. Archetype Sustainable House

The Toronto and Region Conservation Authority (TRCA) along with the Building Industry and Land Development (BILD) Association has implemented the Sustainable Archetype House project at The Living City Campus at Kortright in Vaughan, Ontario, Canada. This prototype twin house is designed to demonstrate sustainable housing technologies through research, education, training, market transformation, and partnership programs. Included in the sustainable technologies is a two-stage variable capacity air source heat pump in House A (the house at the left in Figure 1) [7].

The thermal performance of two-stage variable capacity air source heat pump was investigated at the Archetype Sustainable House [8]. It was tested in heating mode under extreme winter conditions. In heating mode, the results showed that the peak electricity demand was 8.30 kW which occurred when the ambient temperature was -22.11°C, with a considerable lower COP of 1.58.

Figure 1. South-west side of twin houses

The heating season was supposed to start on October 1st and end on May 22nd. The total heating demand for House A at the end of heating season was 17594 kWh with maximum heating demand of 6.76 kW. The seasonal electricity consumption was 6421 kWh resulting in seasonal COP of 2.74 for winter [9], [10]. In this feasibility study, analyses for possible improvement in the heat pump performance and potential reduction in electricity demand for combining PV/T system with two stage variable capacity air source heat pump at the Sustainable Archetype House was conducted.

3. Energy analysis for PV/T system

Figure 2 shows a cross section for PV/T system. Several assumptions have been made to simplify the analyses: 1) capacity effects of system components are negligible except for flowing air, 2) the upper and lower channel heat transfer coefficient are constant, 3) side losses are negligible, 4) properties or air and solid material remain constant, 5) the temperature variations are considered only in the flow direction, and 6) the temperature of the back surface of the insulation is considered the same temperature of the air/collector back interface zone.

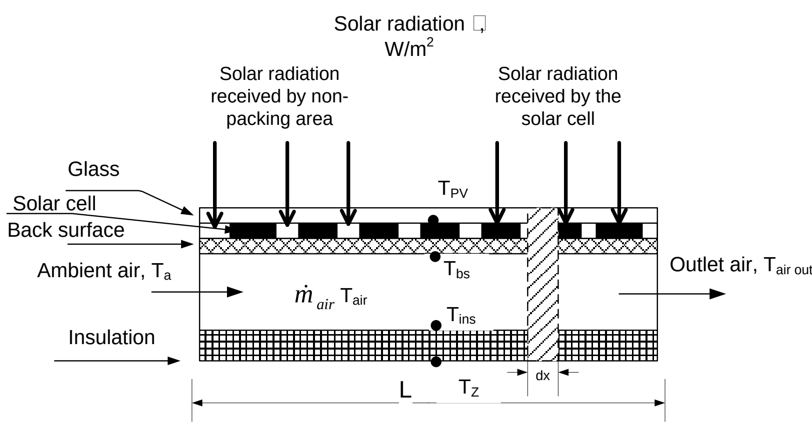

Figure 2. Cross section of PV/T system with air flow pattern over elementary area b dx

Based on these assumptions and considering an element area b dx, the energy balance equations for the PV cells, Tedlar back surface of the PV module, air flowing in the duct of BIPV/T and back insulation surface can then be written as follows:

$$(\tau_g\ \alpha_c\ P\ I_T + \tau_g(1-P)\ \alpha_T\ I_T - \eta_{panel}\ I_T)bdx = h_{rs}(T_{PV}-T_s)bdx + U_{top}(T_{PV}-T_a)bdx + U_{back}(T_{PV}-T_{bs})bdx \quad (1)$$

$$U_{back}(T_{PV}-T_{bs})bdx = h_{air}(T_{bs}-T_{air})bdx + h_r(T_{bs}-T_{ins})bdx \quad (2)$$

$$\dot{m}C\frac{dT_{air}}{dx}dx = h_{air}(T_{bs}-T_{air})bdx + h_{air}(T_{ins}-T_{air})bdx \quad (3)$$

$$h_{air}(T_{air}-T_{ins})bdx + h_r(T_{bs}-T_{ins})bdx = U_{ins}(T_{ins}-T_z) \quad (4)$$

The energy balance equations above have been solved to determine the outlet temperature of the flowing air (T_{out}) in the duct of the PV/T system and the mean surface temperatures T_{bs}, T_{PV} and T_{ins}. Table 1 gives the physical properties of the air and supposed design parameters of PV/T system.

Table 1. The supposed physical properties and design parameters used in solving the mathematical model

b [m]	L [m]	τ_g	α_C	α_T	ϵ_{PV}	ϵ_u	ϵ_l	ρ_{air} [kg/m3]	C [kJ/kg.k]
0.8	1.55	0.95	0.9	0.7	0.6	0.9	0.9	1.292	1007

4. Estimation of Heat transfer coefficients

The radiation heat transfer coefficients, h_{rs} and h_r, between the PV panel and the atmosphere and between the upper surface and lower surface of the air channel respectively, can be obtained as [11]:

$$h_{rs} = \sigma\epsilon_{PV}(T_{PV}+T_s)(T_{PV}^2+T_s^2) \quad (5)$$

$$h_r = \frac{\sigma(T_{bs}^2+T_{ins}^2)(T_{bs}+T_{ins})}{\frac{1}{\epsilon_u}+\frac{1}{\epsilon_l}-1} \quad (6)$$

The convection heat transfer coefficient due wind effect, h_o, was determined by [12]:

$$h_o = 2.8 + 3 * V_w \quad (7)$$

In this paper, the amount of heat removed from the PV/T system was estimated for different configuration arrangements of connected PV panels. Therefore, the entrance effect was considered in calculating convection heat transfer for airflow inside the channel. The convective heat transfer coefficient is higher at the entrance region before the fully developed flow is achieved.

The forced convective heat transfer coefficient for the air inside the duct can be obtained from the following equations [11]:

For laminar flow $(R_e \leq 2300)$: $N_u = 4.9 + \frac{0.0606\ (R_e P_r D_h/L)^{1.2}}{1+0.0909(R_e P_r D_h/L)^{0.7} P_r^{0.17}}$ (8)

For turbulent flow $(R_e > 2300)$: $N_u = 0.0158\ R_e^{0.8}\left[1 + \frac{C}{L/D_h}\right]$ (9)

In Equation (9), the part in brackets was considered by [13] to include the effect of the entrance region and is multiplied by Nusselt for fully developed flow presented by [11]. For abrupt-contraction entrance, C=6 is used in this study.

Sky temperature was calculated using the following formula [14]:

$$\mathrm{T_s} = 0.037536\mathrm{T_a}^{1.5} + 0.32\mathrm{T_a} \quad (10)$$

5. Methodology

The hourly solar intensity on tilted surface, the ambient temperature and the wind velocity for Toronto were obtained from TRNSYS Meteonorm weather data [15]. These data were used as inputs for solving the mathematical model. The assumed tilted angle for the PV/T system was 45°. The calculations have been done only for the heating season, which starts on October 1st and ends on May 22nd. For the analysis, the configuration arrangement consists of rows of PV/T systems (N_r) connected in parallel and each row consists of PV/T systems connected in series (N_s). For the considered PV/T system, the air enters at constant mass flow rate and is equally distributed in rows.

The calculations have been done panel-by-panel connected in series. The temperature of the air which enters the first PV/T system is considered to be the ambient temperature; the outlet air temperature (T_{out}) coming out from each PV/T system is considered to be the input temperature for the next PV/T system. The final outlet air temperature was used to calculate the rate of thermal energy extracted from the PV/T systems per row. Different configuration arrangements, different mass flow rates, and different duct depth for the PV/T systems have been studied in order to estimate the recovery of solar thermal energy and electrical energy production.

With Equation (11), the new value of the efficiency of each PV panel was calculated using its mean temperature T_{PV}. Since the air becomes warmer in moving forward under the PV panels, the first panel has higher efficiency and produces more electricity than the second PV panel. The second PV panel produces more electricity than the third one and so on.

$$\eta_{panel} = \eta_{ref}\left[1 - 0.004\left(T_{PV} - T_{ref}\right)\right] \quad (11)$$

After obtaining the efficiency for each panel corresponding to its temperature, the electrical energy per panel was obtained from the following equation:

$$E = \eta_{panel} * b * L * I_T \quad (12)$$

The thermal energy for each row was estimated from the following equation:

$$Q = \dot{m}\ C\ (T_{out} - T_a) \quad (13)$$

Heat pump coefficient of performance (COP) strongly depends on the source temperature. In this study, the source temperature is the air coming from the BIPV/T system (T_{out}), which removes the excess heat from the PV panels, leading to reduce PV cells temperature and produce more electrical energy. Equation (14) is an empirical equation which shows the relationship between the coefficient of performance of the ASHP in Archetype Sustainable House and the outdoor temperature [8].

$$COP = 0.1158 * T_a + 3.7258 \quad (14)$$

The air leaving the PV/T system with temperature, T_{out}, has been considered as a source of the heat pump. In this case, T_a in Equation (14) becomes T_{out}. Consequently, the COP of ASHP would be improved. Therefore, the electricity consumed by the heat pump decreased for the same heating demand of House A.

6. Results and Discussion

The seasonal heating COP of ASHP in House A was obtained as 2.74. In this study, the enhancement of the COP was investigated by having warm air generated in the BIPV/T fed into the ASHP for heat production.

Figures 3 and 4 show the effect of the air mass flow rate and the duct depth on the seasonal heating COP with three assumed arrangements (N_SxN_R): 3x5, 4x5 and 5x5. It is shown that the COP decreases with increasing row mass flow rate because higher mass flow rate is related to higher heat removal from the PV panels and lower rise in temperature from inlet to outlet. In both figures, the arrangement with N_S=5 has higher COP than the arrangement with less N_S and the same N_R. This is because the more PV/T systems connected in series we have, the warmer air is generated. In addition, when the duct depth of the PV/T system is reduced from 3 to 1.5 in, the maximum COP increases from 3.41 to 3.45 for 5x5 arrangement, due to higher heat transfer coefficient corresponding to higher velocity. In this study, the inlet air temperature of the PV/T system was considered the ambient air temperature (T_a). Generally, the air enters the PV/T system with a temperature slightly higher than the ambient temperature due to passive heating from the facade [16]. If this rise in inlet air temperature is taken into account, the predicted seasonal heating COP would be higher than 3.45. Add to this, the ambient air temperature during the cold winter of Toronto is below 0^oC most of the time. Consequently, the exit air temperature (T_{out}) is relatively low (between 0^oC and 15^oC in this feasibility analysis). To have higher exit air temperature from PV/T system, which leads to higher seasonal heating COP, it is recommended to add a solar air collector at the end of the PV/T system.

Figure 5 shows the total thermal energy produced for 5x5 arrangement with different total mass flow rates and different duct depths. The thermal energy grows dramatically until the mass flow rate reaches 5 kg/s, amounting to around 14000 kWh/heating season. For greater mass flow rate values, the evolution of the thermal energy production is more gradually. It is noticed that the yield of the thermal energy is higher with low duct depth. This is again because of high heat transfer coefficient for the flowing air inside the duct.

Figure 6 shows the total electricity produced for 5x5 arrangement with different total mass flow rates and different duct depths. Increasing mass flow rate leads to more heat removed from PV panels, consequently, the production of electricity goes up to the value of 4050 kWh/heating season. This is due to the improvement of the PV panels efficiencies. For a higher mass flow rate, the electricity production changes very slightly.

Figures 7 and 8 represent the electricity and the thermal energy production for one row and for the whole array, with different (N_SxN_R), 1.2 kg/s as total mass flow rate and d=1.5 in. For individual rows (Figure 7), it is shown that for the same N_R=5, the configuration with N_S=5 makes larger amount of row thermal energy than the configuration with N_S=3 and N_S=4. While for the same N_S=5, the configuration with N_R=3 makes larger amount of row thermal energy than the configuration with N_R=4 and N_R=5. This is because the row mass flow rate is obtained by dividing the total mass flow rate by N_R. Therefore, one row of the 5x3 array, which produces the highest thermal energy among the other arrays, has the largest row mass flow rate (0.4 kg/s) and the highest T_{out}. Nevertheless, the maximum thermal energy produced from the whole array (Figure 8) is obtained by the 5x5 configuration because there are more rows and accordingly more thermal energy.

The electricity production depends on the number of panels. In Figure 7, it is obvious that arrangement with N_S=5 produces more electricity per row than the arrays with less N_S. In Figure 8, for the whole arrangement, 5x5 arrangement produces the highest amount of electricity (3964 kWh/heating season) since there are 25 PV panels in this array.

Figure 9 shows the total thermal and electrical energy production for 3x5, 4x5, 5x5, 5x4 and 5x3 arrangements with different duct depths. The total mass flow rate was considered to be 1.2 kg/s for each arrangement. The largest numbers of PV panels are 25 panels in the 5x5 array, so this configuration produces the highest quantity of electricity. The 5x3 array produces more thermal energy than the 3x5 array, but both of them produce almost the same amount of electricity. The comparison between the 5x4 and the 4x5 arrays has the same trend.

Figure 10 shows the comparison of the daily cumulative heat pump electricity consumption from October 1^{st} to May 22^{nd} for House A with and without BIPV/T system. The results show that the heat pump electricity consumption was reduced by 20.2% with combining PV/T systems with air source heat pump. The considered system has five PV/T system connected in series, d=2 in and 0.1 kg/s.

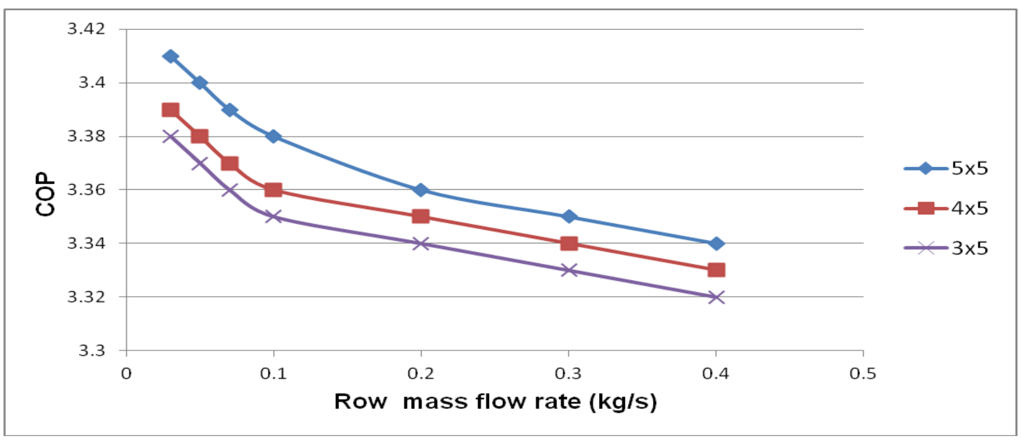

Figure 3. Seasonal heating COP for different row air mass flow rates for 5x5, 4x5 and 3x5 arrangements, d = 3 in.

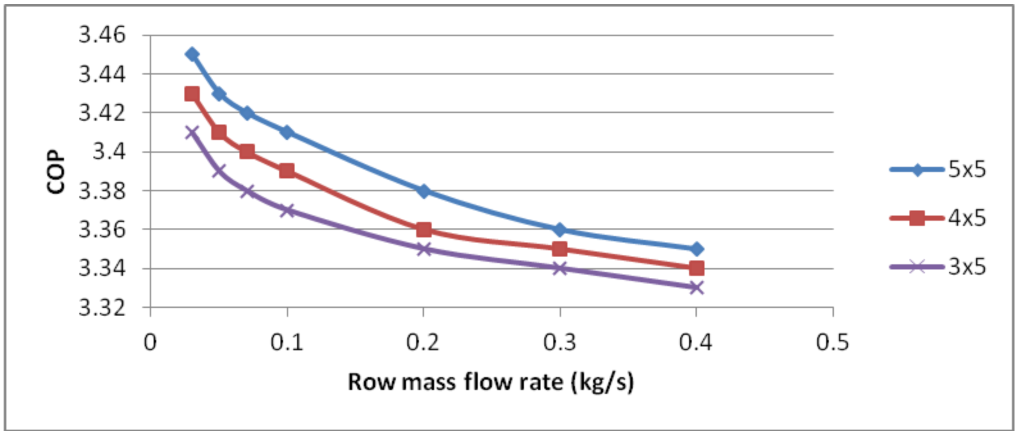

Figure 4. Seasonal heating COP for different row air mass flow rates for 5x5, 4x5 and 3x5 arrangements, d = 1.5 in.

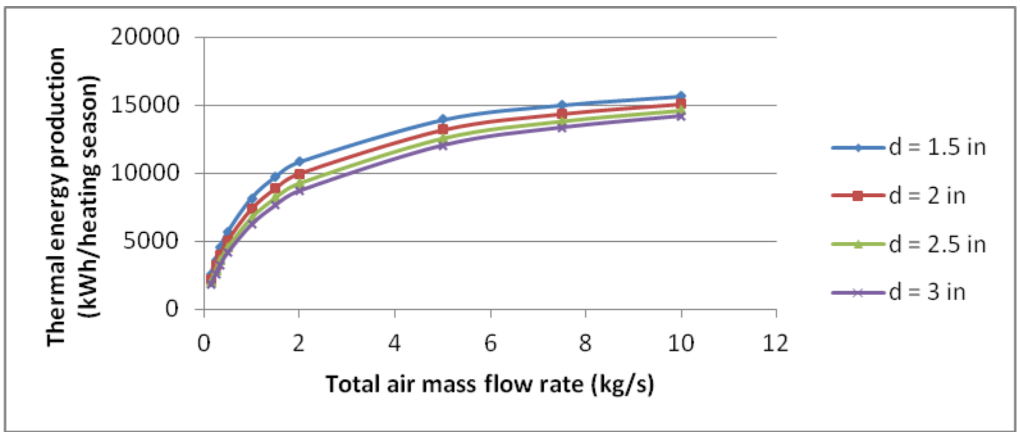

Figure 5. Total thermal energy recovered from PV/T systems of the heating season for 5x5 arrangements with different total air mass flow rate and different duct depth.

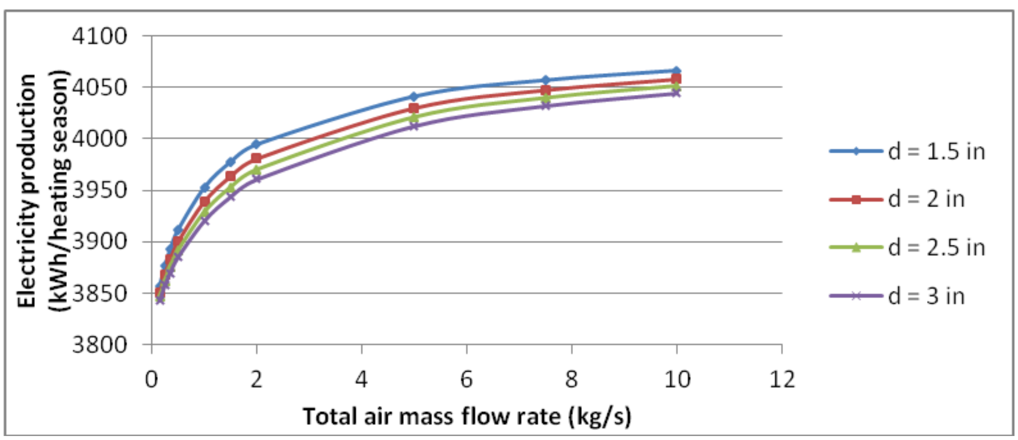

Figure 6. Total electricity production recovered from PV/T systems of the heating season for 5x5 arrangements with different total air mass flow rate and different duct depth.

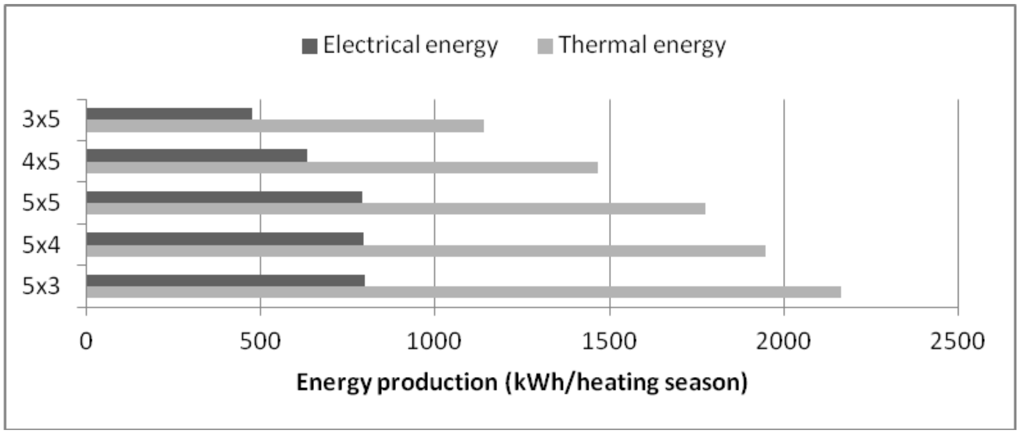

Figure 7. Electricity and thermal energy production of the heating season per row (N_R) for different arrangements, d = 1.5 in and total air mass flow rate = 1.2 kg/s.

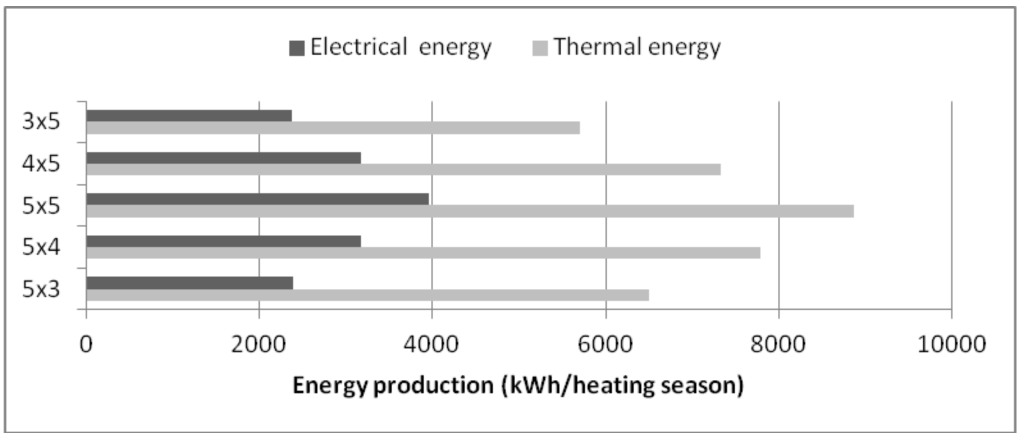

Figure 8. Electricity and thermal energy production of the heating season for whole different arrangements (N_R x N_S), d = 1.5 in and total air mass flow rate = 1.2 kg/s.

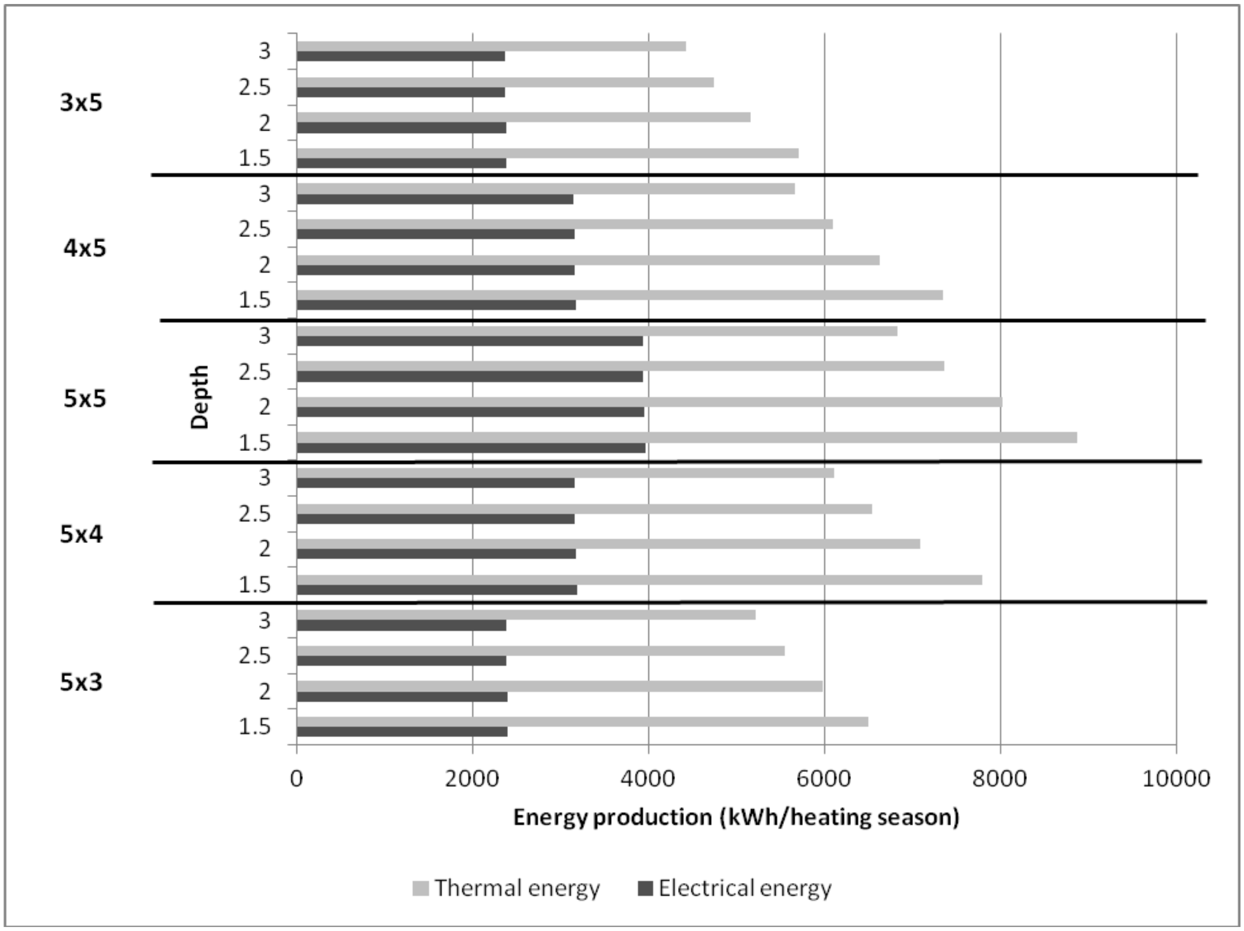

Figure 9. Total electricity and thermal energy production of heating season for different arrangements with different duct depth, total air mass flow rate = 1.2 kg/s

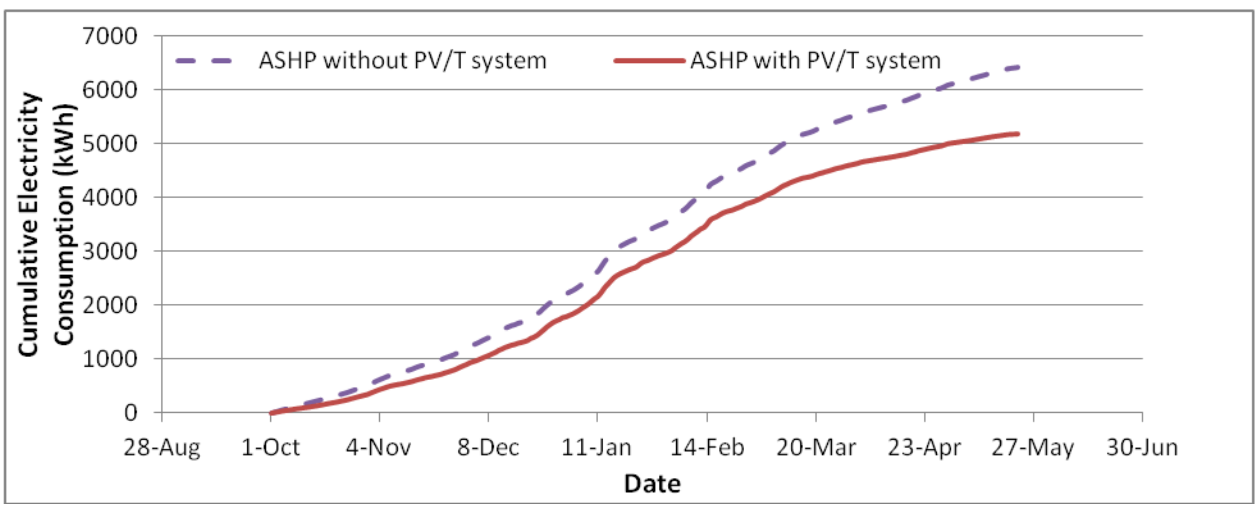

Figure 10. ASHP daily cumulative electricity consumption for heating season with and without PV/T system

7. Conclusion

This study presents a theoretical analysis for building integrated photovoltaic-thermal collector (BIPV/T) with two-stage variable capacity air source heat pump in Toronto area, and is based on previous experimental results obtained from the Sustainable Archetype House.

Having warm air generated in the BIPV/T fed into the ASHP enhances the heat pump coefficient of performance. The results show that the air mass flow rate and the duct depth have an inverse effect on the COP. In other words, low air mass flow rate and low duct depth enhance the COP. The arrangement with a large number of PV/T systems connected in series (N_S) has higher overall COP. This is because the more PV/T systems connected in series, the warmer air is generated. In contrast, the low air mass flow rate results in producing less thermal energy.

For the same total number of PV/T systems used in one array, it is better to have N_S greater than N_R in order to produce more thermal energy. This consideration has a miner effect on the total electricity production.

This study provides a general picture of the benefits for integrating PV/T system with air source heat pump. It is recommended to conduct additional analyses to optimize design and cost parameters.

Nomenclature

b	Duct width [m]	T_{ins}	Mean insulation temperature [°C]
C	Specific heat capacity of air [J/kg.K]	T_{PV}	PV panel mean temperature [°C]
D_h	Hydraulic diameter [m]	T_{ref}	Reference temperature [25 °C]
E	Electricity generated by PV panel [W]	T_s	Sky temperature [°C]
h_{air}	Convection heat transfer coefficient of the air flowing in the duct [W $K^{-1}m^{-2}$]	T_z	Insulation back surface temperature [°C]
h_r	Radiation heat transfer coefficient from the top surface to the bottom surface of the air channel [W $K^{-1}m^{-2}$]	U_{back}	Back heat loss coefficient from PV panel [W m^{-2} K^{-1}]
h_{rs}	Radiation heat transfer coefficient between the PV panel and the sky [W $K^{-1}m^{-2}$]	U_{ins}	Heat loss coefficient from the insulation [W m^{-2} K^{-1}]
h_o	Convection heat transfer coefficient due to wind effect [W $K^{-1}m^{-2}$]	U_{top}	Top heat loss coefficient from PV panel [W m^{-2} K^{-1}]
I_T	Total solar intensity on titled surface [W/m^2]	V_w	Wind velocity [m/s]
L	PV panel length [m]	**Greek symbols**	
$\dot{m}$	Air mass flow rate [kg/s]	τ_g	Transmissivity of glass
N_u	Nusselt number	α_c	Absorptivity of solar cells
P	Packing factor	α_T	Absorptivity of the back surface material behind the PV panel
P_r	Prandtl number	η_{panel}	Panel efficiency
Q	Thermal energy output from PV/T system [W]	σ	Stefan Boltzmann constant [W m^{-2} K^{-4}]
R_e	Reynolds number	ϵ_{PV}	Emissivity of solar cells for long wave radiation exchanges with the

			sky
T_a	Ambient temperature [°C], [K]	ϵ_u	Emissivity of the upper surface of the air channel
T_{air}	Air temperature inside the channel [°C]	ϵ_l	Emissivity of the lower surface of the air channel
T_{bs}	Mean back surface temperature of the PV panel [°C]	η_{ref}	Reference efficiency, 13.9%

Acknowledgements

The authors would like to thank all of our sponsors of the project: Toronto Atmospheric Fund (TAF), MITACS and Natural Sciences and Engineering Research Council of Canada (NSERC) and its Smart Net-zero Energy Buildings Research Network (SNEBRN), and Toronto and Region Conservation Authority (TRCA).

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Biography

Raghad Kamel, ASHRAE Student member, is a PhD student in Mechanical and Industrial Engineering department, Ryerson University, Toronto, Ontario, Canada. She got her Bachelor and Master degree in Mechanical engineering from Baghdad University, Baghdad, Iraq. She was Faculty member and undergraduate (study and examination) coordinator in Mechanical department, Sabrata, Libya.

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Quentin Noire, is an exchange student at Ryerson University from Icam, France.