PCM-WATER THERMAL STORAGE FOR BUILDING INTEGRATED PHOTOVOLTAIC/THERMAL (BIPV/T) COLLECTOR + AIR SOURCE HEAT PUMP (ASHP)

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ABSTRACT

Thermal storage for a building integrated photovoltaic/thermal (BIPV/T) collector combined with an air source heat pump (ASHP) was modelled. The BIPV/T with ASHP provides electrical and thermal energy generation for residential homes with superior performance to competing heating and cooling technologies. A sensitivity analysis was conducted on various water tank sizes containing phase change materials (PCMs) for diurnal energy storage of the ASHPs thermal output. It was found that as storage size and usage of PCM increased, the coefficient of performance (COP) of the system was increased. The use of PCM in the storage tank allowed for a significantly smaller tank to be used than if water alone was used as the storage medium. The use of PCM based water storage can drastically increase the efficiency and effectiveness of the BIPV/T with ASHP.

INTRODUCTION

Due to increasing energy costs and a dwindling supply of natural resources, efficient ways of utilising the current energy supply are necessary. Approximately 17% of energy usage in Canada in 2009 came from the heating, cooling, and electrical loads in residential buildings (NRCan, 2012). Therefore, reducing the energy consumption in the residential sector will have a marked effect on the overall energy consumption of the country.

Heat pumps are one of the most promising energy efficient technologies for residential heating and cooling. Heat pumps move heat from a cold area to a warmer area through the addition of work. A heat pump consists of a compressor, condenser, expansion valve, and evaporator (see Figure 1). Heat pump cycles are often reversible meaning that each condenser/evaporator can perform condensing and evaporating. It is possible to have multiple condensers and evaporators and for them to exchange heat with either air or water. Typically, one condenser/evaporator is placed outdoors while the other is placed indoors. The compressor may be placed indoors or outdoors.

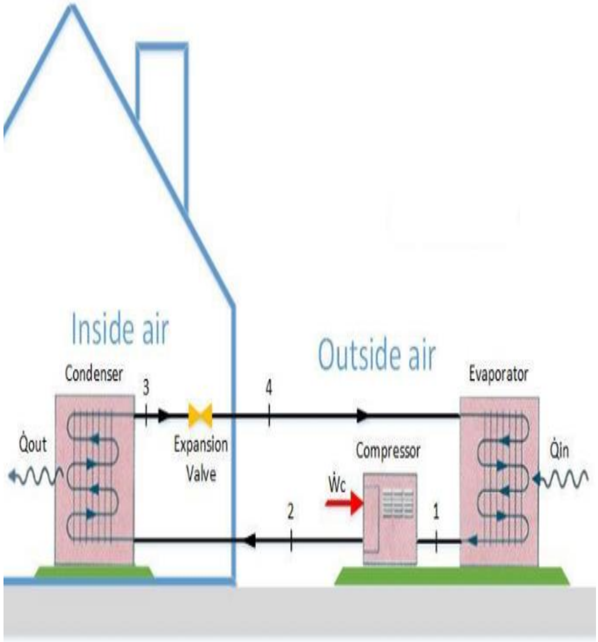

Figure 1: Air-source heat pump in space heating mode (Moran & Howard, 2008)

A common heat pump type for heating and cooling applications is the air-source heat pump. The air-source heat pump utilizes outdoor air as the source for both heating in the winter and cooling in the summer. The indoor coil of an air-source heat pump may exchange energy with either air or water. The coefficient of performance of the heat pump is defined as:

$$COP = \frac{Heat\ out\ of\ condenser}{Work\ into\ compressor} \qquad (1)$$

The COP definition can also be expanded to include evaporator and/or condenser fan consumption in the denominator of Equation 1. Heat pump performance degrades as the temperature between the evaporator and condenser increases. Therefore, air-source heat pumps typically have poor performance in cold climates for residential heating applications.

In Canada, ASHPs are typically equipped with back-up heating systems such as oil, gas, or electric heating to meet demand on very cold days. One solution to poor cold weather performance is to use solar energy to increase the temperature of the air passing through the outdoor evaporator of the heat to obtain a higher COP.

The COP can also include the energy required for back-up heating, this COP definition highlights the effectiveness of energy storage. Equation 2 shows the COP definition including compressor and back-up heating consumption.

$$COP_2 = \frac{Heat\ out\ of\ (condenser + back-up\ heating\ device)}{Work\ into\ (compressor + back-up\ heating\ device)} \quad (2)$$

Kamel et al. (2015) in their review of the integration of heat pumps with solar systems listed two main methods for using solar energy to increase the temperature of the air entering the evaporator; direct expansion solar assisted heat pump (DX-SAHP) and indirect expansion solar assisted heat pump (IDX-SAHP). DX-SAHP combines the evaporator of the heat pump with a solar collector to create a single component. IDX-SAHP uses the solar collector as a separate component that feeds warmed air to the evaporator of the heat pump. The advantage of having the solar collector as a separate component is that the heat pump is able to operate independently of the solar collector. Air passing through the solar collector at night is cooled due to radiation exchange with the sky; therefore, it is beneficial for a heat pump to be independent of its solar collector for night time operation. Additionally, it is advantageous for a heat pump to be independent of the solar collector during the cooling season when the outdoor coil is most efficient with cooler air.

Traditionally, ground source heat pumps (GSHP) have had superior heating performance to the ASHP due to a stable, higher temperature below ground than above. However, due to new technologies in the field of ASHPs, such as the two-stage variable capacity ASHP, the ASHP is able to match the GSHP's performance. A. Safa et al. (2015) experimentally compared a two-stage variable capacity ASHP to a horizontally configured GSHP acting in parallel for the same townhouse and found the two to have almost identical seasonal electrical consumption with the ASHP's payback period being 12.2 years compared to the GSHP's 27.8 years.

Dikici et al. (2008) compared an ASHP, a GSHP and various configurations of solar assisted ASHPs and GSHPs for Elazig, Turkey. The solar collectors were closed loop and liquid based. They found the COP of the GSHP, and ASHP were 2.44, and 2.33 respectively. They found the COP of solar assisted GSHP, solar assisted ASHP were 3.36 and 2.90 respectively. Therefore, they found that the solar assisted ASHP outperformed the base GSHP.

Kegel et al. (2012) compared the life cycle cost of an ASHP with electric back-up, ASHP with natural gas back-up, GSHP with electric back-up, and a solar assisted ASHP with natural gas back-up. All systems were modelled in TRNSYS with five minute time steps in Toronto for a 1980's house, an energy efficient house, and a "Net Zero Ready" house. They used Toronto Hydro (2011) tiered utility rates (based on usage) and Enbridge gas's pricing system. Assuming a twenty year lifecycle they found that the standard ASHP system had the lowest cost for the 1980's house and energy efficient house while the GSHP was the most economically viable for the net zero ready house. The solar assisted heat pump used in this study was of the type where the evaporator of the heat pump was directly installed in the solar collector and was not very effective.

When a photovoltaic/thermal (PV/T) collector replaces building materials, such as the roof or exterior walls, it is called "building integrated". The PV/T collector is simply photovoltaic panels with air, or some other fluid, running underneath the panels to collect thermal energy. PV/T collectors have been shown to produce over 40% more energy than separate photovoltaic and thermal collectors encompassing the same area (De Vries et al., 2002).

The benefits of PV/T systems are numerous. Tripanagnostopoulos et al. (2001) compared twenty-one different configurations of PV and PV/T collectors on an energy, cost and lifecycle assessment basis. They found that PVT systems with glazing had lower electrical output but sufficiently higher thermal output due to the greenhouse effect. They found that the payback period of both glazed and unglazed PV/T systems were approximately two and a half times shorter than PV alone. They also found the PV/T systems had lower lifetime global warming potential than the PV alone systems. The fluid running underneath the PV serves two purposes. One, the fluid cools the photovoltaics resulting in higher electric efficiency. Two, the fluid absorbs heat from the panels which can then be put to other uses, such as input to an air-source heat pump during the heating season.

The performance of the BIPV/T+ASHP is greatest during the day when the sun is available to preheat the air entering the heat pump. However, the demand for heating is greatest at night and thus means of storing the thermal energy produced during the day are necessary to achieve optimum performance.

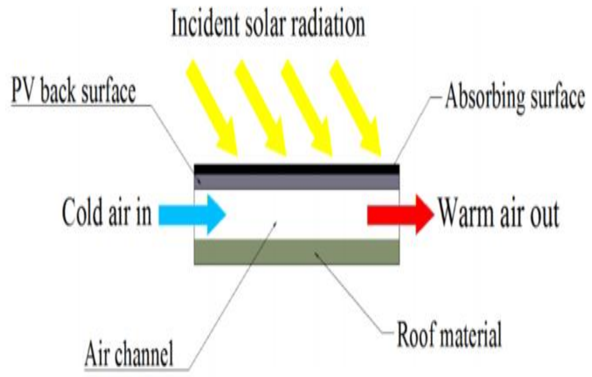

Figure 2: BIPV/T setup (Hailu et al., 2014)

A testing facility is currently being constructed at the Kortright Centre in Vaughan, Ontario to optimize the operation of the BIPV/T + ASHP in a real world setting. The testing facility will incorporate various forms of energy storage, including a PCM water tank, with the goal of maximizing the amount of heat pump operation during the day when the sun is available for the BIPV/T. The BIPV/T system will be a roof mounted five by five solar panel array. The heating loads for the test hut will be manipulated to match a townhouse constructed at the Kortright Centre in Vaughan, Ontario (Zhang et al., 2011).

The focus of this paper is to examine the potential performance enhancements to the BIPV/T + ASHP through the use of water and PCM storage.

METHODOLOGY

House Description

The thermal demand to be met by the BIPV/T + ASHP is from a three-storey townhouse located in Vaughan, Ontario. The house was built for the Toronto and Region Conservation Authority (TRCA) along with the Building Industry and Land Development (BILD) Association to demonstrate sustainable housing technologies. Two similarly sized townhomes were built called the twin-houses named House A and House B. This paper uses the thermal demand from House A, the house on the left-hand side of Figure 3. The house has the following thermal characteristics:

- 261 m^2 (2808 ft^2) floor area
- Windows double glazed with U-value 2.19 W/m^{2}K (0.39 Btu/ft^2 ^{0}F)
- Roxul fibre batt and 3” Styrofoam above grade with overall resistance of RSI-5.31 (R-30)
- Durisol blocks for basement wall/foundation RSI 3.54 (R-20)
- Structurally Insulated Panel (SIP) for roof with RSI-7 (R-40)

The seasonal heating demand has been experimentally verified by Safa et al (2015) to be 17592 kWh and their results will be used for this analysis.

Figure 3: South-West view of House A and House B

System Setup

A 5x5 roof mounted solar panel array was modelled with a 101.6mm (4 inch) channel depth between the surface of the roof and the back of the solar collector by Kamel et al. (2014). The flow rate of the air was set to 1.5 kg/s. Kamel et al. found that lower duct depths and lower flow rates for the BIPV/T resulted in higher COP for the ASHP, but lower flow rates also resulted in less thermal energy being carried through to the heat pump. Therefore, there is a trade-off between gathering enough thermal energy to meet the heat pumps demand and making the flow rate low enough to increase the temperature of the air.

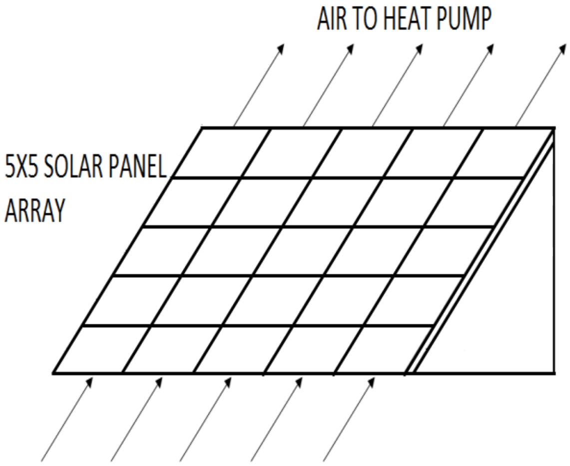

Figure 4: 5x5 BIPV/T photovoltaic array

The heat pump's outdoor coil sits in a duct fed by either ambient outdoor air or the BIPV/T. The heat pump's outdoor coil is located immediately after the outlet of the BIPV/T, to reduce duct losses. When the heat pump is being fed directly by ambient air, the BIPV/T vents outside, through natural convection. The heat pump's source of air will be controlled by dampers and will be whichever provides the best performance.

The heat pump's condenser is located within a water tank which provides in-floor heating.

Figure 5 shows the schematic of the BIPV/T + ASHP with storage. The light coloured arrows in Figure 5 correspond with air pathways and the darker arrows correspond with either refrigerant or water pathways. The source of the air for the BIPV/T is the ambient air located at the roof level soffits. Doiron (2011) found that the layer of air in contact with the siding of a house is heated and rises naturally. The heated air, rather than the ambient outdoor air, enters the BIPV/T system at the soffits. Doiron found that for the two-story ÉcoTerra house located in Eastman, Quebec, Canada, the heated air was on average 4°C higher than ambient and peaked at 14°C above ambient for a south facing wall. The air then flows underneath the BIPV/T and is heated. Next, the air flows over the outdoor coil of the ASHP and then is either exhausted or it is used for other purposes not examined here such as further energy storage. The ASHP transfers heat to the storage tank through the use of refrigerant while the storage tank transfers heat to the floors through the use of water.

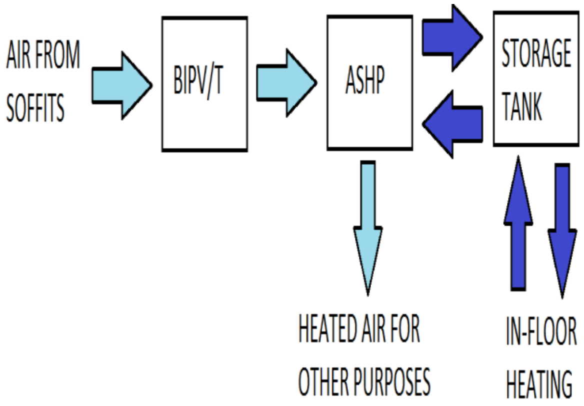

Figure 5: BIPV/T+ASHP with energy storage schematic

The storage tank was modelled with and without phase change material (PCM) with a phase change temperature of 46^{0}C (D'Avignon & Kummert, 2013). It was idealized that the PCM will both melt and freeze at the temperature of 46^{0}C, instead of doing so over a temperature range. The PCM's only contribution to the energy storage was assumed to be its latent heat of fusion. This means that when the tank temperature rises to 46^{0}C the PCM starts absorbing energy and when the tank temperature falls to 46^{0}C, the PCM releases energy. The set point temperature of the storage tank was 50^{0}C. If the heat pump was not able to keep the tank above 30^{0}C, it was assumed that a back-up system was used for heating with a COP of 0.95. The tank was perfectly insulated and well-mixed. The storage tank was modelled on an hourly basis.

Table 1: Properties of Phase Change Material (PCM) (D'Avignon & Kummert, 2013)

PCM Properties	**Value**	**Units**
Density	1587	kg/m^3
Latent heat of fusion	210 000	J/kg
Melting/freezing temperature	46	^{0}C

A two-stage variable capacity air-source heat pump's performance was experimentally validated by Safa et al. (2015). To model an air-to-water heat pump for this paper, the experimentally verified air-to-air heat pump by Safa et al. was modified by shifting the COP curve to achieve a higher outlet temperature from the heat pump. Safa monitored the energy consumption of the compressor and outdoor fan over a heating and cooling season for the heat pump. Figures 6 and 7 show the power draw and heat output respectively for the heating season. It can be seen in Figures 6 and 7 that the second stage of the heat pump turns on around -15°C in order to provide extra heating. Figure 8 shows the effect of shifting the COP curve 5^{0}C and 10^{0}C higher. To obtain correct floor heating temperatures, the condenser of the water based heat pump must provide a higher temperature than required of the original air based system; however, this results in a performance penalty. Three different COP cases are shown in Figure 8 in order to highlight the effect of shifting the outlet temperature higher.

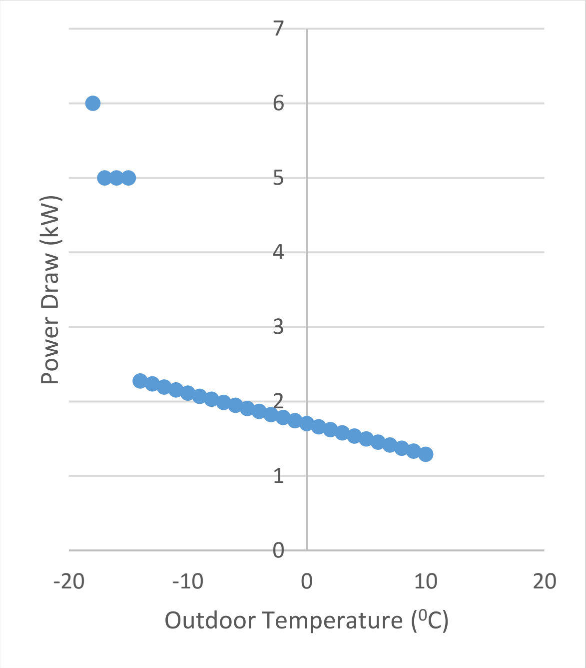

Figure 6: Power draw versus outdoor temperature for original ASHP (Safa et al., 2015)

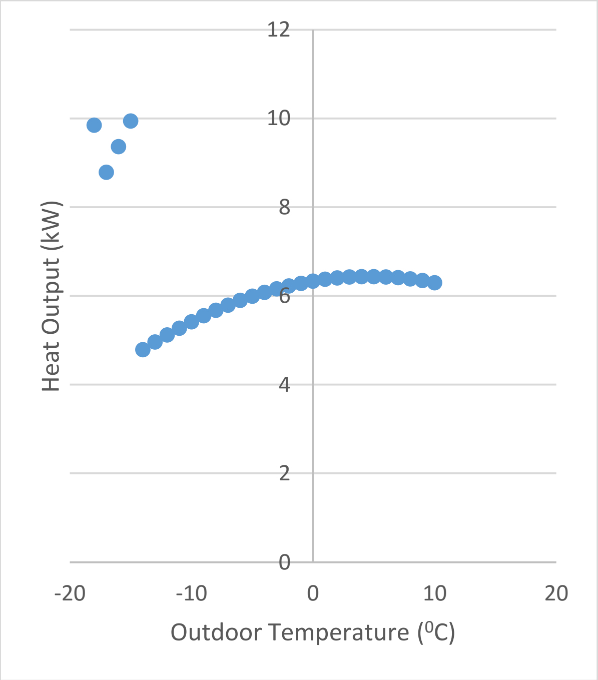

Figure 7: Heat output versus outdoor temperature for original ASHP (Safa et al. 2015)

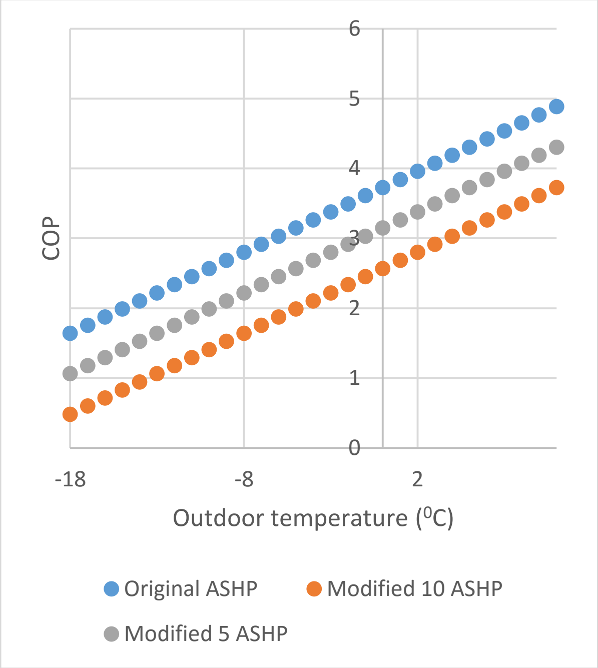

Figure 8: Seasonal COP of the three heat pump curves versus outdoor temperature for heating season of ASHP

RESULTS

The storage tank sizes of 500L, 1000L, and 1500L were all examined and filled with a combination of water and PCM varying from 0% to 70% PCM by volume. Figure 9 shows the percent of heating demand met by the ASHP utilizing the BIPV/T versus the amount of PCM for the three storage tank sizes. Figure 9 does not include the heating provided by the back-up heating and is for the ASHP with the COP curve shifted for 10^{0}C temperatures. Figure 9 also shows the amount of heating demand met if the heat pump were used to provide instantaneous heating without the use of storage. It can be seen that the introduction of a 500L storage tank with no PCM increased the heating demand met by approximately 10% over the use of instantaneous heating, or 1759 kWh. The BIPV/T +ASHP with energy storage was able to meet 80-90% of the annual heating load, which is the heating capacity recommended by NRCan (2009). Figure 9 shows that the 500L tank with 30% PCM was equivalent to a 1000L tank without PCM and a 500L tank filled with 50% PCM was equivalent to a 1500L tank without PCM.

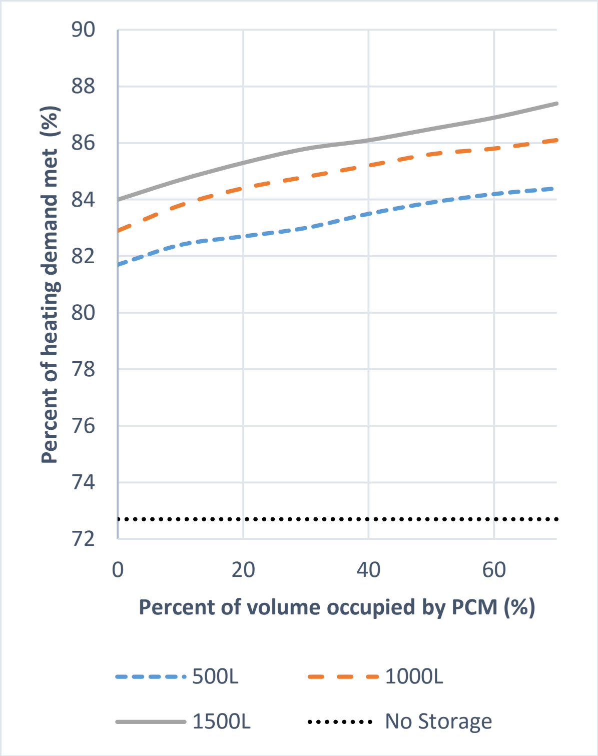

Figure 9: Percent of heating demand met by BIPV/T+ASHP (shifted 10^{0}C) versus amount of PCM for various tank sizes (does not include back-up heating)

Figure 10 shows the tank temperature versus time for a typical winter week for the three tank sizes using the 10^{0}C shifted ASHP curve utilizing the BIPV/T without PCM storage. Figure 10 shows that the 1500L tank changes temperature slower than the 1000L tank and the 500L changes the fastest of the three. From Figure 9 it can be seen that the 500L tank with 50% PCM provides similar performance to the 1500L tank without PCM. Therefore, Figure 10 demonstrates the effectiveness of the 500L tank filled with 50% PCM, by virtue of being similar to the 1500L tank. Figure 10 also shows that there are periods where regardless of the tank size the heat pump was unable to keep the temperature above 30 ^{0}C and thus a back-up system was used to keep the temperature at 30^{0}C during these periods.

Figure 11 shows the seasonal heating energy consumption versus the amount of PCM in the tank for the three tank sizes for the ASHP shifted 10^{0}C curve utilizing the BIPV/T. The energy consumption includes both ASHP consumption as well as back-up heating energy consumption. It is necessary to include back-up heating consumption because as energy storage is increased the heat pump is used more often and the back-up heating is used less; therefore, if back-up heating were not included it would seem like energy consumption was increasing with the use of storage, when in fact overall energy consumption is decreasing. It can be seen that increasing the tank size or increasing the amount of PCM in the tank reduces the overall energy consumption.

Figure 12 shows the heating season COP$_2$ versus the amount of PCM in the tank for the three tank sizes with the ASHP shifted 10^{0}C curve utilizing the BIPV/T and includes back-up heating energy consumption. Figure 12 shows that the seasonal COP$_2$ increases as either the tank size is increased or the amount of PCM in the tank is increased. Figure 8 shows that the COP of the 500 L tank with 50% PCM is the same as the 1500L tank without PCM. Therefore, the use of PCM allows for a drastically smaller storage tank.

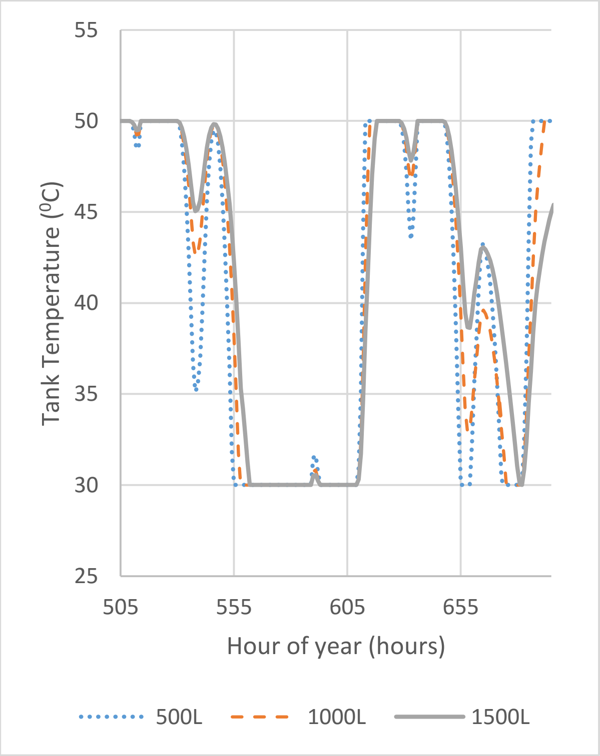

Figure 10: Tank temperature versus hour of year of typical winter week without the use of PCM for BIPV/T+ASHP (shifted 10^{0}C)

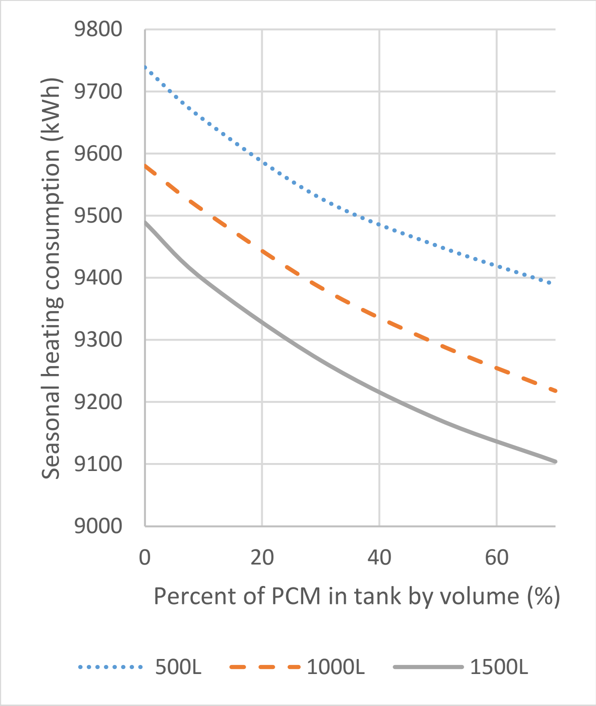

Figure 11: Seasonal heating energy consumption of BIPV/T +ASHP (shifted 10^0C) and back-up heating versus amount of PCM in storage tank for various tank sizes

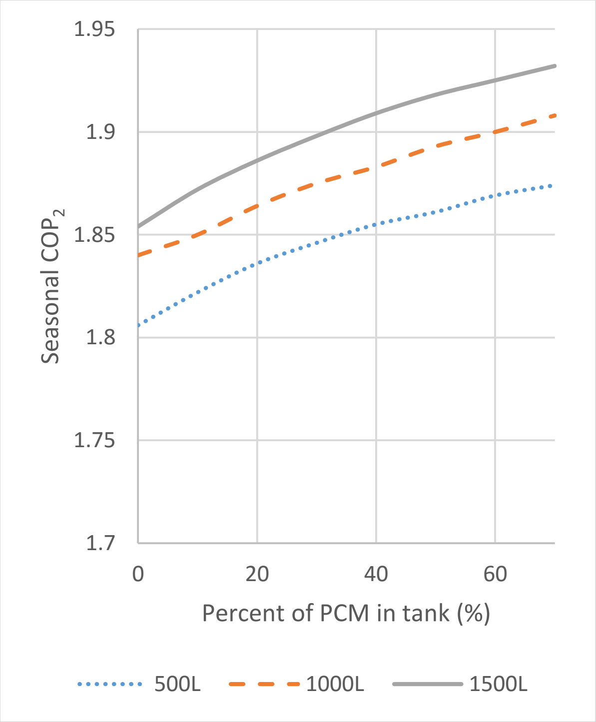

Figure 12: Seasonal COP$_2$ for air-water heat pump with various amounts of PCM for the three storage tanks during heating season

Table 2 shows the heating season COP versus for the three separate ASHP curves all utilizing the BIPV/T. The COP of the BIPV/T+ASHP was not affected by the use of energy storage. In fact, the energy consumption of the ASHP increased with the use of energy storage. However, the energy storage allowed for the back-up heating usage to be decreased and resulted in an overall higher COP (COP$_2$).

Table 2: Seasonal COP for various heat pump curves with BIPV/T (does not include back-up heating)

Heat pump type	Seasonal COP
BIPV/T+ASHP	3.4
BIPV/T+ASHP (+5^{0}C)	2.8
BIPV/T+ASHP (+10^{0}C)	2.4

CONCLUSIONS

Thermal storage for a building integrated photovoltaic/thermal (BIPV/T) collector combined with an air source heat pump (ASHP) was modelled. A sensitivity analysis was conducted on various water tank sizes containing phase change materials (PCMs) for diurnal energy storage of the ASHPs thermal output. It was found that as storage size and usage of PCM increased, the coefficient of performance (COP) of the system was increased. It was found that increasing the tank size or increasing the amount of PCM in the tank reduced the overall seasonal energy consumption. The use of PCM in the storage tank allowed for a significantly smaller tank to be used than if water alone was used as the storage medium, for example a 500L tank filled 50% with PCM was found to have equivalent benefits to a 1500L without PCM. The use of PCM based water storage can drastically increase the efficiency and effectiveness of the BIPV/T with ASHP.

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