2016

The Potential of Liquid-Based BIPV/T Systems and Ice Storage for High Performance Housing in Canada

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The Potential of Liquid-based BIPVT and Ice Storage for High Performance Housing in Canada

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ABSTRACT

This paper presents an innovative combination of liquid-based building integrated photovoltaic and thermal (BIPVT) panels with heat pump and ice thermal storage technologies. The system cools roof-integrated PV panels while simultaneously using the recovered thermal energy to efficiently supply heating and hot water to the building. Performance of the proposed system is examined for high performance housing in Calgary and Montreal. Simulated results show strong energy savings potential, with annual net energy use reductions of 13%-34% in comparison to an air-source heat pump + PV only case. BIPVT technologies increase annual PV electrical production by up to 10%, while the integration of ice storage reduces heating/hot water energy use by approximately 26%.

1. INTRODUCTION

ASHRAE Vision 2020 has defined market viable net-zero energy buildings as a key objective for new construction in North America (ASHRAE, 2008). Designing for this target requires the effective integration of renewable energy generation into the building. However, many buildings have limited roof and façade area to incorporate such technologies, making it difficult to achieve a net zero energy design. Building Integrated Photovoltaic and Thermal (BIPVT) systems could facilitate the greater adoption of net zero energy targets by converting the building envelope into a simultaneous producer of both thermal and electrical energy.

Photovoltaic (PV) electrical efficiencies decrease with higher cell temperatures. BIPVT systems address this issue by cooling PV panels with a heat transfer fluid, and then using recovered heat to supplement building heating and/or hot water systems. Commonly, BIPVT systems in North America use air as a working fluid. While this offers easy integration with building ventilation systems and minimizes potential damage from leaks, air also has a lower thermal capacitance which reduces the amount of thermal energy extracted from a collector. Additionally, there is no simple method of directly storing thermal energy for later use. This becomes an important issue in residential buildings, where there is often a time discrepancy between solar supply and peak building demands.

Liquid based BIPVT (and also non-building integrated PVT) systems offer improved heat transfer characteristics and a simpler integration with existing thermal storage technologies. These systems can generally use two collector types (Zondag, 2008):

i. Glazed Modules. Glazed systems prioritize the recovery of thermal energy by adding an additional glass cover over the PV cells. This reduces thermal losses, allowing glazed configurations to achieve fluid temperatures high enough to directly meet heating or domestic hot water (DHW) loads. However, the additional glass cover and higher fluid temperatures combine to reduce PV electrical efficiencies, and can lead to high stagnation temperatures which damage the PV modules (Dupeyrat *et al.*, 2011).

ii. Unglazed Modules. Unglazed collectors remove the glass covering in an effort to simplify collector design and improve electrical efficiencies. Working fluid temperatures must be kept low in order to minimize thermal losses, especially in cold climates. As such, these systems require the integration of heat pump and thermal storage technologies to store and then deliver recovered thermal energy to the building.

The strong potential of combining low-grade solar thermal energy with heat pump systems has been previously noted (Zondag, 2008). In particular, several authors have proposed the combination of solar collectors, ice storage, and heat pumps as a means of improving energy storage densities and collector thermal efficiencies (Trinkl *et al.* 2009, Tamasauskas *et al.* 2012, Dott & Afjei 2014, Carbonell *et al.* 2016). In these concepts, a cold working fluid is circulated to the solar collectors to reduce losses and improve thermal efficiencies. The low grade thermal energy recovered is then upgraded via a heat pump to meet heating and DHW demands. However, while results are promising, there has been little work to date on the potential of these systems in combination with BIPVT technologies for the Canadian climate, where cold temperature working fluids could have the dual benefit of increasing both the thermal and electrical efficiency.

This paper examines the potential of using liquid based BIPVT panels with ice storage and heat pump technologies to meet the thermal and electrical demands of high performance Canadian homes. Detailed simulation models are developed and used to examine system performance in two Canadian cities. Simulated results are compared to two base cases to quantify the benefits of BIPVT and ice storage technologies. Finally, the performance of key system components is discussed to better understand system operations.

2. DEVELOPMENT OF BASE CASE MODELS

Two base systems were developed to identify the impact of heat pumps and ice storage on annual energy use.

2.1 Housing Model

High performance housing models were developed for Calgary, AB and Montreal, QC. Each climate is summarized below in Table 1 (data from (Pelland *et al.*, 2006) and (CCBFC, 2010)). Heating degree days are based on temperatures below 18°C, while solar potential is based on a surface tilted to the latitude of the location. While both cities experience cold winters, they differ significantly in terms of solar availability, with Calgary amongst the sunniest cities in Canada. It is also important to note that while Calgary has more heating degree days, mean air temperatures from January through March are actually higher than for Montreal. Calgary, however, experiences cooler spring and summer conditions which increases the duration of time spent below 18°C.

Table 1: Selected Climate Characteristics

	Calgary	**Montreal**
Heating Degree Days	5000	4200
Heat T_{Design} (°C,DB)	-30	-23
Annual Solar (kWh/m^2)	1292	1185

The shell of the home used in this study was based on the Canadian Centre for Housing Technology (CCHT) test home located in Ottawa, Ontario (Swinton *et al.*, 2003). This home is typical of single family Canadian housing, and consists of two above ground floors and a finished basement, with a total heated floor area of 284 m^2. The envelope and systems of the home were modified to represent a high performance design achieving a minimum ERS-86 rating on the EnerGuide Rating Scale (OEE, 2005). Further details on the development of this model can be found in Kegel *et al.* (2012). Table 2 summarizes the key performance characteristics of the building.

Table 2: Housing Characteristics

Roof RSI	8.93 m^2°C/W
Wall RSI	5.65 m^2°C/W
Basement Wall RSI	4.95 m^2°C/W
Basement Slab RSI	2.58 m^2°C/W
Window U-Value	1.01 W/m^2°C
Infiltration	0.75 ACH_{50}
Generation	PV, 40 m^2, 6.0 kW_P

Each home is assumed to be grid-tied, with the local electricity network acting as an unlimited source/sink of electrical energy. PV panels are integrated into the south facing roof of the home.

2.2 Base Mechanical Systems

Two mechanical systems were selected to represent both conventional and more efficient approaches to supplying building heating and DHW. In all cases, the above ground floors are maintained at a minimum 21°C, while the basement is maintained at 18°C. Cooling is met using natural ventilation, with cooling available Apr. 15 to Oct. 15.

Base Case 1

Heating is provided using electric baseboards on each level of the home. DHW loads are met using a conventional DWH tank with electric resistance elements.

Base Case 2

Heating and DHW are met using a cold climate air-water heat pump operating against a warm storage tank (Figure 1). Cold climate heat pumps are specifically designed for colder winter climates like those in Canada, and can operate down to an outdoor air temperature of -25°C while still maintaining a significant portion of heating capacity. In this system, warm water is drawn from the top of the tank to serve radiant flooring on all three levels of the home, while DHW loads are met by passing cold water from the city mains through a vertical coiled heat exchanger internal to the tank. Auxiliary heating (if needed) is provided using electric resistance elements in the floor loops and DHW loop.

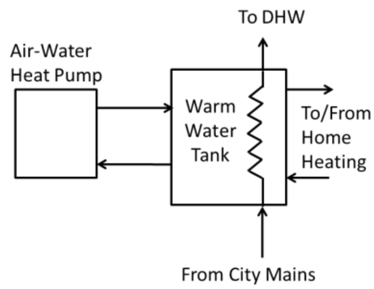


Figure 1: Air-Water Heat Pump Integration

A summary of key system parameters is provided in Table 3. The warm tank volume for Base Case 2 is larger because this tank serves both heating and DHW loops.

Table 3: Base Case Mechanical System Parameters

	Base Case 1	**Base Case 2**
Heating	Electric baseboards (BB)	Air-Water HP (COP 3.7[1])
DHW	Electric resistance	HP + tankless electric auxiliary (if needed)
Notes	Conventional DHW tank (V=0.23 m^3)	Radiant flooring (Basement, 1st, 2nd) Warm storage tank (V=0.5 m^3)

[1]Rated at 8.3°C outdoor dry bulb, 30°C inlet water temperature

3. PROPOSED SYSTEM CONCEPT AND OPERATIONS

The proposed BIPVT system layout is shown in Figure 2. Priority was given to a simple configuration to reduce system complexity and equipment requirements.

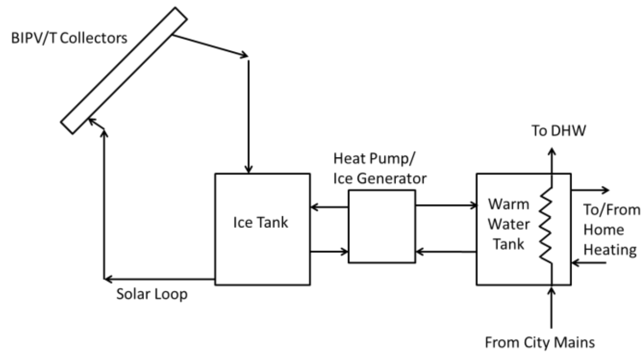


Figure 2: Proposed System Integration

3.1 System Description

The proposed system combines BIPVT panels with a heat pump and ice-based thermal storage. In this study, ice storage is based on the use of ice slurry (a mixture of small diameter ice particles and water) as described in Tamasauskas *et al*., 2015. BIPVT collectors (both glazed and unglazed are examined) operate in series with the ice tank, improving panel thermal and electrical efficiencies. A water to water heat pump links the ice tank with the warm water storage, upgrading low-temperature fluid obtained from the collectors for use within the building. The warm tank serves as the main heat distribution point for the building. Hot water is drawn from the top of the tank to serve radiant floor heating loops on each level of the home. DHW demands are met by passing cold water from the city mains through a coiled heat exchanger located internal to the warm tank. Auxiliary heaters in the floor loops and DHW loop operate as needed to supplement system operations.

BIPVT panels should be cooled year round to maximize PV electricity generation. During the winter, building loads far outweigh thermal energy gains from the collectors, increasing ice mass in the ice tank and allowing a consistently cold fluid to circulate and cool the BIPVT array. However, this situation is reversed in the summer. Excess thermal gains from the BIPVT array substantially increase fluid temperatures in the ice tank and reduce its available cooling capacity. To counter this, a simple cooling mode is added for the summer months for systems operating with unglazed BIPVT collectors. During the night-time, fluid can circulate to the BIPVT array, where it is cooled via radiative heat exchange with the cold sky. This builds cooling capacity for the following day, allowing PV panels to operate more efficiently.

3.2 System Operations

System operations can be divided into solar, heat pump, and radiant flooring loops.

<u>Solar Loop</u>

Control of the solar loop is based on the combination of three control variables:

i. *BIPVT Cooling*
The solar loop operates only when collector cooling is required. In this study, a predicted initial fluid temperature rise ($\Delta T_{BIPVT,I}$) of 3°C in the winter and 5°C in the summer is required to start the solar loop.

ii. *Ice Tank Temperature*
Ice tank fluid temperatures ($T_{IT,Fluid}$) are limited to avoid exceeding the maximum heat pump evaporator inlet temperature. This limit also ensures that fluid entering the collector will have some cooling effect on the panels. For this study, the maximum temperature was set to 26°C (ClimateMaster, 2010).

iii. *Heat Rejection Potential* (Unglazed collectors, Cooling only)
For the unglazed system only, the night cooling mode is activated during the cooling season (Apr 15 to Oct 15) whenever the BIPVT plate temperature ($T_{BIPVT,PLT}$) falls at least 1°C below the ice tank temperature.

Flow rates in the solar loop are proportional to collector area, and were set to 65 L/h/m^2 (Solimpeks, 2011).

Heat Pump Loop

Heat pump operations are based on two control variables:

i. *Ice Mass*

Heat pump operations are limited by the maximum ice capacity of the ice storage tank. For this study, the maximum ice mass ($M_{IT,Max}$) is set to 60% of the tank fluid mass, based on experimental results derived from a test bench (Tamasauskas *et al*., 2015).

ii. *Warm Tank Temperature*

The heat pump operates to maintain a warm tank fluid temperature ($T_{WT,Fluid}$) of 45°C at the top of the tank. This value is selected to meet a significant portion of both space heating and DHW demand.

Radiant Floor Loop

Radiant flooring loops in the basement, first, and second floors are used to meet space heating requirements. The flow rate through each loop is varied using a PID controller to maintain an air temperature of 21°C on the two above ground floors, and 18°C in the basement. Supply temperatures were varied using an outdoor air temperature reset.

Loop controls are summarized by mode/season below in Table 4

Table 4: Control Summary for BIPVT Cases

	Mode	Control Summary
Solar Loop	Heating Season	$T_{IT,Fluid}$<26°C, and $\Delta T_{BIPVT,I}$>3°C
	Day, Cooling Season	$T_{IT,Fluid}$<26°C, and $\Delta T_{BIPVT,I}$>5°C
	Night, Cooling Season	$T_{IT,Fluid}-T_{BIPVT,PLT}$>1°C
Heat Pump	All Seasons	$M_{Ice}<M_{Ice,Max}$, $T_{WT,Fluid}$<45°C
Radiant Floor	All Seasons	$T_{RF}=-0.3659T_{Out}+31.59$, 25°C≤$T_{RF}$≤ 40°C

4. SIMULATION METHODOLOGY

TRNSYS (Klein *et al.*, 2010) is used to model the selected systems because of the complexity and range of component models required. A time step of 3.75 minutes is selected to properly represent system control decisions. Systems are simulated with a one month warm up period to reduce the impact of assumed initial conditions.

4.1 Summary of Simulation Components

For all cases, Type 56 was used to develop a detailed model of the building based on parameters outlined in Table 2.

Key HVAC simulation components for each base case are provided in Table 5. Storage tank volumes are based on Kegel *et al.* (2012), Tamasauskas *et al.* (2015) and mechanical space considerations. Heat pump performance is based on manufacturer data (Ecologix, 2016).

Table 5: Key Simulation Components for Base Cases

	Component	TRNSYS Type	Notes
Base Case 1	Hot Water Tank	Type 4	V=0.23 m^3
	Baseboards (BB)	Equation Type	Separate BB for each level
	Heating Control	Type 23	Separate BB PID control for each level
Base Case 2	Heat Pump	Type 941	4 ton, COP_{Rated}=3.70[1]
	Hot Water Tank	Type 534	V=0.5 m^3, 4 nodes
	Heating Control	Type 23	Separate PID control for each RF Loop
	Radiant Flooring	Type 56 Active Layer	Separate loops for all three levels
Common	PV	Type 562	A_{Panel}=1.37 m^2 /panel, N_{Panels}=29

[1]Rated at 8.3°C outdoor dry bulb, 30°C inlet water temperature

Table 6 summarizes selected HVAC components for the BIPVT analysis. Heat pump data and tank volumes are derived from an experimental test bench (Tamasauskas *et al.*, 2015). Pump performance is obtained from manufacturer data (Wilo, 2016).

Table 6: HVAC Simulation Components for BIPVT Cases

Component	TRNSYS Type	Notes
Heat Pump	Type 927	4 ton, COP_{Rated}=4.28[1]
Ice Generator	Equation Type	Derived from Guilpart & Fournaison (2005)
Ice Tank	Type 217	V=5 m^3, custom model
Warm Tank	Type 534	V=1.5 m^3, 4 nodes
BIPVT Array	Type 563 (unglazed)/Type 50 (glazed)	A_{Panel}=1.37m^2 /panel, N_{Panel}=29
BIPVT Pump	Type 654	Constant speed, 60W, 65 L/h/m^2 collector area
Heating Control	Type 23	Separate PID control for each RF Loop
Radiant Flooring	Type 56 Active Layer	Separate Loops for all three levels

[1] Rated at 0°C evaporator water temperature, 28°C condenser water temperature

4.2 Simulation of Solar Systems

Table 7 summarizes key PV and BIPVT panel parameters for each case. All solar systems are integrated into the south facing roof of the home. PV type, area, and rated cell efficiency were held constant across all systems to provide a common base of comparison. Listed PV efficiencies are for the cell only, and do not include corrections for the glass covering (these are, however, accounted for in the simulations). Provided information is derived from Solimpeks (2011), Notton *et al.* (2005), and Boubekri *et al.* (2009).

Table 7: PV and BIPVT Properties

PV Type	Mono-Crystalline
PV Cell Efficiency	14.88%
PV Temperature Efficiency Modifier	-0.0044
PV and BIPVT Dimensions (L x W)	1.66 m x 0.828 m
PV and BIPVT Glass Covering(s)	3.2 mm Low-Tempered Glass
	Transmittance-Absorptance:0.855
Slope/Orientation	40°/Due South

5. RESULTS

Results are presented on both a system and component level to better assess the energy performance of the proposed design.

5.1 System Level Performance

Table 8 summarizes annual energy performance in Calgary. A significant decrease in energy use is evident from Base Case 1 (Electric Baseboards) to Base Case 2 (Air-Water HP), which results from the efficiency of the heat pump and its ability to address both space heating and DHW loads. Integrating BIPVT and ice storage also has a clear impact on system energy performance, with both BIPVT cases reducing net annual electricity use by 28%-34% from Base Case 2. The unglazed configuration increased PV generation by 10% with a 13% decrease in heating/DHW in comparison with Base Case 2. The glazed configuration reversed this trend, with strong heating/DHW energy savings of 29%, but a decrease in PV generation of 7%.

Table 8: Annual Energy Use in Calgary

	Base 1: Electric BB	Base 2: Air-Water HP	BIPV/T (Unglazed)	BIPV/T (Glazed)
Heating+DHW (kWh)	13087	6273	5440	4454
Fans+Pumps (kWh)	964	1552	1747	1620
Lighting+Receptacles (kWh)	4476	4476	4476	4476
Total Electricity Use (kWh)	18526	12300	11664	10550
Total PV Generation (kWh)	8053	8053	8883	7513
Net Electricity Draw (kWh)	10473	4247	2780	3037

Table 9 summarizes annual energy performance in Montreal. The integration of an air-water heat pump again shows strong benefits, with a 54% reduction in net energy use in comparison to electric baseboards. The impact of the BIPVT system is less evident in Montreal because of reduced available solar radiation. Unglazed BIPVT collectors improve PV electricity production by 10% but reduce net annual electricity use by only 13% in comparison to Base Case 2. This can be attributed to the poor thermal performance of the unglazed collectors during the cold winter months. The glazed BIPVT system offers a greater net annual electricity savings of 20% in comparison to Base Case 2, but with a reduction in PV production of 5%.

Table 9: Annual Energy Use in Montreal

	Base 1: Electric BB	Base 2: Air-Water HP	BIPV/T (Unglazed)	BIPV/T (Glazed)
Heating+DHW (kWh)	12479	6102	6044	4653
Fans+Pumps (kWh)	964	1538	1720	1593
Lighting+Receptacles (kWh)	4476	4476	4476	4476
Total Electricity Use (kWh)	17918	12116	12241	10722
Total PV Generation (kWh)	7227	7227	7975	6834
Net Electricity Draw (kWh)	10691	4889	4266	3888

Each BIPVT configuration reduces energy use in both cities in comparison to a simple PV+HP system. However, the selection of an optimal BIPVT configuration is highly dependent on several additional factors, including initial costs, and utility rate structures. Given similar performance characteristics, it is likely that the unglazed model would be preferred, as this model represents a simpler and less expensive collector design. The unglazed model also offers the additional benefit of increased PV production, financially benefiting the homeowner in areas where feed-in tariffs are in place.

It is also important to view system performance within the context and operational objectives of the target building. Homeowners simply looking to reduce energy use are likely to achieve acceptable performance and payback periods with the HP + PV-only combination. The true benefit of the proposed BIPVT system is seen for buildings attempting to achieve near/net zero energy, where the building envelope must play an important role in the generation and management of energy. In these situations, the simulated savings of the proposed systems (13%-34%) represent a major step towards meeting these performance objectives in a simple and cost effective manner.

5.2 BIPVT Performance

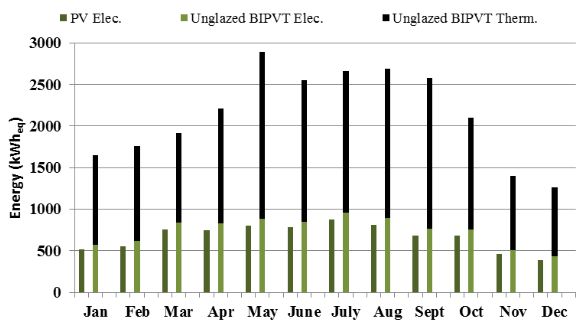
While Table 8 and Table 9 present the thermal and electrical demands of the house, Table 10 summarizes BIPVT performance in both regions. Integrating BIPVT substantially increases energy output from the solar array, with the unglazed unit in particular offering strong annual electrical, thermal, and heat rejection performance. Interestingly, thermal energy outputs are higher for the unglazed unit than the glazed configuration. This primarily relates to summer collector performance: The unglazed unit integrates a night cooling mode, which allows the system to have greater capacity to cool the BIPVT panels during the day. Conversely, the glazed system does not include this feature as the additional cover would greatly reduce the night cooling effect. This results in less capacity to cool the BIPVT panels during the day and subsequently, less thermal energy inputs into the system. For both configurations, it is clear that operating the BIPVT loop improves system performance, with useful heating/cooling extracted from the panels far greater than pump energy use.

Table 10: BIPVT Annual Energy Performance

	Calgary			Montreal		
	PV	Unglazed BIPV/T	Glazed BIPV/T	PV	Unglazed BIPV/T	Glazed BIPV/T
PV Electrical (kWh)	8053	8883	7513	7227	7975	6834
PV Thermal (kWh)	NA	16381	9269	NA	14548	8581
PV Heat Rejection (kWh)	NA	8254	0	NA	7542	0
PV Total Useful Energy (kWh)	8053	33517	16782	7227	30065	15415
BIPV/T Pump Day (kWh)	NA	106	85	NA	103	85
BIPV/T Pump Night (kWh)	NA	104	NA	NA	114	NA

Figure 3(a) compares the monthly breakdown of energy generation for the PV-only and unglazed BIPVT configurations in Calgary. The unglazed BIPVT module consistently offers a small boost in electricity production throughout the year, primarily resulting from average PV cell temperatures 3.1°C lower than a PV-only system. Thermal energy production is lowest in November and December when the duration and intensity of incident solar radiation is at a minimum.

Figure 3(b) compares the monthly performance of the unglazed and glazed BIPVT modules in Calgary. As explained above, although the glazed unit offers an improvement in thermal gains in the winter months, the glass covering prevents the possibility of using passive night-time cooling, subsequently reducing its capacity to cool the PV cells during the summer months. The added glazing also has a clear impact on electrical generation, which is consistently lower throughout the year because of higher cell temperatures and a reduced amount of incident solar radiation transmitted through the covering.



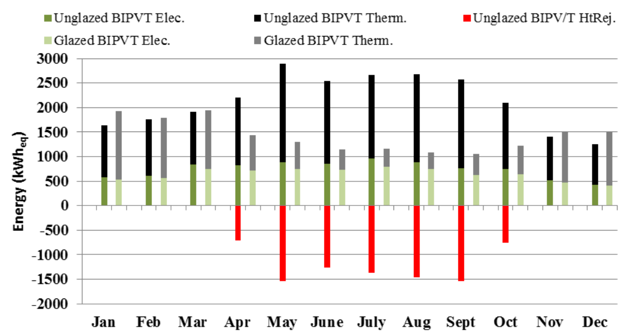
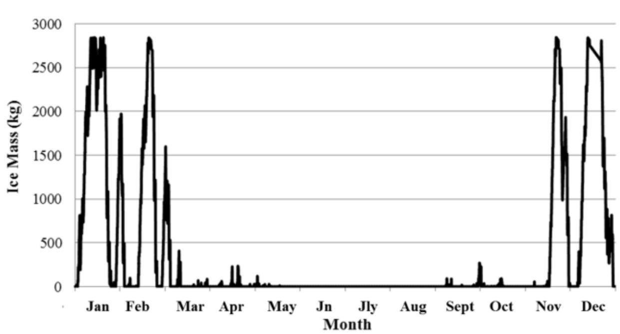


Figure 3: (a) System Energy Use Comparison: Base Case (b) System Energy Use Comparison: Collector Types

5.3 Ice Tank Performance

Figure 4(a) shows the annual change in ice mass for the unglazed system in Calgary. The ice capacity of the tank is used significantly throughout the core heating months when building thermal demands outweigh solar energy inputs. Maximum ice fractions are reached briefly from November through February, suggesting that the system is sized to effectively use ice storage while allowing consistent heat pump operations. In fact, an additional simulation for unglazed BIPVT in Calgary shows that the integration of ice storage yields a 26% reduction in heating/DHW energy use (1954 kWh) in comparison to an identically sized system using only sensible storage.

Figure 4(b) shows the average monthly fluid temperature in the ice tank. Temperatures remain low during the winter months when ice is built up, helping to improve BIPVT electrical and thermal efficiencies. Although temperatures rise significantly in the summer, fluid temperatures remain well below those seen when BIPVT is coupled directly to a warm storage such as a DHW tank (Haurant *et al.*, 2015).



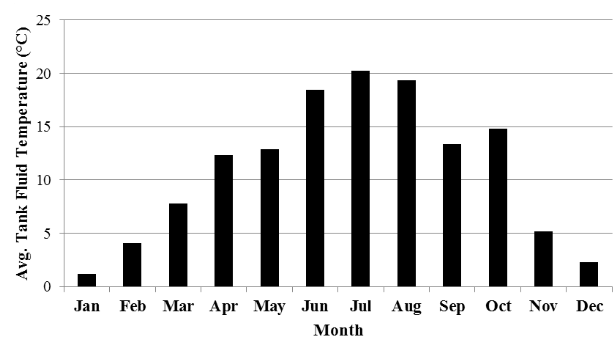


Figure 4: (a) Ice Mass in Ice Tank (b) Monthly Average Fluid Temperatures in Ice Tank

6. CONCLUSIONS

This paper presents an analysis of liquid-based BIPVT combined with heat pump and ice thermal storage technologies. Roof integrated BIPVT panels provide both electricity and low-grade thermal energy to the system. The ice tank serves as a cold temperature storage reservoir, increasing energy storage densities and BIPVT electrical and thermal efficiencies. A heat pump upgrades collected thermal energy as needed to meet space heating and DHW loads.

The proposed system is integrated into high performance housing in Calgary and Montreal. Simulated results demonstrate a clear reduction in net annual energy use, with predicted savings ranging between 13% and 34% depending on the city and collector configuration. Cooling and recovering heat from the PV array improved annual electrical production by up to 10%, while integrating the ice tank increased system storage capacity and reduced heating and DHW energy use by 26% in comparison with a sensible only system design.

NOMENCLATURE

Symbols

Δ	Difference	(-)
BB	Electric baseboards	(-)
COP	Coefficient of performance	(-)
M	Ice mass	(kg)
T	Temperature	(°C)
V	Volume	(m^3)

Subscript

BIPVT	Building integrated photovoltaic and thermal
Fluid	Fluid in tank
I	Initial
Ice	Ice mass
IT	Ice tank
Max	Maximum
Out	Outdoor
P	Peak
PLT	BIPVT plate
RF	Radiant floor
WT	Warm water tank

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ACKNOWLEDGEMENT

The authors acknowledge the financial support provided by Natural Resources Canada through the Program of Energy Research and Development (PERD) built environment heat pumps program.