

Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept

Yuxiang Chen, A.K. Athienitis, Khaled Galal

Dept. of Building, Civil and Environmental Engineering, Concordia University, 1455 De Maisonneuve West, EV6.139, Montréal, Québec, Canada H3G 1M8

Received 5 October 2009; received in revised form 19 May 2010; accepted 21 June 2010

Available online 4 August 2010

Communicated by: Associate editor Harvey Bryan

Abstract

This paper is the first of two papers that describe the modeling, design, and performance assessment based on monitored data of a building-integrated photovoltaic-thermal (BIPV/T) system thermally coupled with a ventilated concrete slab (VCS) in a prefabricated, two-storey detached, low energy solar house. This house, with a design goal of near net-zero annual energy consumption, was constructed in 2007 in Eastman, Québec, Canada – a cold climate area. Several novel solar technologies are integrated into the house and with passive solar design to reach this goal. An air-based open-loop BIPV/T system produces electricity and collects heat simultaneously. Building-integrated thermal mass is utilized both in passive and active forms. Distributed thermal mass in the direct gain area and relatively large south facing triple-glazed windows (about 9% of floor area) are employed to collect and store passive solar gains. An active thermal energy storage system (TES) stores part of the collected thermal energy from the BIPV/T system, thus reducing the energy consumption of the house ground source heat pump heating system. This paper focuses on the BIPV/T system and the integrated energy concept of the house. Monitored data indicate that the BIPV/T system has a typical efficiency of about 20% for thermal energy collection, and the annual space heating energy consumption of the house is about 5% of the national average. A thermal model of the BIPV/T system suitable for preliminary design and control of the airflow is developed and verified with monitored data.

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Keywords: Net-zero energy solar house; Building-integrated photovoltaic-thermal system; Passive solar heating; Active solar heating; Thermal modeling

1. Introduction

Residential energy consumption in cold climate areas is primarily for space and domestic hot water (DHW) heating. In Canada, about 17% of the annual national end-use energy is attributed to the residential sector (Statistics Canada, 2009); this amounts to about 233 kW h per square meter of floor area in 2006 (Natural Resources Canada, 2009). About 59% of the residential energy consumption

is for space heating and 18% for DHW heating (Natural Resources Canada, 2009). Significant savings can be achieved by optimizing passive heating, improving the efficiency of mechanical systems, using airtight envelopes with high thermal performance, and employing renewable energy technologies.

This paper focuses on the modeling, design and integration of a BIPV/T system in a near net-zero energy solar house (NZESH) in Canada; a NZESH produces from solar energy as much electrical and thermal energy as is imported from the utility/grid over an average year. The general approach in the design of the house in a cold, but relatively sunny climate, is based on the optimal combination of energy efficiency technologies and passive plus active solar

Corresponding author. Tel.: +1 514 848 2424 7080; fax: +1 514 848 7965.

E-mail addresses: yuxia_ch@hotmail.com (Y. Chen), aathieni@encs.concordia.ca (A.K. Athienitis), galal@bcee.concordia.ca (K. Galal).

Nomenclature

A_{step}	top or bottom boundary area of the control volume in the BIPV/T thermal model	$T_{top,mean}$ and $T_{btm,mean}$	the arithmetic mean temperature of the top and bottom boundaries, respectively
A_{top} and A_{btm}	the areas of the top and bottom boundaries	U_{btm}	thermal conductance of insulation at the bottom surface of the BIPV/T system ($W/m^2/K$)
F_{air}	the product of the mass flow rate and specific heat of air ($J/s/K$)	V_{wind}	free stream wind speed (m/s or km/h)
F_E	emissivity factor	$V_{air,pvt}$	average air velocity inside the cavity of the BIPV/T system (m/s)
F_A	angle (view) factor	α_{rf}	absorptance of the roofing material
$h_{c,pvt}$	convective heat transfer coefficient inside the BIPV/T system cavity ($W/m^2/K$)	σ_{SB}	Stefan–Boltzmann constant ($5.67E-8 W/m^2/K^4$)
$h_{c,wd}$	wind-induced convective heat transfer coefficient on the BIPV/T roof ($W/m^2/K$)	μ_{PV}	efficiency of electricity generation of the PV panels
$h_{r,top,btm}$	linearized radiative heat transfer coefficients between top and bottom boundaries ($W/m^2/K$)	$\Delta T_{air,pvt}$	BIPV/T air temperature increase between exterior and outlet
$h_{r,top,sky}$	linearized radiative heat transfer coefficient between roof and sky ($W/m^2/K$)	Acronyms	
I_{rf}	solar irradiance incident on the BIPV/T roof (W/m^2)	BIPV/T	building-integrated photovoltaic-thermal
$T_{air,outlet}$	air temperature at BIPV/T system air outlet	CHTC	convective heat transfer coefficient
T_{attic}	attic temperature	DHW	domestic hot water
T_{ext}	exterior temperature	HVAC	heating, ventilation, and air conditioning
$T_{PV,outlet}$	temperature of PV panels and metal roofing at the BIPV/T system outlet (top)	GSHP	ground source heat pump
		NZESH	net-zero energy solar house
		TES	thermal energy storage
		VCS	ventilated concrete slab

systems. First, an airtight, highly insulated envelope is designed with large near-equatorial facing windows. The size of the windows and their optical plus thermal properties are chosen in conjunction with adequately distributed interior thermal mass so as to capture high levels of passive solar gains while avoiding room overheating (Athienitis, 1994). Adopting direct gain passive solar heating to reduce space heating load is generally considered cost effective (Anderson, 1990; Athienitis and Santamouris 2002; Balcomb, 1992). The optimal ratio of window-to-façade or window-to-floor-area in passive solar design has been investigated by Tzempelikos and Athienitis (2005) for commercial buildings and O'Brien et al. (2008) for houses. When passive solar design is employed, the distribution of interior thermal mass, especially in the direct gain zone is critical in moderating temperature swings (Athienitis and Chen 2000; Balcomb 1983; Howard and Fraker 1990). Active approaches, such as solar thermal and photovoltaic (PV) systems (Duffie and Beckman 2006; Eicker 2003; Mørck et al. 2000), can also be employed to reduce the house energy consumption to near net-zero annually, so that energy generated from renewable sources is equal to the total energy consumed.

After optimally designing the passive systems that in the present case mainly depends on the south-facing façade, the roof needs to be designed for solar electricity and heat generation. The concept of building integration – integration

with the building roof and with the HVAC system – was adopted in the present demonstration house. The core of the active system adopted is a building-integrated photovoltaic/thermal (BIPV/T) system that generates electricity and collects heat from the same building envelope surface, which can be a roof or façade (Bazilian et al., 2001; Charron and Athienitis, 2006; Huang et al., 2001). In building-integrated photovoltaic (BIPV) systems, photovoltaic panels are an integral part of the building envelope (Benemann et al., 2001). This enhances the aesthetic appeal of the building and eliminates the need for extra land which is required for a stand-alone PV (SAPV) system, and is usually more economical than SAPV system (Chel et al., 2009; Chel and Tiwari, 2010). However, one major potential problem with BIPV systems is overheating (Krauter et al., 1999) which will reduce the electrical efficiency and also shorten their life span. BIPV/T systems are hence introduced to alleviate this problem. A BIPV/T system collects much of the heat absorbed by the PV panels through a heat transfer fluid in an open-loop (usually air) or closed-loop (usually liquid) configuration while reducing the problem of PV panel overheating (Krauter et al., 1999). Thus, the benefits are twofold: collecting more energy and lowering PV temperature. Furthermore, comparing the energy output (electricity and thermal energy) and the construction cost of the BIPV/T system with that of the BIPV system, the BIPV/T configuration has considerably higher cost-effectiveness (Bazilian

et al., 2001). The collected heat can be used for space, ventilation or DHW heating either by direct means or through a heat pump (Candanedo and Athienitis, 2008).

Recently, several studies have been conducted on low energy houses or buildings (Pasini et al., 2006; Parker, 2009; Steinbock et al., 2007; Wang et al., 2009). However, there is a need for documented work focused on the design and performance of affordable, near-net-zero energy solar houses in cold climates. For these houses, efficiently collecting and utilizing solar energy to significantly reduce the energy consumption presents some challenges, such as choice of active or passive heat storage, integration issues associated with making a BIPV/T system an integral part of the building envelope, and efficiently transporting and storing the collected heat. This paper focuses on the modeling and design of a BIPV/T system implemented in a low energy solar house in Canada. The assessment of the thermal performance based on monitored data of the BIPV/T system and the house is also presented. The companion paper part 2 presents a model and thermal performance assessment of a ventilated concrete slab (VCS) included in the basement of the same house to store much of the collected solar thermal energy so as to reduce heating loads.

2. Integrated energy design concept and BIPV/T system

In the winter of cold climate areas, such as in much of Canada, the sky is usually clear and sunny and thus, the solar energy is available when it is most needed. Houses with optimized solar design generally need to collect as much solar energy as possible in a relatively short time (the daytime is short in winter) and retain it over a longer period (up to several days) to approach zero average annual energy consumption. Passive solar gains through triple-glazed windows can satisfy most of the daytime heating needs, while thermal energy collected from active solar thermal devices can be stored for use at night. Advanced thermal energy storage (TES) system is needed to efficiently store, retain and release the collected solar thermal energy. For auxiliary heating, conventional air-to-air heat pumps cannot function efficiently (i.e. with coefficient of performance higher than 2) during much of the heating season due to low outdoor air temperatures during much of the winter (around -15°C for extended periods). Therefore, advanced solar building technologies and an integrated design approach are needed for the development of solar homes that achieve near net-zero energy consumption under Canadian climatic conditions.

ÉcoTerra (Fig. 1) – the solar house considered in this paper, was built in 2007 by a prefabricated home manufacturer and is located in Eastman, Québec, Canada. Table A1 in Appendix A provides the monthly average dry bulb temperature and horizontal global solar radiation of Eastman. One of the objectives of building this house is to demonstrate how it can achieve near net-zero annual energy consumption and yet be relatively affordable. Two of the approaches are the optimal integration of the relatively



Fig. 1. ÉcoTerra demonstration house, November 2007 (the photovoltaic system made up of amorphous laminate panels attached to metal roof is on the upper roof section).

low cost amorphous silicon PV system and the pre-fabrication of the BIPV/T system in a factory environment. Selecting such a PV system with heat recovery as opposed to a higher efficiency crystalline silicon PV system covering the same surface reduced the additional cost of the house. The house is designed to accommodate a four-person family. The total floor area is about 140 m^2 plus an additional 90 m^2 basement which is conditioned but has a lower heating setpoint temperature (19°C) than the main living space. Fig. 2 shows a schematic of the ground floor plan and the passive thermal mass.

Low net energy consumption in ÉcoTerra is achieved by reducing energy use through energy-efficient building design, and by generating energy on-site with renewable energy systems. Fig. 3 shows a schematic of the integrated energy system implemented in ÉcoTerra. Large, south-facing, high performance windows with distributed thermal mass in the direct gain zone are adopted for passive solar heating. A grid-connected BIPV/T system generates

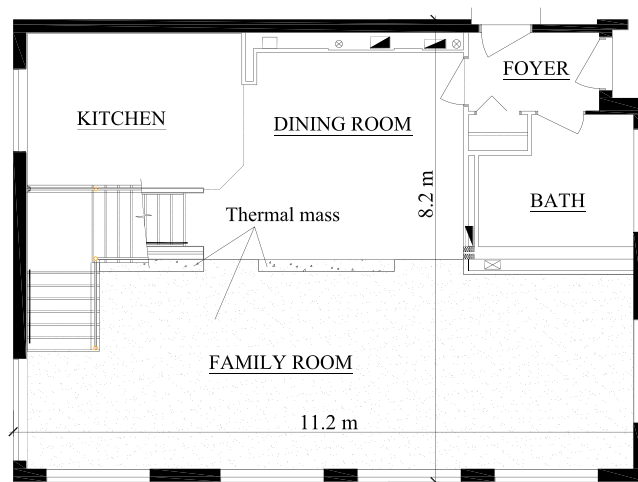


Fig. 2. Schematic of the ground floor plan and the passive direct gain thermal mass (15 cm thick concrete slab and 25 cm thick, 1 m high concrete walls).

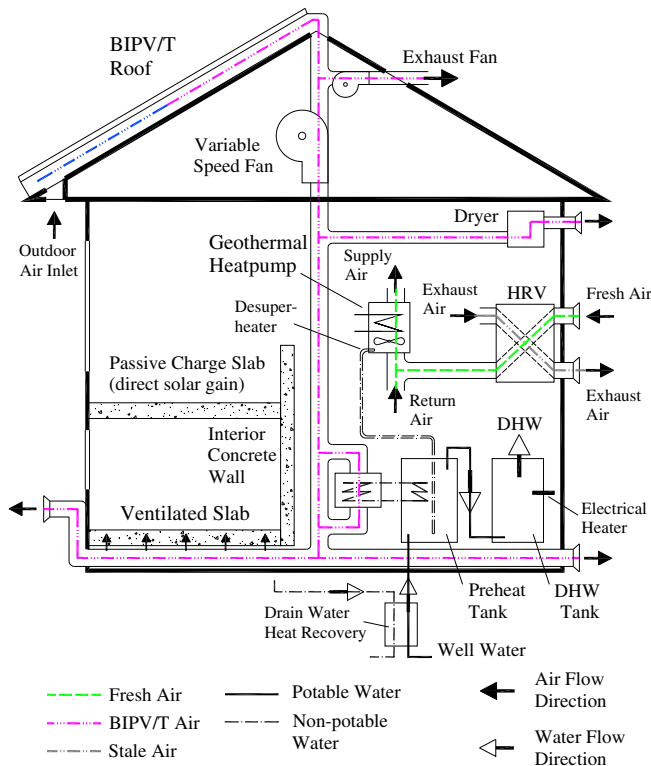


Fig. 3. Schematic of the integrated energy system and locations of thermal mass.

electricity and collects thermal energy. A VCS system is thermally coupled with the BIPV/T system for active solar heating. During the design, high performance windows

were quickly adopted as the most cost-effective measure to utilize solar radiation incident on the south facade, while the thermal insulation value of the envelope was increased gradually until the optimal cost-effectiveness was reached based on simulations with the HOT 2000 software (Natural Resources Canada, 2007a). A ground source heat pump (GSHP) provides space heating/cooling and partially heats DHW through a desuperheater. In order to optimize the integrated system overall performance, a home automation system is employed to operate the system based on appropriate control strategies and order of priority. A heat recovery ventilator (HRV) and a wastewater heat recovery exchanger were also installed for heat recovery from the ventilation air and waste hot water, respectively.

The BIPV/T system (Fig. 4a) is integrated on the upper south-facing roof of ÉcoTerra (Fig. 1). Fig. 4b shows the construction of the BIPV/T building module in the factory – showing the framing in the cavity, the installation of metal roofing with PV panels, the insulated manifold for collecting the air, and the finished module delivered on-site for assembly with other house modules. Instead of performing all the above mentioned work onsite, pre-fabrication of the BIPV/T roof ensures high-quality construction in terms of air tightness, thermal insulation and balance of pressure drops across the manifold so as to achieve uniform flow and heat collection. Pre-fabrication also allows for construction in a factory environment during winter when it is not possible to perform site work due to the low outdoor temperatures. The BIPV/T roof has a tilt angle of 30° chosen while taking into account pre-fabrication requirements

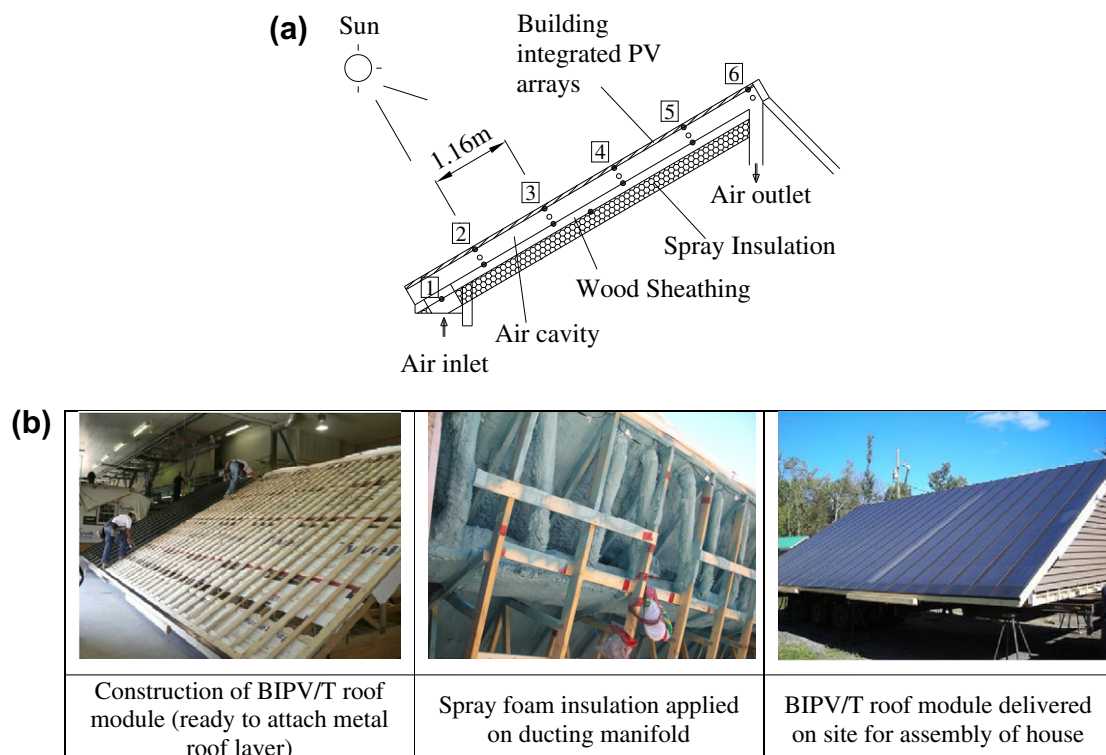


Fig. 4. (a) Schematic of the BIPV/T system and temperature monitoring points and (b) construction of BIPV/T prefabricated module in the factory.

and aesthetics. The PV panels are attached on the metal roofing with a peel-off adhesive and metal screws at the top covered by a metal ridge cap. The BIPV/T system is designed to cover one continuous roof surface to enhance aesthetic appeal and to ensure that the system is watertight. The dimensions of the BIPV/T roof are 6.2 m long in the sloping direction and 10.4 m wide. The thickness of the air cavity (i.e. the distance between the metal roofing and the insulated plywood sub-roofing) is 0.038 m. The net cross sectional area (normal to the air path) of the BIPV/T air cavity is 0.332 m². The inlet of the BIPV/T system is at the front soffit. The BIPV/T system consists of 21 amorphous laminate photovoltaic panels. Each panel is rated at 136 W at standard test conditions and the electricity generation efficiency under standard normal operation condition (NOC) is 6.1% (Uni-Solar 2009). The electricity generated by the PV system, as estimated by RETScreen (Natural Resources Canada 2007b), is 3265 kW h/y.

The BIPV/T system is an air-based open-loop system (see Figs. 3 and 4a). Outdoor air drawn by a variable speed fan is used as the heat transfer fluid. The heat collected from the BIPV/T roof generally needs to be stored since passive solar heat gains through the south-facing windows satisfy daytime heating loads. The fan speed is controlled by a supervisory control system in order to control air flow so as to achieve the desired supply temperature. The heat collected can be used for DHW, space heating and clothes drying as described later. A VCS located in the basement and an air–water heat exchanger for heating DHW are designed to store the heat from the BIPV/T system (see companion paper part 2 for details on the VCS). The VCS stores much of the thermal energy from the air passing through its air channels. Generally, with a target temperature of 19 °C in the basement, the floor slab will be at approximately 17–18 °C. If the air from the BIPV/T system is at 21 °C or higher, it can be used to heat the thermal mass. The stored thermal energy is slowly released to the living space passively from the top surface of the slab. The fan of the forced-air heating system runs at low flow (about 300 L/s) when auxiliary heating is not required, facilitating redistribution of stored heat in the whole house.

The VCS is utilized to store part of the thermal energy collected by the BIPV/T system. The collected thermal energy can also be used for heating DHW with an air-to-water heat exchanger and for drying clothes by running the dryer in fan mode and drawing BIPV/T air through it. The order of priority of the three usages for the BIPV/T-heated air is:

1. If the BIPV/T air is 15 °C or higher (and RH < 50%) and drying of clothes is needed, activate the dryer (a building information display will inform the user who needs to initiate the dryer in fan mode).
2. Use the BIPV/T air for DHW heating or VCS heating depending on which one has the lower initial temperature.
 - (a) If the BIPV/T air is warmer by at least 5 °C than the water in the preheat DHW storage tank, then use it for DHW heating.

- (b) If the mass in the VCS slab is at least 3 °C lower than the BIPV/T air temperature, activate VCS heating (if the DHW tank is relatively hot, the air can pass through the air–water heat exchanger first and then enter the VCS if it is still higher in temperature than the VCS).

The overall energy analysis at the design stage was carried out using a combination of HOT 2000, RETScreen, and numerical models developed by the authors. HOT 2000 was used to calculate the general energy consumption of the house and optimize the envelope. RETScreen was used for the estimation of the PV electricity generation, and numerical models were used for the optimization of the BIPV/T system and the active TES, and for passive solar heating (see Appendix A for the detailed description of the passive solar design, the envelope, and the HVAC and DHW systems).

3. Modeling of the BIPV/T system

After construction in 2007, the house underwent commissioning and testing (unoccupied) for about 18 months. Data under a variety of weather conditions were collected and utilized to create thermal models of the BIPV/T and VCS systems. In the case of the BIPV/T system, a major objective was to develop relationships that can be used for control of the airflow (see Appendix A for the BIPV/T monitoring system setup description).

3.1. Measured performance

Fig. 5 shows a thermographic image taken with an infrared camera¹ during a warm summer day when the BIPV/T system was operating. The temperature of the PV panels was in the range of 50–60 °C. At the same time, the temperature of the metal roofing of the lower roof (without PV – metal roof only) was higher than 70 °C. While taking an infrared picture during daytime involves significant error, the relative difference between the two roof regions is still reliable. The necessity and significant cooling effect of the air flowing underneath the PV panels is obvious.

Figs. 6–8 show the measured data for three typical days: a cold sunny day (March 17th, 2008), a warm sunny day (April 17th, 2008) and a warm partially cloudy day (June 25th, 2008). The variation and the standard deviation at each time interval are calculated for the measured temperatures of the PV panels (near the outlet) and outlet air temperatures on these 3 days. The standard deviation is 2.1 °C for the PV panels, and 1.3 °C for the air outlet temperature (see Appendix A for the locations of the thermocouples). These calculated values and the thermographic image indicate that there is no significant horizontal temperature

¹ FLIR SYSTEMS thermaCAM PM595 infrared camera, accuracy of $\pm 2\%$ of readings or 2 °C.



Fig. 5. Thermographic image of BIPV/T roof (upper roof section) compared with the lower metal roof section.

variation. The air flow in the BIPV/T cavity is evenly distributed. The air flow component and the associated transverse heat transfer across the roof (perpendicular to the airflow path) are minimal. Therefore, the thermal model can be approximated as two dimensional.

Fig. 6 shows the BIPV/T temperature profiles on a cold sunny day (March 17th, 2008). The maximum air temperature increase ($\Delta T_{air.pvt}$) along the flow path was slightly more than 40 °C. Near the outlet, $T_{air.outlet}$ tends to be very close to the $T_{PV.outlet}$ (about 5 °C lower). When the flow rate was reduced from 200 L/s to 110 L/s, the temperature increase was marginal. The reason for this is that when the air flow rate increases, the fluid capacity rate and air velocity also increases and due to this high air velocity, the interior convective heat transfer coefficient (CHTC) $h_{c.pvt}$ increases. The stream-wise length of the BIPV/T system is long enough for the air to develop its temperature close to the $T_{PV.outlet}$ (Fig. 6) near the outlet. This also reveals that $T_{PV.outlet}$ cannot be greatly reduced by applying larger

flow rate. Therefore, it is beneficial in this case to use larger flow rates to improve thermal efficiency.

Two consecutive days, April 17th and 18th (Fig. 7) have almost identical weather conditions – warm and sunny. In order to document the effect of having no BIPV/T airflow, the fan was off on April 18th. By comparing the data from these two days (Table 1), the advantages of the BIPV/T system and the PV-panel-cooling effectiveness was evaluated. On April 17th, at noon, 9.7 kW of thermal energy was collected from the BIPV/T roof – a thermal efficiency of about 20% (the ratio of collected thermal energy to incident solar energy). Of this collected thermal energy, 1.5 kW was used for DHW heating and 2.5 kW was used for VCS heating – approximately 40% of the collected energy was useful. If the house was occupied more heat would have been used for DHW as there would be water consumption. The PV metal temperature near the inlet at noon was cooled down by about 10 °C as compared with that on April 18th; however, near the outlet, $T_{PV.outlet}$ was only reduced by about 5 °C. The slight cooling effect did not significantly increase the efficiency of electricity generation (Fig. 7), as the efficiency of each panel is determined by the PV panels' highest temperature and the temperature coefficient is low for the amorphous PV panels used in this case. The $\Delta T_{air.pvt}$ was 40 °C, as it was on the cold sunny day, March 17th (Fig. 6), which confirms that solar irradiance is more critical in determining the $\Delta T_{air.pvt}$ than the outdoor temperature. One may also note that the air entering the soffit openings is passively pre-heated by the south-facing facade and its temperature typically rises by about 5 °C before it enters the soffit inlets (the temperature profiles of the cavity air are shown in Fig. 12 in a following subsection).

On a warm partly cloudy day (Fig. 8), when air was drawn at a relatively high flow rate of 290 L/s (average

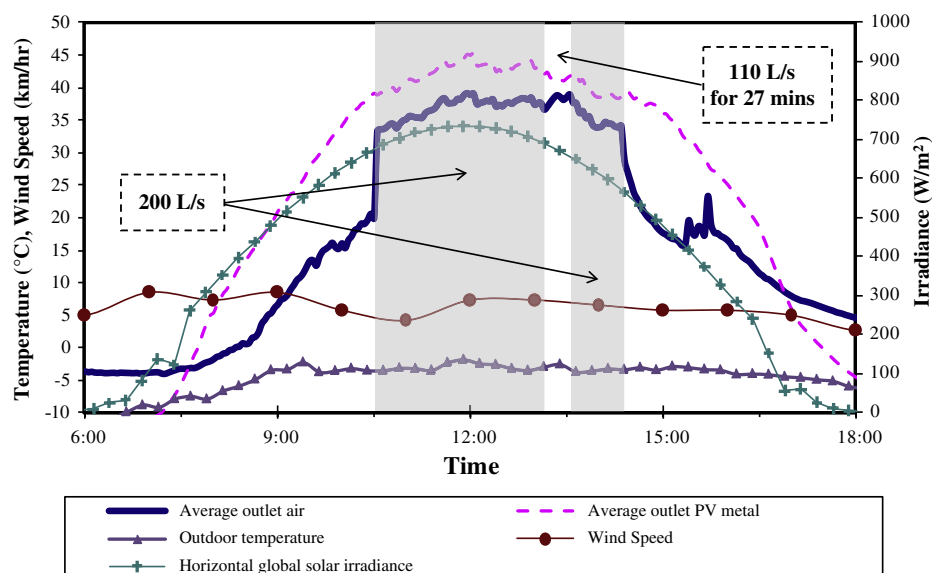


Fig. 6. BIPV/T system temperatures on a cold sunny day, March 17th, 2008 (shaded/unshaded regions show duration of two different BIPV/T flow rates).

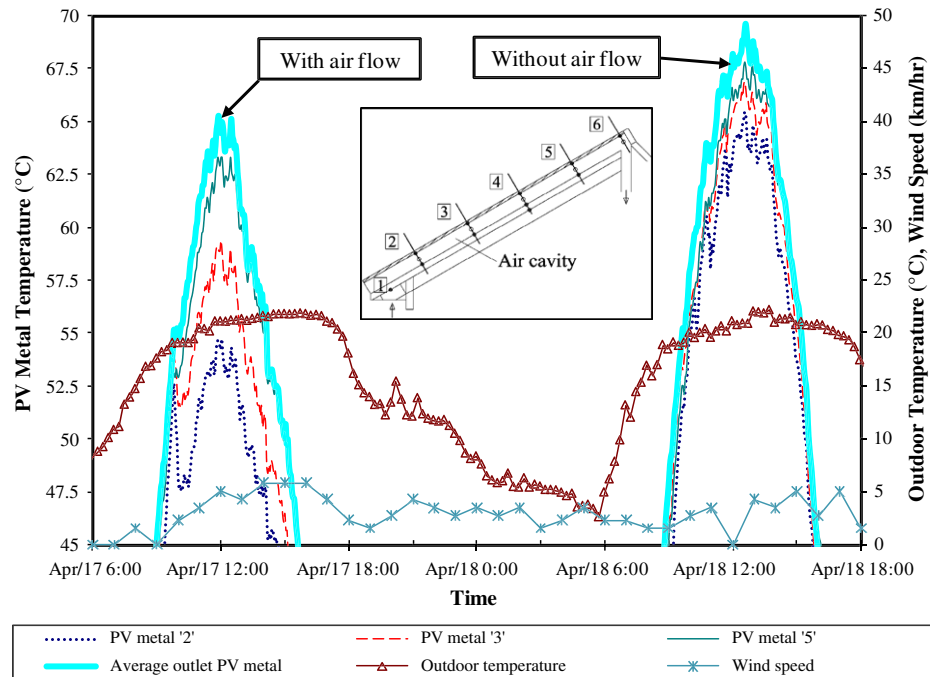


Fig. 7. PV temperature profiles and effect of BIPV/T air flow on energy performance for two clear sunny days (BIPV/T fan is on for April 17th and off for April 18th, also see Table 1).

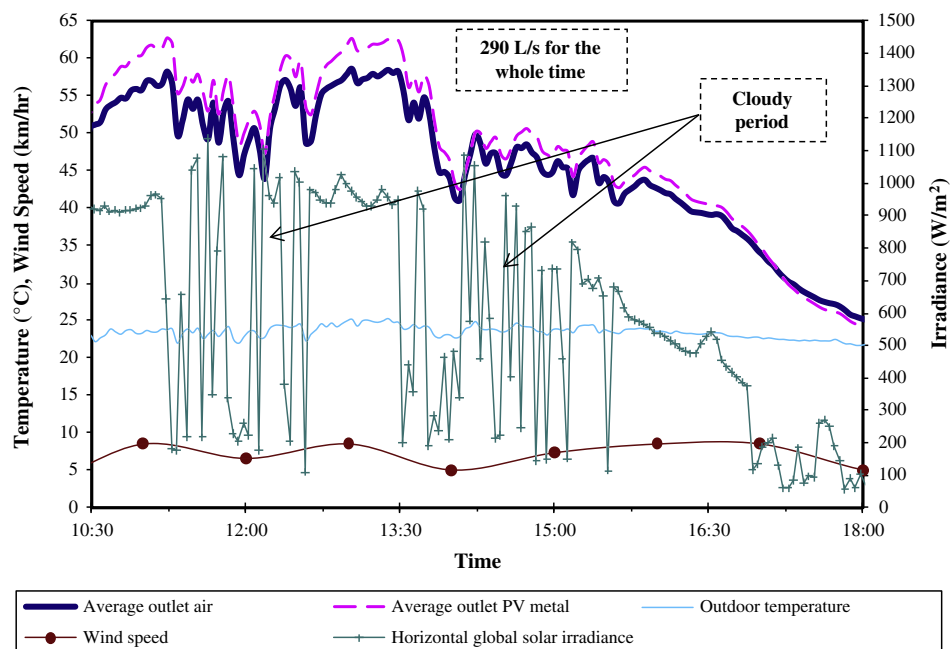


Fig. 8. BIPV/T system temperatures on a warm and partially cloudy day, June 25th, 2008.

velocity in the cavity equal to 0.82 m/s), the BIPV/T system still performed well, in terms of $\Delta T_{air,pvt}$. Comparing to the temperature recorded on April 17th around 1:00 pm, which had similar weather conditions, the larger flow rate further reduced the highest panel temperature by about 2–3 °C. As was discussed previously, $T_{PV,outlet}$ cannot be greatly reduced by applying larger flow rate. Fig. 8 also shows that

the temperature profiles closely followed the solar irradiance profile. This suggests that using a steady state model for hourly simulation is acceptable.

In order to assess the sensitivity of the wind effect on the thermal behavior of the BIPV/T system, data from different days with similar weather conditions are compared. It can be observed that for every 1 km/h increase in wind

Table 1
Comparison of the energy output with and without BIPV/T airflow (see Fig. 7).

Date	Values measured and calculated at noon						
	Electricity generation (kW)	Flow rate (L/s)	Heat recovery (kW)	DHW heating (kW)	VCS heating (kW)	Fan power (kW)	Net energy gain (kW)
April 17th	2.41	196 ± 10.5	9.7 ± 0.55	1.5 ± 0.10	2.5 ± 0.15	−0.4 ± 0.05	6.01 ± 0.30
April 18th	2.31	n/a	n/a	n/a	n/a	n/a	2.31

speed, the outlet air temperature from the BIPV/T system, $T_{air.outlet}$, drops by about 2 °C. This reveals that the wind effect on the thermal performance of the BIPV/T system is significant, and hence the choice of the correlation for wind-induced CHTC ' $h_{c.wd}$ ' in the BIPV/T thermal modeling is critical. This is also stated by Sharples and Charlesworth (1998).

3.2. Interior CHTC calculation

The control volume concept is used in calculating the interior CHTC ' $h_{c.pvt}$ '. The space between each two adjacent thermocouples in the cavity is treated as one control volume (Fig. 9). There are only three sections available to be used as control volumes for the CHTC calculation. These three sections are 'lower section' between positions '2' and '3', 'middle section' between '3' and '4', and 'higher section' between '4' and '5' (see Fig. 4a). At the inlets and outlets of these three sections, the temperatures of the top boundary (back of the PV metal), the air, and the bottom boundary are measured.

Eq. (1) provides the energy balance equation of the air control volume, where $q_{top.to.air}$ (the heat exchange between the top boundary and the air) and $q_{btm.to.air}$ (the heat exchange between the bottom boundary and the air) are the only two heat sources for the air control volume. By setting $q_{btm.to.air}$ equal to the difference between $q_{top.to.btm}$ (the radiative heat flux from the top boundary to the bottom boundary) and $q_{btm.to.attic}$ (the conductive heat flux

from the bottom boundary to the attic) in Eq. (2), the CHTC for the bottom boundary is not needed for calculating $q_{btm.to.air}$. The calculated CHTC in Eq. (3), based on the above assumptions, will be the CHTC between the air and the top boundary. Recorded data show that the temperature profile of the air is close to that of the bottom boundary, with the maximum temperature difference between the two being less than 2 °C. Thus, the main direct heat source for the air is from the top boundary, and the $q_{btm.to.air}$ is relatively small. An accurate CHTC for the bottom boundary is not important because of the low heat transfer at this surface. Thus, for simplicity in the thermal modeling of the BIPV/T system in the following sections, the CHTC for the bottom boundary is assumed to be equal to that for the top boundary.

$$(T_{out} - T_{in}) \cdot F_{air} = \Delta q_{air} = q_{top.to.air} + q_{btm.to.air} \quad (1)$$

where

$$q_{btm.to.air} = q_{top.to.btm} - q_{btm.to.attic} \quad (2)$$

$$q_{btm.to.attic} = U_{btm} \cdot A_{btm} \cdot (T_{btm.mean} - T_{attic})$$

$$q_{top.to.air} = h_{c.pvt} \cdot A_{top} \cdot (T_{top.mean} - T_{air.mean})$$

$$q_{top.to.btm} = A_{top} \cdot \sigma_{SB} \cdot F_E \cdot F_A \cdot (T_{top.mean}^4 - T_{btm.mean}^4)$$

From the above equations we obtain,

$$h_{c.pvt} = \frac{(T_{out} - T_{in}) \cdot F_{air} - (q_{top.to.btm} - q_{btm.to.attic})}{A_{top} \cdot (T_{top.mean} - T_{air.mean})} \quad (3)$$

In the above equations, arithmetic mean temperature is used for mean temperatures. The temperature of the attic T_{attic} is monitored, and the thermal conductance of the bottom layer U_{btm} is 1 W/m²/K.

Using data from more than 600 different full-scale measurements for different air velocities and outdoor conditions, the average $h_{c.pvt}$ of each section was calculated for each air velocity. Fig. 10 shows the average $h_{c.pvt}$ of the three sections. When the air velocity is between 0.3 and 0.6 m/s (Reynolds number ranging from 1500 to 3000), the $h_{c.pvt}$ remains approximately constant at about 10.5 W/m²/K; in this region we have mixed convection and at the low end of 0.3 m/s natural convection dominates. For air velocity larger than 0.6 m/s, the increase can be approximated as linear and forced convection dominates. A two-segment, linear correlation – Eq. (4) – is adopted for design and control of such systems and plotted in Fig. 10.

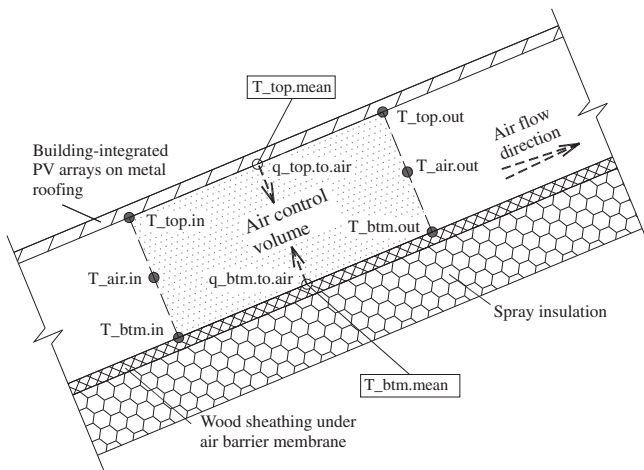


Fig. 9. Schematic for control volume in BIPV/T system.

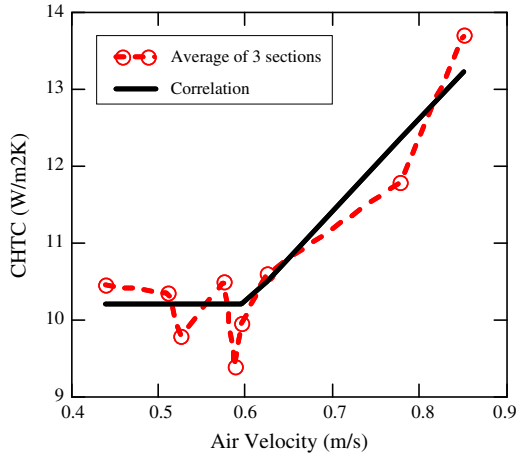


Fig. 10. Average CHTC in BIPV/T cavity as a function of average air velocity and correlation fit.

$$h_{c,pvt} = \begin{cases} 10.2 & (0.4 \leq V_{air,pvt} \leq 0.6) \\ 12 \cdot V_{air,pvt} + 3 & (V_{air,pvt} > 0.6) \end{cases} \text{ [W/m}^2\text{/K]} \quad (4)$$

where $V_{air,pvt}$ is the air velocity inside the cavity in m/s.

3.3. Modeling and simulation of BIPV/T

A quasi-two dimensional, control volume, steady state model is created for the BIPV/T roof. The thermal network of the system is shown in Fig. 11. The discretized energy balance Eqs. (5)–(7) are given below. The Peclet number corresponding to 0.1 m/s cavity air velocity is 350. This indicates that advection dominates the heat transfer inside the BIPV/T cavity. Hence, the ‘upwind scheme’ (Patankar 1980) is applied in developing the finite difference equation

for the air control volume (Eq. (5)). In this study, since the prevailing wind direction is from north-west (i.e. from the back of the south-facing BIPV/T system), a correlation from Palyvos (2008) was judged appropriate and was used for the exterior convective heat transfer coefficient $h_{c,wd}$. Different grid sizes were checked and compared with each other. A grid size (length along the air path) of 0.15 m (36 control volumes for the 5.5 m long path in this case) was found to predict the $T_{air,outlet}$ to a satisfactory level (within 4 °C compared with measurements).

$$T_{air}^i = \frac{F_{air} \cdot T_{air}^{i-1} + h_{c,pvt} \cdot A_{step} \cdot (T_{top}^i + T_{btm}^i)}{F_{air} + 2 \cdot h_{c,pvt} \cdot A_{step}} \quad (5)$$

$$T_{top}^i = \frac{h_{r,top,sky} \cdot T_{sky} + h_{c,wd} \cdot T_{ext} + h_{c,pvt} \cdot T_{air}^{i-1} + h_{r,top,btm} \cdot T_{btm}^i + I_{rf} \cdot (1 - \mu_{pv}) \cdot \alpha_{rf}}{h_{r,top,sky} + h_{c,wd} + h_{c,pvt} + h_{r,top,btm}} \quad (6)$$

$$T_{btm}^i = \frac{U_{btm} \cdot T_{attic} + h_{c,pvt} \cdot T_{air}^{i-1} + h_{r,top,btm} \cdot T_{top}^i}{U_{btm} + h_{c,pvt} + h_{r,top,btm}} \quad (7)$$

where the radiative heat transfer coefficients are linearized as follows $h_r = \sigma_{SB} \cdot F_E \cdot F_A \cdot (T_1^2 + T_2^2) \cdot (T_1 + T_2)$.

The exterior heat convective heat transfer coefficient is determined as:

$$h_{c,wd} = 3.5 \cdot V_{wind,10} + 4.2 \text{ [W/(m}^2\text{ K)]} \quad (8)$$

where $V_{wind,10}$ is the wind speed at 10 m height above the roof in m/s, and approximated using Eq. (10) in Appendix A.

Fig. 12 shows the simulated temperature profiles under the April 17th operating conditions. The simulated temperature profiles match well with the measurements. The difference between the simulated and the measured temperatures for air is within 4 °C. The model is also verified using other measured data and similar agreement is observed.

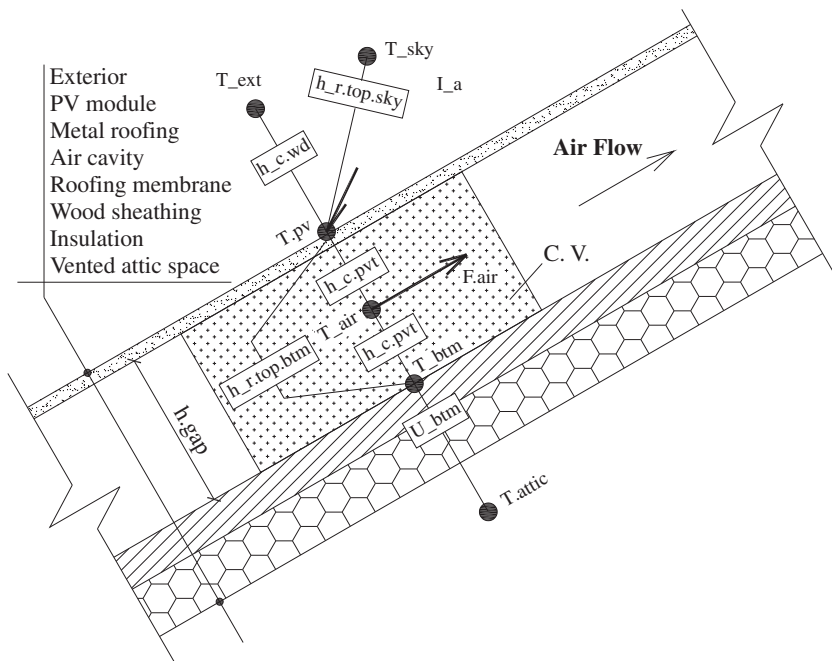


Fig. 11. Thermal network of the BIPV/T system.

The differences between the simulated and measured data are mainly due to the sensor systemic errors (location and accuracy), imperfections in construction of the roof (e.g. uneven insulation spraying) and wind effects on $h_{c,wd}$.

In general, when the length of the BIPV/T roof is chosen, $T_{PV.outlet}$ and $T_{air.outlet}$ are mainly affected by four parameters: solar irradiance (I_{rf}), free stream wind speed (V_{wind}), exterior temperature (T_{ext}) and cavity air velocity ($V_{air.pvt}$). Using the model developed above, $T_{PV.outlet}$ and $T_{air.outlet}$ were simulated under different T_{ext} and $V_{air.pvt}$ with I_{rf} of 800 W/m^2 , and V_{wind} equal to 15 km/h (typical winter conditions) (Fig. 13). It can be seen that $\Delta T_{air.pvt}$ is almost independent of the exterior temperature, as is the temperature difference between the metal layer and the exterior. In another set of simulations (Fig. 14), $T_{PV.outlet}$ and $T_{air.outlet}$ are simulated under different values of I_{rf} and V_{wind} with T_{ext} equal to 0°C and $V_{air.pvt}$ set at 0.8 m/s (typical winter conditions). It can be seen that both the air temperature rise $\Delta T_{air.pvt}$ and the temperature difference between the PV and the exterior have linear relationships with I_{rf} .

Once $T_{PV.outlet}$ and $T_{air.outlet}$ are obtained for a known set of the above-mentioned four parameters (T_{ext} , I_{rf} , V_{wind} , and $V_{air.pvt}$), the new $T_{PV.outlet}$ and $T_{air.outlet}$ for different of

T_{ext} and I_{rf} can be approximated using the Eq. (9). For example, Fig. 15 shows the simulated $T_{PV.outlet}$ and $T_{air.outlet}$ (i.e. T_1) for the ÉcoTerra BIPV/T system under the conditions of $T_{ext,1}$ of 0°C and $I_{rf,1}$ of 500 W/m^2 . With T_1 from Fig. 15 (i.e. knowing the V_{wind} and $V_{air.pvt}$), T_2 for $T_{ext,2}$ and $I_{rf,2}$ can be obtained quickly using Eq. (9). The difference between the simulated $T_{PV.outlet}$ and $T_{air.outlet}$ using the thermal model developed previously and those using Eq. (9) is less than 2°C when the $V_{air.pvt}$ is larger than 0.5 m/s (typically this is the minimum velocity of interest). Eq. (9) is applicable for other BIPV/T systems with different lengths. In the preliminary design stage, once the length of BIPV/T is set and graphs similar to Fig. 15 are produced, Eq. (9) can be used as a quick reference. This relationship can be used in real-time by the building automation system to determine optimal flow rates based on the weather information.

$$T_2 = T_1 \cdot \frac{I_{rf,2}}{I_{rf,1}} + (T_{ext,2} - T_{ext,1}) \quad (9)$$

where subscripts 1 and 2 represent previous value and current value respectively and T represents either $T_{PV.outlet}$ or $T_{air.outlet}$.

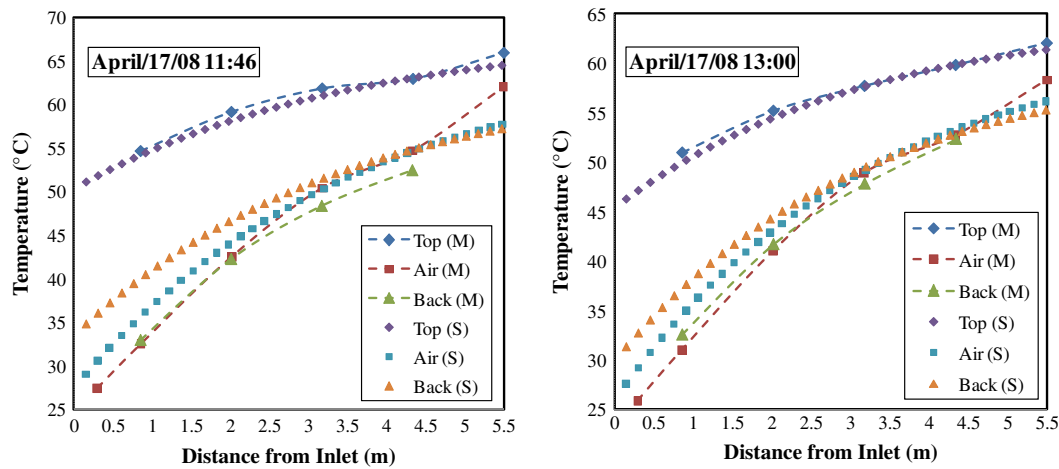


Fig. 12. Comparison of simulated and measured BIPV/T system temperatures (M: measured; S: simulated; SS: steady state).

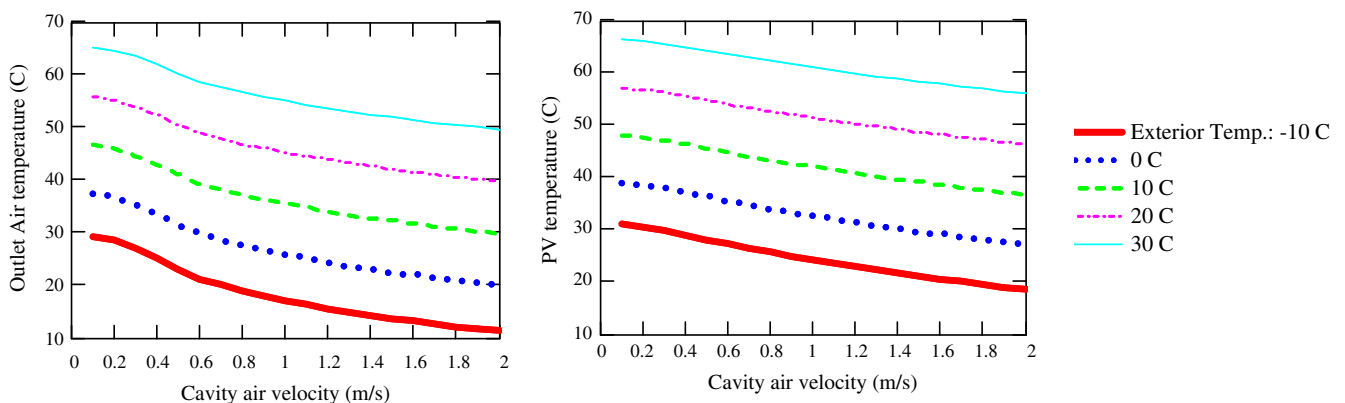


Fig. 13. Simulated $T_{PV.outlet}$ and $T_{air.outlet}$ under different T_{ext} and $V_{air.pvt}$ ($I_{rf} = 800 \text{ W/m}^2$, and $V_{wind} = 15 \text{ km/h}$).

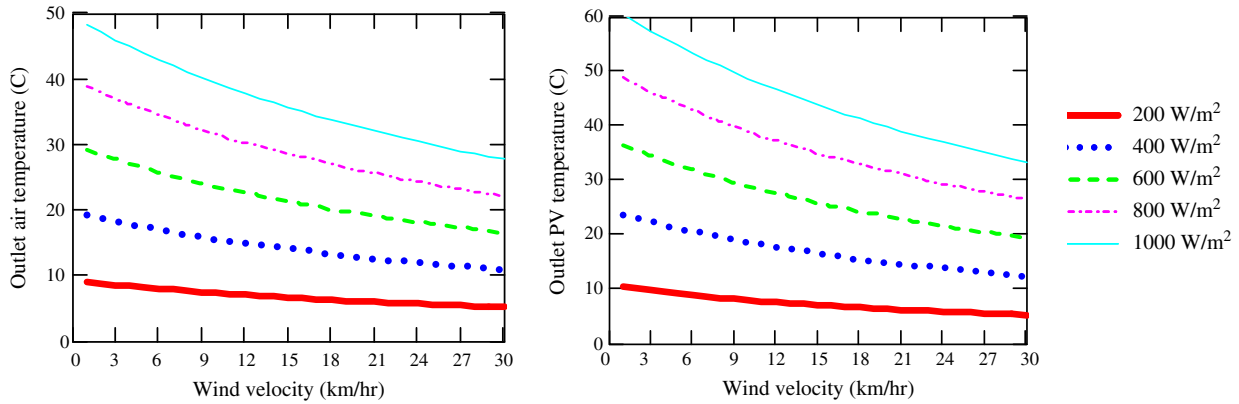


Fig. 14. Simulated $T_{PV,outlet}$ and $T_{air,outlet}$ under different solar radiation levels I_{rf} and V_{wind} ($V_{air,pvt} = 0.8$ m/s, and $T_{ext} = 0$ °C).

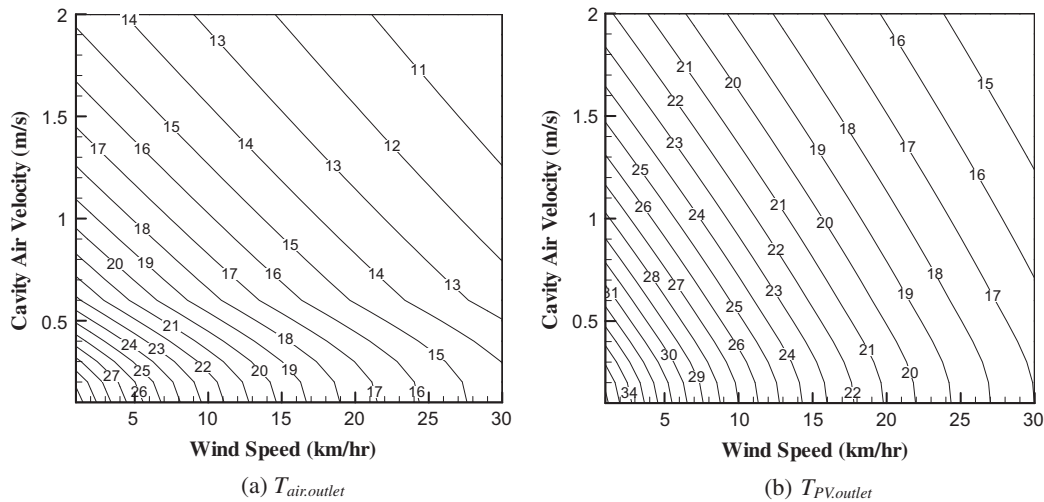


Fig. 15. Simulated $T_{PV,outlet}$ or $T_{air,outlet}$ under different BIPV/T cavity air velocities and wind speeds ($I_{rf} = 500$ W/m², and T_{ext} of 0 °C).

4. Analysis of the house

4.1. Energy modeling during design

During the initial design stage the house was first analyzed without renewable energy use. Based on HOT 2000 simulations, the annual gross space heating load (without solar gains) was predicted to be 21,390 kW h. The heating setpoint was set at 21 °C for the main floor and 19 °C for the basement. Predicted usable passive solar gains of 9459 kW h/y plus useful internal gains of 3724 kW h/y were found to reduce the space heating system load to 8226 kW h/y. If the south glazing area was reduced from 25 to 16 m², the space heating system load would be increased to 9803 kW h/y. Using a geothermal heat pump (water–air) results in an estimated annual space heating energy consumption of 2106 kW h/y in electricity. The DHW energy consumption (for 150 L/day hot water at 55 °C) with electric heating and tank insulation of RSI 1 was predicted to be 3338 kW h/y. The electricity usage due to appliances and lighting was estimated at 3975 kW h/y, including about 900 kW h/y for the dryer (if no solar air heating is used).

Using the thermal energy collected by the BIPV/T system can greatly reduce the energy consumption of the dryer. The predicted total energy consumption, before accounting for the contribution from the BIPV/T system (both electricity and thermal energy), is about 9419 kW h/y (~38 kW h/m²/y). This is about 16% of the national average value. With electricity and heat generation from the BIPV/T system the net energy usage (consumption minus production) is expected to fall to about 5000 kW h/y.

4.2. Measured thermal performance of the house

In 2008 the house was generally unoccupied and was monitored, commissioned, and sometimes open for public visits. By comparing the data between cold sunny days and cold overcast days with or without the systems operating, the contributions to the reduction of space heating energy consumption from passive and active solar heating systems can be evaluated.

For three continuous days (see Fig. 16), during which BIPV/T and VCS did not operate, the heating load (i.e. gross integrated heat loss of the house) was 78 kW h for

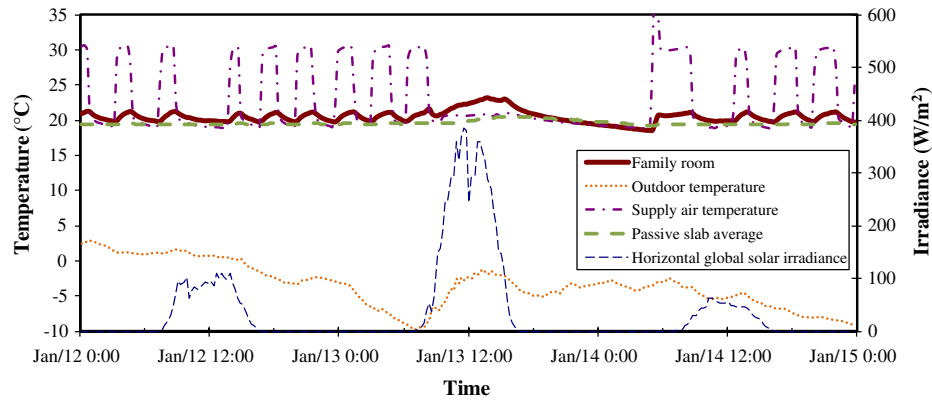


Fig. 16. Temperature profiles on cold days with (January 13th) and without passive heating.

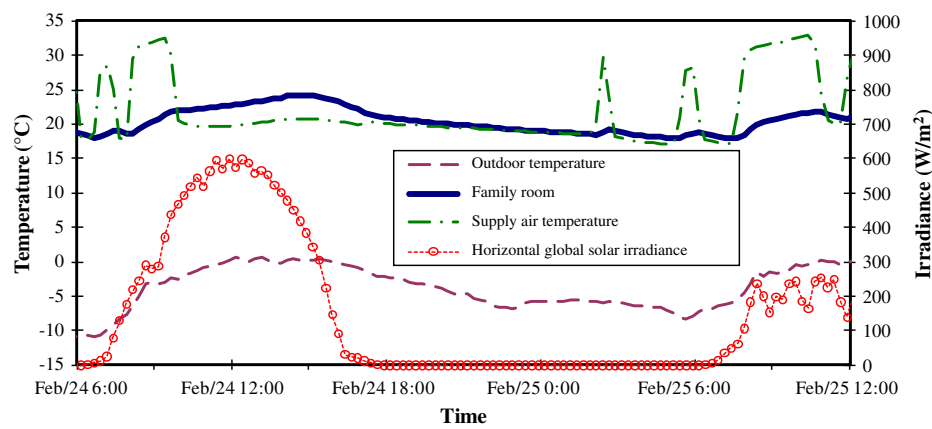


Fig. 17. Temperature profiles on cold days using passive and active solar heating, February 24–25, 2008.

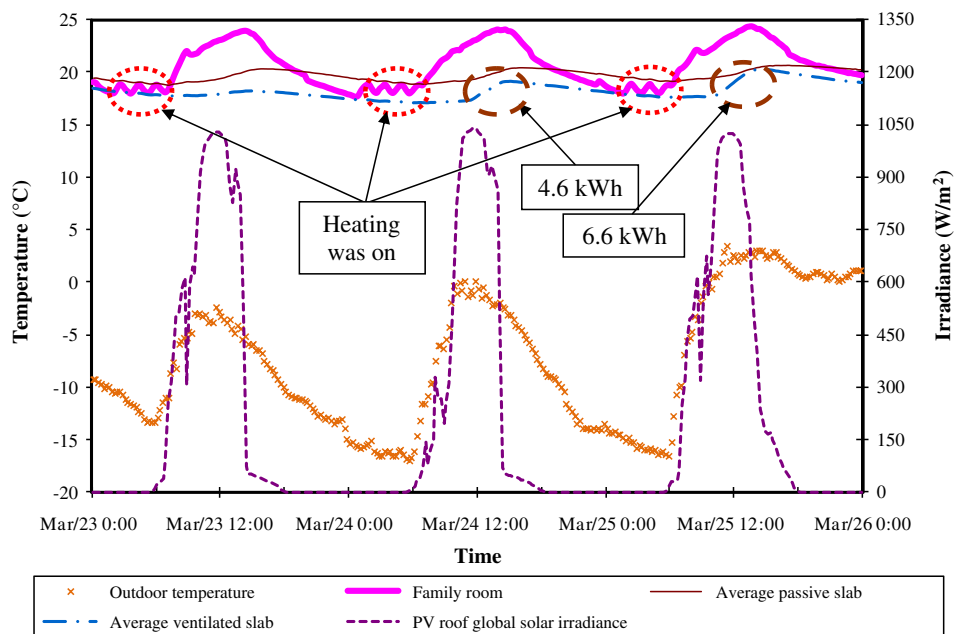


Fig. 18. Temperature profiles on cold sunny days using passive and active solar heating (March 23–25, 2008).

January 12th, 60 kW h for January 13th, and 96 kW h for January 14th. The average outdoor temperature on Janu-

ary 12th was about 5 °C higher than that of January 13th, but the latter day has lower heating load due to the

contribution of passive solar heating. As can be seen from Fig. 16, the cycling period of the forced-air heating system is about 4 h (about 2 h on and 2 h off). The fluctuation of the slab average temperature is small compared to that of the room air temperature. This implies that if the room air is further thermally coupled with the thermal mass, the effective thermal storage capacity of the room will be increased. The frequency of the cycling of the heating system will hence be reduced.

When the VCS is used to store thermal energy from the BIPV/T system the space heating load is reduced approximately by an equivalent amount. Fig. 17 shows that on a completely clear day, February 24th, with the passive solar space heating and the thermal energy collected from the BIPV/T (about 3 kW h of heat stored in the VCS and 1 kW h released from the VCS to the living space during the storing process), the room temperature was raised by about 4 °C (from 21 °C to almost 25 °C) during the daytime even though the average outdoor temperature was around −1 °C. The thermal energy stored was adequate to keep the room air temperature above the heating setpoint until 3:00 am of the next day when the nighttime outdoor temperature dropped to around −5 °C.

Fig. 18 shows the thermal performance on three consecutive cold sunny days in 2008. On March 23rd, the active TES was not operated. For March 24th and 25th, 4.6 and 6.6 kW h of thermal energy was stored in the VCS, respectively. During the two nights between the 23rd and 25th, heating was only required for about 4 h just before dawn. The average heating load was 65 kW h per day. Another set of data from April 15th (a perfect sunny day; graph is not included) shows that about 14 kW h thermal energy was stored in the VCS after 7 h, excluding the 4 kW h heat released from the slab to the living space during the storage process. The measured outdoor temperature of that day ranged from −5 to 7 °C, and the 24-h heating load was about 30 kW h.

5. Conclusion

This paper presented a detailed study of the modeling and design of a BIPV/T system implemented in a near net-zero-energy house in a cold climate, the integrated energy concept of the house, and an analysis of the measured thermal performance of the BIPV/T system.

The integrated concept of the house combines three technologies to approach net-zero energy consumption over a year: direct gain passive system, an active BIPV/T system and a ground source heat pump. It also uses a combination of passive and active thermal storage integrated in the floors of the house.

The study shows that a BIPV/T system can be implemented in near net-zero energy houses in a cold climate, and provide significant potential for reducing their space heating energy consumption. The full-scale monitored data presented in the paper indicate that the BIPV/T heat recovery system can lower the PV panels' operating temperature

significantly and can collect a considerable amount of solar thermal energy. The typical temperature rise of the BIPV/T air on a sunny winter day is about 30–35 °C with 250 L/s flow rate giving 8.5–10 kW thermal energy output for a BIPV/T roof surface area equal to 64 m². The typical thermal efficiency is at least 20% based on the gross roof area.

An integrated design concept is important in limiting the energy consumption of such houses to a low level without excessive cost (e.g. an unnecessarily large or expensive PV system). The preliminary monitored data over a year shows that this house is expected to have annual net energy consumption less than 5000 kW h – about 10% of the national average, and its annual space heating energy consumption will be about 1600 kW h – about 5% of the national average. The space heating load of ÉcoTerra is greatly reduced by the collective contribution from active and passive solar heating technologies. However, occupant behavior may result in higher values, particularly with room thermostat setpoint changes and addition of appliances. Monitoring will continue with the house occupied and the control algorithm will be modified based on occupant input to optimize both thermal comfort and energy performance.

A quasi-two dimensional, control volume, steady state model for simulating the thermal performance of the BIPV/T system, as well as a linear equation (Eq. (9)) for predicting the temperature of the PV panels and air at the outlet have been developed based on measured data. The model and the equation can be applied to other BIPV/T systems with similar configurations. They are useful in preliminary design and for control of the air flow in the BIPV/T system.

The combination of active and passive solar technologies with airtight highly insulated envelope and geothermal heating for a cold climate requires further integration and optimization so as to reduce costs that will enable NZESHs to become widely adopted. For example, the heat recovered from the BIPV/T system may not be completely used due to a low outlet air temperature. However, if it is used as the heat source in an air-source heat pump system (indirect solar source heat pump), then the useful heat extraction may be enhanced. The issue of optimal sizing of the solar and geothermal systems is another topic that requires further attention. Control of solar gains in the intermediate seasons is required to prevent overheating and the utilization of automatically controlled motorized blinds for this purpose is one possible solution. Finally, the design of the BIPV/T system itself, including roof slope and area, along with PV system choice require further study to take into account the different prices of electricity and useful heat as well as the potential energy production.

Acknowledgments

Canada Mortgage and Housing Corporation (CMHC) conducted the EQUilibrium demonstration program. The house was built by Alouette Homes, an industrial partner of the Solar Buildings Research Network. Financial

support of this work was provided by Natural Sciences and Engineering Research Council (NSERC) of Canada through the Solar Buildings Research Network (SBRN). The BIPV/T prototype concept was developed by Dr. Athienitis and his research group. The BIPV/T system was funded through the TEAM (Technology Early Action Measures) program of NRCan.

Appendix A

A.1. Passive solar design

The selected windows were triple glazed with two hard low-e coatings, two Argon filled gaps, and vinyl frame with thermal break. Their effective thermal resistance is about RSI 0.85 and the solar heat gain coefficient (SHGC) is about 0.5. The total south-facing window area ($\sim 24 \text{ m}^2$) is about 41% of the south facade area. The south-facing window area of the ground floor ($\sim 13 \text{ m}^2$) is approximately 15% of the ground floor area. The optimal size of the overhangs (e.g. soffit) over the south-facing windows was calculated. They allow the window to be exposed to direct solar radiation as much as possible in the heating season, but block most of the direct solar radiation in the cooling season. Motorized awnings controlled by home automation system can block excessive solar radiation.

Concrete mass is used on the floor and wall of the main direct gain zone (i.e. south portion of the ground floor) to partially absorb the transmitted solar radiation. Based on simulations using customized thermal models (Athienitis and Santamouris, 2002), the optimal location and size of the thermal mass are chosen (Figs. 2 and 3). In the south portion of the ground floor, one 150 mm thick concrete slab is cast directly on top of the wooden subfloor supported by wood trusses. Two 0.3 m thick and 4 m high concrete walls are placed in the center of the house plan.

A.2. Envelope design

Two types of advanced spray-in-place foam insulation are used in ÉcoTerra: 'Enertite' (CCMC, 2007) and 'Walltite' (CCMC, 2006). In addition to providing high thermal resistance, Enertite can also improve the acoustic insulation of the envelope. Meanwhile, Walltite acts as an air or vapor barrier, and also contributes structural rigidity and air tightness to the walls. With the considerations of ease of construction, initial cost for construction and materials, and the effectiveness of thermal insulation, insulation values were chosen for different components of the envelope: RSI 9.1

for the roof ceiling, RSI 6.3 for walls above grade, RSI 5 for the walls below grade, and RSI 1.5 for the basement slab. Fig. A1 shows the cross section of the envelope. The air tightness of the house, verified by a blower door test, is about 0.85 air changes per hour (ACH) under a 50 Pa pressure differential across the building envelope.

A.3. Mechanical system: HVAC and DHW systems

The primary heating and cooling is provided by a 3-ton (10.5 kW) two-stage water-to-air GSHP. The ground heat exchanger is closed-loop and composed of two vertical U-tubes connected in series. The heat pump, through its desuperheater is estimated to provide about 700 kW h/y of heating for DHW. A heat recovery ventilator is installed to maintain the mechanical ventilation rate at about 0.25 air changes per hour (ACH). Combined with an estimated natural air infiltration of 0.07 ACH, the total ventilation rate will be about 0.32 ACH, which complies with health standards (ASHRAE, 2005).

The DHW system consists of two 227 L (60 US gallon) tanks in series. The cold well water entering the house is first heated by the heat from a waste hot water heat recovery system and then enters the first storage tank. In the first storage tank, the water is heated using the desuperheater of the GSHP and/or the hot air from the BIPV/T system (if available) through an air-to-water heat exchanger. The DHW can be heated up to the final supply temperature (55°C) in the second storage tank using a backup electrical heater. The waste hot water heat recovery is predicted to reduce DHW heating load by 700 kW h.

A.4. Monitoring setup for the BIPV/T system

In order to carefully study the thermal performance of the BIPV/T system, the system is fully instrumented. The monitored values include the temperature distributions, solar irradiance and wind speed.

'T' type thermocouples with accuracy of $\pm 0.5^\circ\text{C}$ were installed during the pre-fabrication of the BIPV/T system. Thermocouples are installed along the air path inside the air cavity (Fig. 4a). Air temperatures are measured at all the six positions. Top surface (back of the metal roofing) temperatures are measured at all locations except location '1'. Back surface (top of the wooden sub-layer) temperatures are measured only at position '2', '3', '4', and '5'. Thermocouples are also installed horizontally along the outlets – position '6'. At every second outlet, one thermocouple is installed to measure the metal temperature and

Table A1

Monthly average dry bulb temperature and horizontal global solar radiation for Eastman, QC. Source: Environment Canada, 2009

Month	January	February	March	April	May	June	July	August	September	October	November	December
Dry bulb temperature ($^\circ\text{C}$)	−10.9	−10.7	−3.3	3.6	11.1	16.2	18.3	16.8	12.2	6.6	0.1	−8.1
Horizontal global solar radiation ($\text{MJ/m}^2/\text{day}$)	5.66	8.90	12.72	16.16	18.40	19.76	19.93	17.04	12.70	8.79	4.84	4.25

one for the outlet air. There are a total of 10 thermocouples to measure the metal and 10 to measure the outlet air temperatures. These 20 thermocouples are used to check if the BIPV/T system is balanced in terms of heat extraction along its width. An additional thermocouple measures the air temperature in the vented attic.

Global solar irradiance is measured at three locations: on the vertical plane of the south facade, on the plane of the BIPV/T roof, and on the horizontal plane on top of the roof. Li-200 model pyranometers with error less than 5% are used. The flow rates in the BIPV/T roof were measured manually at the outlets of different paths (e.g. outlet after the heat exchanger or after the VCS).

To measure the exterior wind speed, a cup anemometer was installed on the pitch of the roof. However, the lower limit of wind speed measurement is 7 km/h. Since the wind, even at low speeds, has a significant effect on the thermal performance of the BIPV/T system (Sharples and

Charlesworth, 1998), lower wind speed values are needed for the detailed study of the BIPV/T system. Local wind speeds are approximated using the concept of a gradient mean wind speed V_g at the gradient height Z_g (Hutcheon and Handegord, 1983). The mean wind speed V_z at any height Z is given by:

$$\frac{V_z}{V_g} = \left[\frac{Z}{Z_g} \right]^\alpha \quad (10)$$

where Z_g equals to 400 m and α is 0.25 for well-wooded area (the case of ÉcoTerra).

Hourly meteorological wind data from Environment Canada for the airport of the city Sherbrooke (50 km East of Eastman, nearest publically available data) is used to calculate the value of the gradient mean wind speed V_g (ASHRAE, 2005). The comparison between the calculated wind speeds (V_z) and the locally measured values at roof

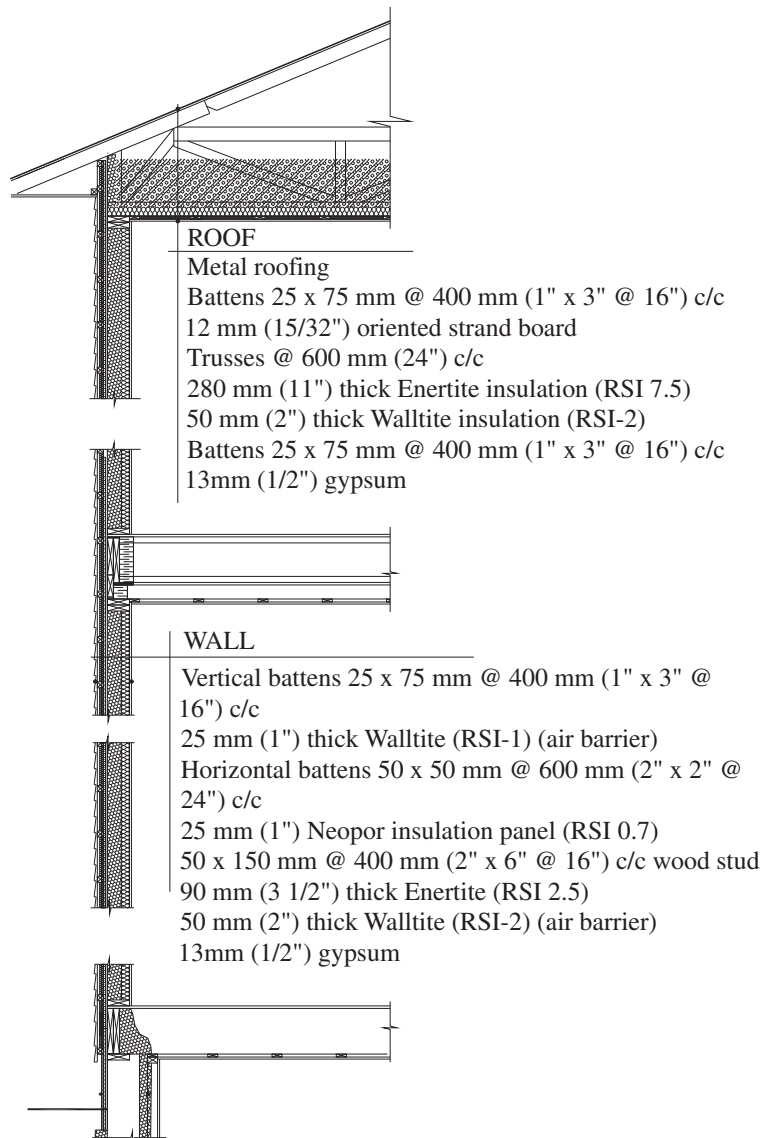


Fig. A1. Cross section of the north wall above grade (courtesy of Alouette Homes).

height (Z) shows an average discrepancy of about 1 km/h in the measured range.

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