Modelling of Predictive Control Strategies in a Net Zero Energy House with Active and Passive Thermal Storage

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Abstract

This paper presents the results of simulations used in the design of predictive control strategies for the Alstonvale Net Zero Energy House (ANZEH), an advanced demonstration solar house to be built near Montréal, Canada. A description of the ANZEH is presented. Predictive control was used for managing the interaction of the energy resources with passive and active thermal storage. This action has significant impact on the overall energy consumption, peak demand and comfort. It has been found that, in this house, a properly designed control strategy can achieve free space heating over two consecutive cloudy days, if preceded by three sunny days, relying solely on the solar resource.

Keywords: active storage, passive storage, net-zero energy house, passive solar house

1. Introduction

The Alstonvale Net Zero Energy House (ANZEH) is one of the winners of the *EQuilibrium Initiative*, a design competition organized by the Canada Mortgage and Housing Corporation (CMHC) between 2006 and 2007 [1]. This house is currently under construction in the town of Hudson, in the metropolitan region of Montréal. Numerical models were used to study the response of the house under several control strategies. A description of this house, as well as the results of these simulations, is presented here.

Figure 1. Alstonvale Net Zero House: south façade (left) and street view (right)
(Images courtesy of Sevag Pogharian)

2. Description of the Alstonvale Net Zero House

2.1. General features

The ANZEH is a two storey, wood-frame, detached building, with 210 m^2 of inhabitable area. The insulation values selected for the building envelope are higher than conventional Canadian homes: walls with 5.6 RSI ($U = 0.18\ W/m^2K$), ceiling with 12 RSI ($U = 0.08\ W/m^2K$) and floor insulation of 4.6 RSI ($U = 0.22\ W/m^2K$). This house relies heavily on passive solar design to satisfy its energy needs. It has been designed with advanced (low-e, triple-glazed, argon-filled) south-facing windows (50 m^2 in total), occupying 43% of the south façade. There are also windows on the east and west walls, while there are no windows on the north façade. In order to increase its thermal mass, and therefore its capacity for **passive** thermal storage, the house was designed with 15-cm thick concrete slab floors and a large interior masonry wall. The ANZEH has a solar chimney connected to the indoor space. This chimney has an east-facing controllable damper, which remains closed during the winter; during the summer, it enhances natural convection currents, thus removing hot air from the house interior. Other features include the use of energy-efficient appliances and a design that enhances daylighting complemented with low consumption compact fluorescent lamps. Properly-sized overhangs prevent excessive solar heat gains during the summer. Motorised theatre curtains, located behind the main south-facing windows, contribute to controlling solar heat gains, while improving comfort and adding to the aesthetic value.

Hudson is located 50 km northwest of Montréal (45°26’ N and 74°10’ W). Montréal weather data was used in the design of the house; the winter design temperature is -23 °C [2].

2.2. BIPV/T roof

Perhaps the most novel feature of the house is its Building Integrated Photovoltaic/Thermal (BIPV/T) roof, and the solar heating system based upon it. This roof has an array of polycrystalline photovoltaic panels mounted on a commercial photovoltaic framing system designed for roof installations. The peak capacity of the PV, 5.5 kW_p in the first design, was increased to 7 kW_p to provide energy to a plug-in hybrid vehicle. As in many roofing systems, in this framing structure each frame slightly overlaps the one located below. This is significant, as these PV panels, which occupy 55% of the total area of the roof (105 m^2), are not used only for generating electric power: they also play an important role as part of the building envelope by replacing asphalt shingles. The roof has a 45° slope (roughly equal to Montréal’s latitude) and due south azimuth orientation.

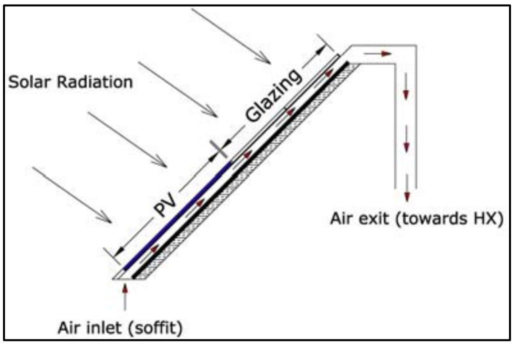

Figure 2. BIPV/T of the ANZEH.

An air inlet under the soffit permits the use of a variable-speed fan to draw exterior air through a gap under the PV arrays. This system allows for the recovery of useful heat from the roof and has the additional advantage of lowering the temperature of the PV panels. For a system such as that in the ANZEH, this represents additional electric power on the order of hundreds of watts, which might partially or totally offset the energy consumed by the fan. A glazing section filling the remaining area of the roof above the PV panels helps to increase the temperature of the BIPV/T air. The glass panes are mounted on the same framing system used by the PV arrays. Below the glazing section, a low-emissivity absorber surface enhances the recovery of solar thermal energy. The air temperature rise depends on several factors, the most important being solar radiation, exterior temperature, air flow rate and wind speed. For a clear sunny day during a Montréal winter and a flow rate of about 450 L/s, the air temperature rise may exceed 40 °C. As the stagnation temperatures of the BIPV/T system can be quite high during the summer (up to 100°C) a small fan will be used to remove hot air from under the roof through an opening on the east side of the roof. A manifold located at the rooftop connects the BIPV/T roof to a ducting system. The ducting system has been designed to minimize the pressure drop and therefore the power requirements of the variable-speed fan (with a maximum power of about 500 W).

2.3. Heat exchanger, heat pumps and active thermal energy storage (TES)

Two ducts bring the hot air from the roof to an air-to-water heat exchanger (HX). Due to its size (cross-section of approximately 1.2 m x 1 m) this HX is located in the ceiling of garage. The HX allows the use of the BIPV/T to heat the water in a large reservoir in one of two ways: (a) directly, via a piping system connecting it to a coil inside the TES tank; or (b) by using the hot air to heat the water of the source side of two twin heat pumps (HPs). System (a) can be used when the BIPV/T air temperature is considerably higher than that of the bottom of the tank. During the winter, however, the BIPV/T air temperatures will often be between 10 and 30 °C, which is an optimal source temperature range for the operation of the HPs. The details of the selection of these HPs have been described elsewhere [3]. Each heat pump is rated at 10.6 kW. They can operate together or one at a time, extending the range of air flow rates that can be useful to provide thermal energy; it has been rated from about 400 to 1000 L/s.

The aforementioned large water reservoir represents the main active thermal energy storage (TES) of the ANZEH. Its volume (about 4000 L) permits storing about one day’s worth of heating for a heating load of 6 kW. Apart from the coil making the direct link to the HX, and the pipes connecting it to the HPs, the TES tank has an additional coil connecting it to the domestic hot water (DHW) tank. The TES tank will deliver the thermal energy to a plate heat exchanger, which in turn transfers heat to a low temperature radiant floor heating system installed in the concrete slabs in the basement, main and upper floors. A vertical division, and two adjustable horizontal baffles with a perforation in the centre, will enhance the thermal stratification of the tank. However, the main factor limiting this stratification is the high flow rates required by the HPs; the temperature difference between the maximum and minimum temperature in the tank will be about 5-8 °C.

2.4. Backup ground source loop

Eventually, a sequence of consecutive cloudy days in winter will require discharging the TES without additional heat supply from the BIPV/T roof. A backup system is therefore necessary. One of the most important design revisions has been the change of the backup system from a large pellet boiler to a ground source loop using the same HPs as the BIPV/T system. The pellet boiler presented several shortcomings: cost, higher operating temperatures (implying more complex piping), and the need for a stock of wood pellets. In contrast, using a ground source for the heat pumps has the advantage of simplicity: a single 3-way valve allows for easy selection between the BIPV/T air and the ground to provide thermal energy to the HPs.

2.5. Solar collector and domestic hot water (DHW) system

Two 20-tube vacuum (Apricus 20) tube solar collectors will be the main source of thermal energy for the DHW needs. A heat exchanger wrapped around the grey water drain (“power-pipe”) contributes to increasing the temperature of the water entering the DHW tank. The evacuated tubes will be located on the south façade of the house overhangs, at a 45° inclination angle. A heat dissipater will release excess thermal energy gathered by the collector during the summer. A controllable rolling canopy will extend over the collector and over the edge of the overhangs to improve shading during the summer months. The DHW tank will have a volume of 400 L. An internal coil, having a piping system with a set of controllable valves will allow heat transfer between the tank, the solar collectors and the TES reservoir. A desuperheater coil installed in one of the heat pumps can also transfer heat to the DHW tank via a coaxial pipe linked to the tank's drain valve. To guarantee the supply of hot water, an instant electric water heater can raise the temperature of the water supplied to the piping system.

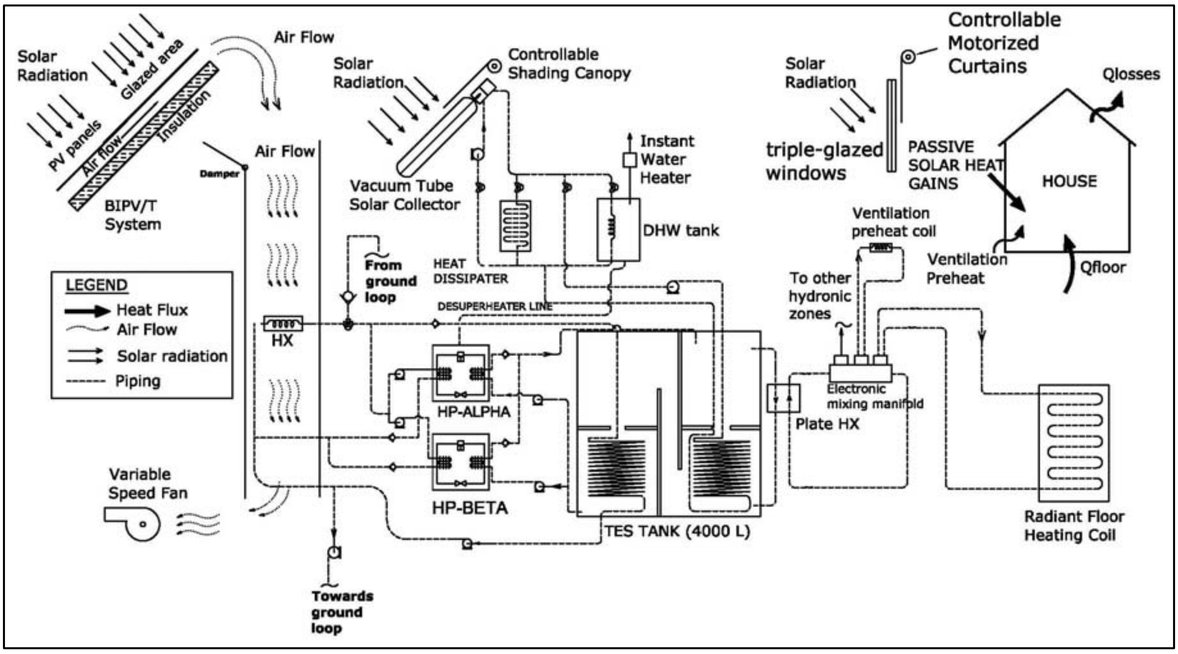

Figure 3. Main components of the ANZEH mechanical system.

3. Modelling of the House and its Systems

A thermal network based on a control volume finite difference discretisation of the house was used. The model used was implemented in MATLAB [4]. Two zones were used: a basement zone and the rest of the building. MATLAB subroutines were written to model the performance of the BIPV/T system, the heat exchanger/heat pumps group, the ground source/HPs interaction, and the TES reservoir.

The BIPV/T model [1, 3] was based on dividing the channel lengthwise in a given number of sections, assuming uniform temperatures at the top and bottom surfaces. An exponential profile is assumed within each section; temperatures and heat transfer rates are found iteratively using a 1-D thermal network between the air and the surfaces. The exit temperature of each section is used as the entrance temperature of the next section.

A simple model based on the variation of effectiveness of the heat exchanger with varying flow rates and manufacturer's data was used to model the performance of the HX and one or both HPs [2]. This model was modified to use an adjusted temperature of the ground as an input.

Finally, a 4-node simple model, as described in [5], was used to model the TES reservoir. In this model, the water in the TES is divided into four nodes (a convenient model since there are also four internal divisions in the tank). The water entering the tank (either from the radiant floor heating system or the HPs) is assumed to go to the node having the highest temperature *below* that of the incoming water. Simple water exchanges are then assumed to take place between the nodes to guarantee mass flow rate balance. According to [5], the use of 3 or 4 nodes is a good compromise between an accurate model and a conservative design (which would assume only one node).

4. Control Strategy

4.1. Passive and active thermal storage in the house

Simulations indicate that during a clear sunny or even a partially sunny day, no heating will be required [1]. The main challenge of the control strategy thus consists of gathering as much thermal energy as possible during sunny days, and storing it so that it can be used over a sequence of cloudy days (at least 2 days), thus minimising the use of the backup (i.e., the ground source). The many systems of this house make controlling it a challenging task. However, despite the inherent complexity of the problem, the key issue is the rational balance of the two thermal storage media for stockpiling solar thermal energy: the **passive thermal storage** in the building's structure thermal capacity (mainly in the floor slab and the masonry wall) and the **active thermal storage** (TES tank).

The passive storage of the ANZEH is charged by the solar heat gains obtained through the windows (which are practically an essential component of the heating system) and by the radiant floor heating pipes. The passive storage is discharged when it gives heat to the indoor space. Naturally, this thermal energy is eventually released to the surroundings of the house. **The TES reservoir (active storage)** can be charged in four ways: (a) through the direct recovery of thermal energy from the BIPV/T air, via the HX; (b) with one or both HPs using the BIPV/T air; (c) with the HPs, but using the ground as the heat source; and (d) with excess energy from the solar collector loop. The TES is discharged mainly by its use as a source for the radiant floor heating system; it is also discharged by delivering thermal energy to the DHW tank and through natural heat losses to the surroundings.

The following considerations should be addressed in the design of the control strategy:

- Although temperature fluctuations are needed to take advantage of the thermal mass potential for storing thermal energy, comfortable indoor conditions must be maintained at all times.
- These temperature fluctuations occur at time scales of several hours, much longer than the time constants of the sensors and of the HVAC system.
- The COP of the HP(s), and thus the energy delivered to the TES, depends mainly on the temperatures of the BIPV/T air and the bottom of the TES tank. The COP also depends on the water flow rates on both sides of the HP(s), and the air flow rate through the HX.
- The thermal energy stored in the tank increases with its temperature. Since the COP of the HP(s) decreases as the temperature of the tank increases, the decision to charge the tank should be made based on the availability of thermal energy at the present time and in the future.

4.2. Simple weather scenarios for testing predictive control

On account of the aforementioned reasons, the implementation of **predictive control** (i.e., control taking into account estimates of future loads or conditions) is highly advisable in a house with active and passive storage capacities, such as the ANZEH. At the present time, predictive control is facilitated by the availability of reliable and complete weather forecasts.

To study the response of the ANZEH under different conditions, artificial sequences of 5 days, attempting to represent typical series of cloudy and sunny days, were designed. In these sequences, a sunny day was assigned a daily clearness index (K_T) of 0.7, an intermediate day was assigned a K_T of 0.5, and a cloudy day was assigned a K_T of 0.3. The model of Liu and Jordan, as described in [5], was used to determine a typical distribution of hourly clearness indexes (k_T) for both conditions. The Erbs model [5] was used to calculate the diffuse fraction of the global horizontal radiation. Finally, the Perez model [6] was used to calculate radiation on surfaces with different orientations.

In the sequences of 5 days used in this study, the last two days were assumed to be cloudy, while the first three days can be either cloudy (represented by a C), intermediate (represented by an M) or sunny (represented by an S). These sequences can be applied to any five consecutive days in the year. After choosing an initial day (from 1 to 365) astronomical angles can be taken into account. The graphs below correspond to the days from January 15th to January 19th.

Temperatures for Montréal were modelled using a steady-periodic curve using an average value and average fluctuation range for the corresponding month, and the design day data (quasi-sinusoidal) proposed by ASHRAE [7]. Wind speed data from a TMY2 (TRNSYS typical meteorological file) [8] corresponding to the dates examined, was used.

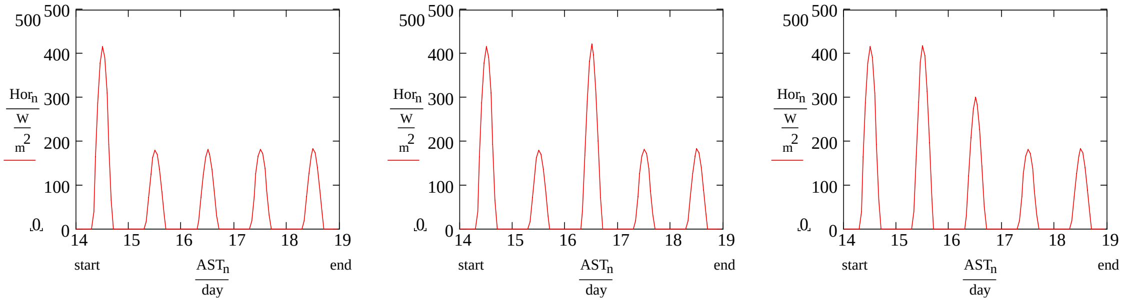

Figure 4. Global Horizontal Radiation corresponding to scenarios SCCCC, SCSCC and SSMCC.

4.3 Tank charging, space heating, and ventilation

The tank will only be charged when the top tank temperature is below the setpoint. For all cases, the HX is used directly if the BIPV/T air temperature is at least 3 degrees above the top tank's temperature. If this is not the case, but the BIPV/T air temperature is above 10 °C, then both heat pumps are used to charge the tank. If the temperature is between 3.5 and 10 °C, then only one heat pump is used. Finally, if the BIPV/T air temperature is below 3.5 °C, one heat pump is turned on using the ground as a source. If the temperature in the house is too high (28.0), then the ventilation rate will be increased from 0.3 ACH (including natural and mechanical ventilation) to 1 ACH per hour.

4.4 Predictive supervisory control strategy

For space heating, a simple PI control strategy is used to obtain the prescribed setpoint. To avoid overheating, if the temperature at 6:00 a.m. exceeds the setpoint, the theatre curtains are moved to a position depending on the radiation expected for the current day. In order to incorporate predictive control, the design of control strategies has been based on a simple control strategy: both the **tank temperature setpoint** (active storage) and the **operative temperature** (an indicator of the status of passive storage) depend on current conditions and the solar irradiance expected for the following day. Some results of applying this control strategy are shown below.

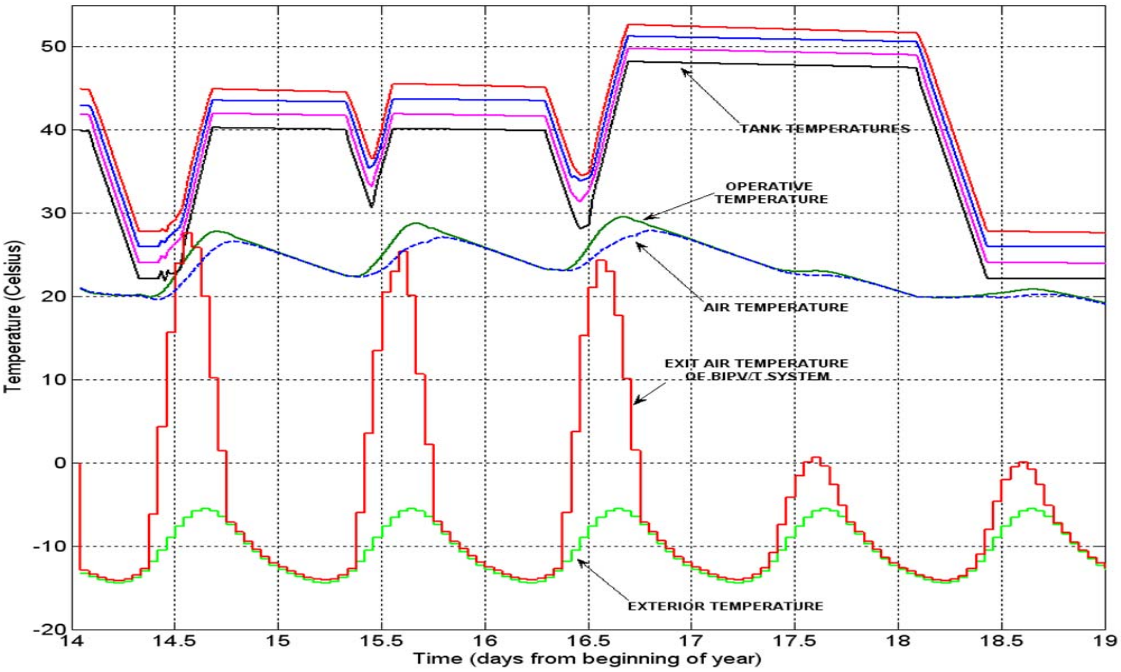

Figure 5. Results of the application of a predictive control strategy for a SSSCC sequence.

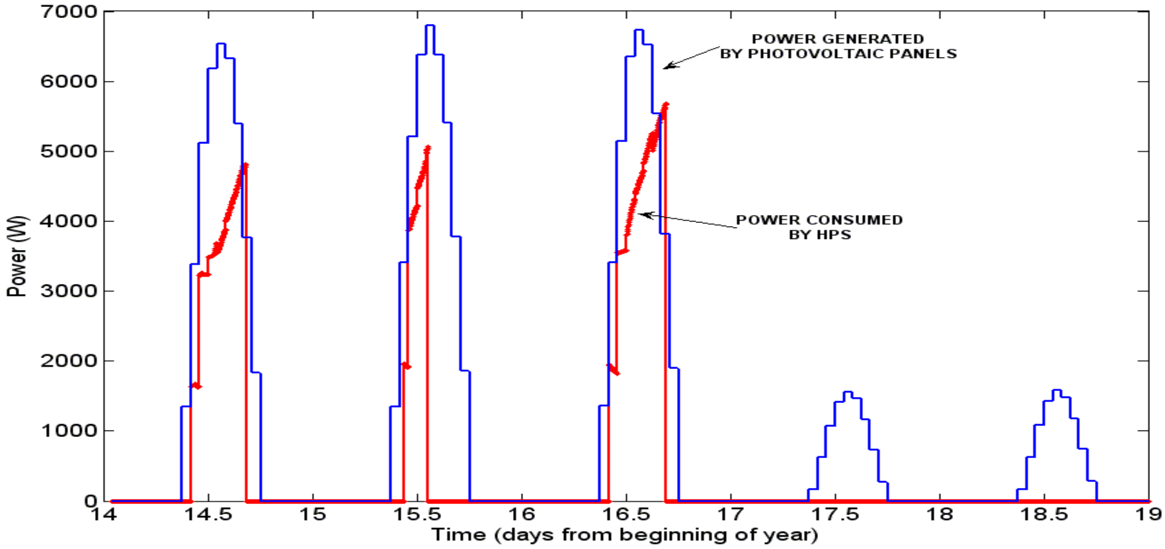

Figure 6. Power consumption of the heat pumps and generation of the PV system for the case of Fig. 5.

It has been found that heating can be provided over the 2 cloudy days following the first three sunny days without using the ground source heat pump. It has also been found that the PV generation exceeds the power consumption of the heat pumps. As no additional electric power is needed for the grid, this has interesting implications for load management. As expected, the heat pumps consume more energy as the tank gets hotter. This is one factor that should be considered in the design of the control strategy. It has been calculated that over these 5 days, the heat pumps consumed approximately 61 kWh for heating the house. The total yearly electric energy consumption of the house has been calculated to be about 7100 kWh, of which 2500 kWh is consumed by the HPs. The PV panels generate 8600 kWh. The remaining energy (1500 kWh) is intended to be used for the plug-in hybrid car.

5. Discussion and Conclusion

The control strategies presented here have assumed perfect knowledge of future conditions. It is desirable to incorporate modelling of “imperfect” forecasts for these events, and statistical uncertainty as an element in the decision. A statistical analysis of historical weather data could be used to study the probability of having a series of cloudy days, and could therefore be used as a decision-making tool in sizing a TES reservoir and the backup system. For example, this could help to decide what tank size is large enough to provide heat over 3 days, one week, etc., and the likelihood of that event. Other important aspects to take into account in the development of predictive control strategies are load management and the use of several operative temperatures throughout the day. On account of the different time scales involved, effective local loop control should also be emphasized to achieve the goals established by the supervisory control strategy. So far, a full house simulation has been used, but a simplified model (based on transfer functions) [9] could be implemented in order to apply techniques such as model predictive control (MPC). Finally, simulations using several zones are needed to properly evaluate thermal comfort and its relation to handling passive thermal storage. Although these strategies have been applied to a particular solar house, the idea of balancing active and passive storage has general validity.

6. Acknowledgements

Financial support of this work was provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada through the Solar Buildings Research Network (SBRN). Other SBRN partners include: Natural Resources Canada, which funded the BIPV/T system through the TEAM (Technology Early Action Measures) program; CMHC, which conducted the EQuilibrium demonstration program; and Hydro Québec, which participates in the monitoring of the house. We would like to thank Québec’s Agence de l’Efficacité Énergétique for their valuable contribution to this project. We would like to thank Sevag Pogharian, developer of the ANZEH project. The first author would like to thank the financial support of NSERC through a CGS D2 Alexander Graham Bell Graduate Scholarship. We would like to express our gratitude to André Fry (Concept-R), Jocelyn Harel (Régulvar) and Claude Agouri (Air Techni) for their contribution of ideas.

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