Solar Buildings Research Network Demonstration Projects: Towards net zero energy consumption

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ABSTRACT: The Solar Buildings Research Network (SBRN) carries out research and development on design techniques and technologies suitable for the incorporation of solar energy in residential, institutional and commercial buildings. This paper describes three demonstration projects developed with the guidance of the SBRN: (a) the Ecoterra™ Alouette House; (b) the Alstonvale Net Zero House; and (c) the BIPV/T façade of the new John Molson School of Business (JMSB) building at Concordia University. These three projects make use of building integrated photovoltaic thermal (BIPV/T) systems, combining electricity generation and heat recovery. They also illustrate the potential of current technologies in achieving the net-zero energy target. The Ecoterra™ house and the Alstonvale Net Zero House have been designed to achieve or approach this goal. The façade of the JMSB, located in downtown Montréal, is the largest PV installation in Québec and showcases an innovative system for heat recovery, appropriate for high-rise buildings.
Keywords: passive solar design, solar-optimized building, net-zero energy building

INTRODUCTION

Buildings represent about 30% of Canada's energy use and account for half of its electricity consumption [1]. The energy consumed by buildings and the associated GHG emissions keep rising due to several factors, which include population growth, larger dwelling spaces and the rising standard of living. Fortunately, opportunities exist for improving energy efficiency in buildings and for distributed energy generation with renewable energy sources. It is now possible to build net-zero energy buildings (NZEBs), so named because they generate as much energy as they consume over the course of a year. There is growing international interest in building energy efficiency, as well as net-zero and near net-zero energy buildings. The International Energy Agency (IEA) has recently established a Task focused on NZEBs [2].

The Solar Building Research Network (SBRN) is a Canada-wide NSERC strategic network, created in 2005 with a 5-year mandate, with the purpose of researching solar techniques and technologies applicable to buildings, developing practical solutions for the Canadian climate and conditions, and training highly qualified personnel [3]. The SBRN includes among its members 13 universities and several government agencies and industrial partners. SBRN research activities include passive solar design, daylighting, natural ventilation, solar thermal systems, development of software design tools, control algorithms, photovoltaic electrical generation and power conversion, and the integration of these technologies into the built environment.

As an important part of its vision, the SBRN participates in technology transfer activities, which include several demonstration projects. This paper presents an overview of three demonstration projects in Québec in which the SBRN has played a relevant role: (a) the EcoTerra™ House (Eastman); (b) the Alstonvale Net Zero House (Hudson); (c) the building-integrated photovoltaic/thermal (BIPV/T) façade of the new Concordia building (Montreal). The first two projects illustrate the possibilities of building net-zero energy solar homes (NZESHs) [4], in which the net-zero goal is attained with passive solar design, photovoltaic electricity generation and active collection of solar thermal energy [5].

ECOTERRA HOUSE

The EcoTerra™ House was selected as one of the winners of the *EQuilibrium Initiative*, a competition organized in early 2007 by the Canadian housing agency, CMHC. This 140 m^2, single-family, detached house is located in the town of Eastman (N45°20', W72°20').

The EcoTerra™ House (see Figure 1) relies heavily on passive solar design to fulfill its heating needs. About 40% of its south façade is covered by triple-glazed, low emissivity, argon-filled windows with an R-value of about 5.5. The solar heat gain coefficient (SHGC, the fraction of the solar radiation received by the windows that enters the house) is about 60%. Properly sized overhangs prevent overheating during the summer months and the shoulder seasons. As part of its passive solar design, the EcoTerra™ House has high levels of thermal insulation: R-34 on the walls; R-45 on the ceiling; R-23 on the basement walls and R-8.5 under the basement concrete slab. The house is also extremely air-tight: a blower-door test recorded 0.8 ACH at a pressure difference of 50 Pa. Maisons Alouette, the builder of EcoTerra™ House, constructed the house in four prefabricated modules, which were then assembled in less than a day in November 2007.

Figure 0. The EcoTerra™ House.

The upper roof of the EcoTerra™ House consists of a BIPV/T system with 22 amorphous silicon panels, having a total nominal electrical generation capacity of 2.9 kW. As shown in Figure 1, the BIPV/T roof is practically indistinguishable from the conventional lower metal roof. The principle of operation of the BIPV/T roof is illustrated in Figure 2. Exterior air is drawn through a gap under the BIPV/T roof, recovering heat from the PV modules, lowering their temperature and thus increasing their efficiency. The temperature of the air rises as it moves upwards through the gap. Figure 3 shows measurements taken on a day in mid-March 2008, when the BIPV/T flow rate was 400 CFM (190 L/s).

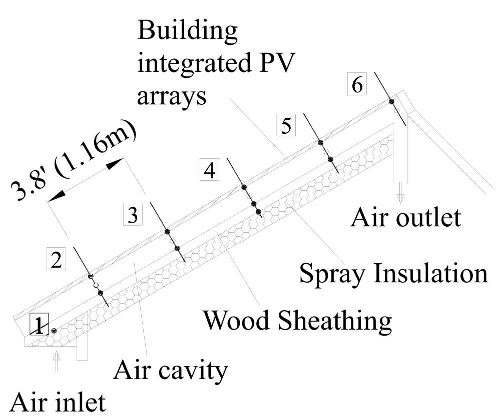

Figure 0. Schematic of the EcoTerra BIPV/T roof. [5]

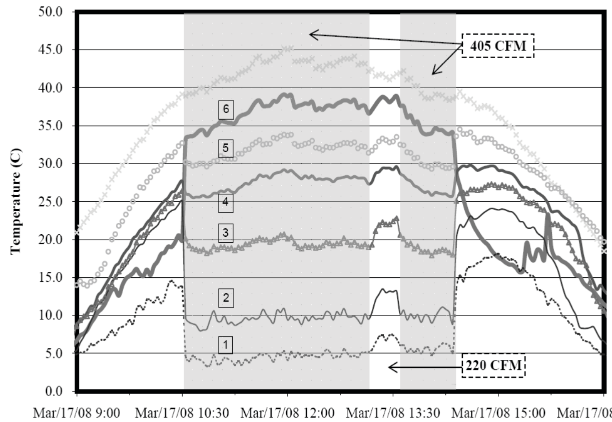

Figure 3. Temperatures corresponding to the measurement points indicated in Figure 2 (March 17th, 2008) [5].

Temperature rises of 35-40°C are obtained. The PV array produces a peak power of 2.8 kW, with a heat recovery of about 8 kW. Increasing the flow rate has permitted increasing the heat recovery up to 12 kW.

A set of ducts connected to a manifold is used to collect the BIPV/T air. Foam insulation is used to reduce heat losses (Fig. 4).

Figure 4. Ducting system with foam insulation.

The solar heated air may be used in three ways (Figure 5): (a) preheating domestic hot water; (b) supply air for a clothes-dryer; (c) raising the temperature of the basement concrete floor slab. The latter function is accomplished by passing air through steel channels inside the concrete slab. This measure significantly contributes to reducing the need for auxiliary heating (which in this case, consists of a 7.6 kW ground source water-to-air heat pump).

In the event of several consecutive sunny days, it has been observed that the temperature of the concrete slab keeps rising, which indicates storage of thermal energy from one day to the next. Simulations indicate that this house will approach the net zero energy goal with an annual *net* energy consumption of 4,000 kWh. In contrast, a conventional Canadian house consumes

40,000 kWh per year, while residences developed under the "Advanced House" program (Natural Resources Canada) consume about 15,000 kWh [6]. More details on

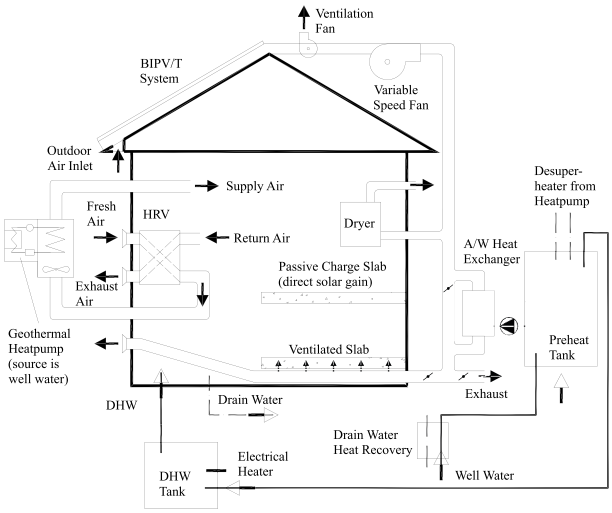

Figure 5. Mechanical system of EcoTerra™ House [2].

the EcoTerra™ house have been presented elsewhere [7].

ALSTONVALE NET ZERO HOUSE

The Alstonvale Net Zero House (ANZH) is also one of the winners of the *EQuilibrium Initiative*. This 210 m^2, two-storey, detached house (Fig. 6) is in an advanced stage of construction in the town of Hudson (N45°27', W74°11'), about 50 km west of Montréal [8].

Figure 6. Alstonvale Net Zero House [8].

As in the case of the EcoTerra™ House, the ANZH makes extensive use of passive solar heating design techniques. The insulation values of walls, ceiling and floor slab are R-32, R-68 and R-26 respectively. About 41% of the south façade is covered by advanced windows (3-glazed, argon-filled, low-emissivity coating), with an R-5.5 insulation value and a SHGC of nearly 60%. Properly sized overhangs prevent excessive solar heat gains. The ANZH has a 6-inch concrete slab in the main level and 2.5-inch concrete floors in the upper level. A masonry wall, behind the main south windows, forms a hallway communicating both levels of the house. This masonry wall provides additional thermal inertia. On sunny days, solar heat gains will obviate the need for auxiliary heating. These solar heat gains will be stored in the building's own thermal mass (where the floors and masonry are the most important contributors), maintaining comfortable conditions for up to nearly 24 hours. Large motorized theatre curtains allow for partial control of the solar heat gains, a useful feature to prevent overheating. A "solar chimney" on the roof of the house has an east-facing opening that can be operated in the summer to complete a natural ventilation path to help maintain comfortable conditions.

The main energy source of the house is its BIPV/T roof, a grid-tied 7.35 kW system of 42 polycrystalline PV modules. The roof is expected to generate about 9,000 kWh of electricity per year, enough to supply the 7,300 kWh needed by the house's lighting system, mechanical system and appliances: the net-zero energy goal is thus reached. The remaining additional capacity (1,500-1,700 kWh) will provide energy for a plug-in neighborhood electric vehicle.

As in the EcoTerra™ house, the ANZH uses air heated by the BIPV/T as a heat source. However, in the ANZH this BIPV/T air is the principal source of auxiliary thermal energy. To increase its heat recovery capacity, glazing panels will be installed on the surface of the south roof not occupied by photovoltaic modules. The ANZH operates with larger flow rates between 1,000 and 1,800 CFM (470 L/s to 850 L/s).

Heat from the BIPV/T air can be recovered either directly with an air-to-water heat exchanger or by using two heat pumps installed in parallel. This configuration permits large amounts of thermal energy (between 6 to 22 kW) to be recovered. A manifold collects the BIPV/T air and two parallel ducts (designed to minimize pressure loss) bring it to the heat exchanger. The flow is driven by a variable speed fan that permits partial control of the BIPV/T exit temperature. The collected thermal energy can be stored in a 4,000-L thermal energy storage (TES) water tank, which can store about one day's worth of heating. If the BIPV/T air is not hot enough, a ground loop connected to the heat pumps provides a backup source of heat. Solar thermal collectors installed on the south-facing overhangs complement the mechanical system by providing heat for domestic hot water (Fig. 7).

Managing the thermal energy sources and storage capabilities is essential to reduce energy consumption and peak loads. This is facilitated by integrating online weather forecasts [9] in the control algorithms as part of "Smart House" features. Another paper about these control algorithms is presented at this conference [10].

The scope of the house's design has been expanded to include power for the aforementioned electric vehicle ("net zero energy transportation"). Awareness of the energy cost and environmental impact of industrial food production has encouraged the project leader to add two garden plots and a greenhouse to approach "net zero food production" [11]. The SBRN is currently participating in the design of an advanced solar greenhouse, which will include photovoltaic/thermal installations and thermal energy storage.

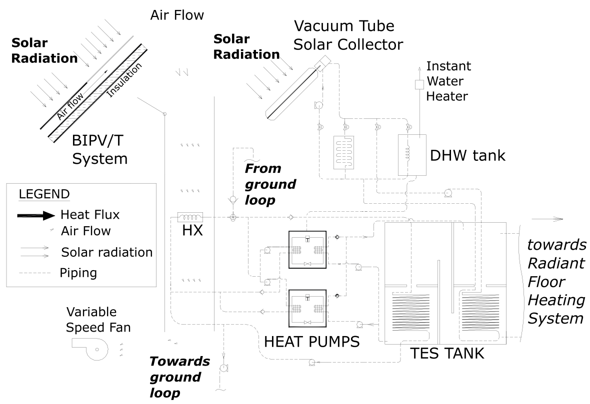

Figure 7. Summary of the ANZH mechanical system.

HOT2000, RETScreen and MATLAB simulations were used during the design process. Figure 8 summarizes the expected energy flows in the house, as calculated from these simulations. It is obvious that passive solar heat gains provide the largest contribution to the heating needs. The BIPV/T air contributes 65% of the heat required as source for the heat pumps (3,000 kWh), while the ground contributes the remaining 35% (1,600 kWh).

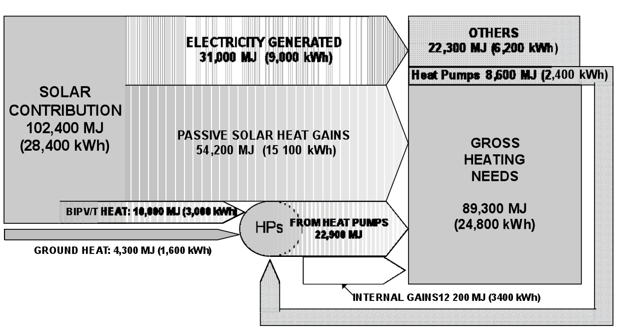

Figure 8. Sankey diagram of the ANZH energy flows.

Figure 9 shows a recent picture of the Alstonvale Net Zero House. Completion of this project is expected for the summer of 2009. More than 200 variables (including power generation and consumption, heat pump performance, BIPV/T temperatures and room temperatures, among others) will be monitored by Concordia University, Hydro-Québec, Natural Resources Canada and the control company (Régulvar).

Figure 9. Alstonvale Net Zero House (March 2009).

BIPV/T FAÇADE OF THE JMSB

During the last half of 2008, an innovative BIPV/T system was installed on the façade of the new building of the John Molson School of Business at Concordia University (Montréal) [12]. This BIPV/T façade (Figure 10), a demonstration of Canadian technology, has a peak electric generation capacity of 25 kW, which makes it the largest PV installation in Québec. It will also be able to recover 75 kW of thermal energy that can be used to preheat fresh air for the JMSB building.

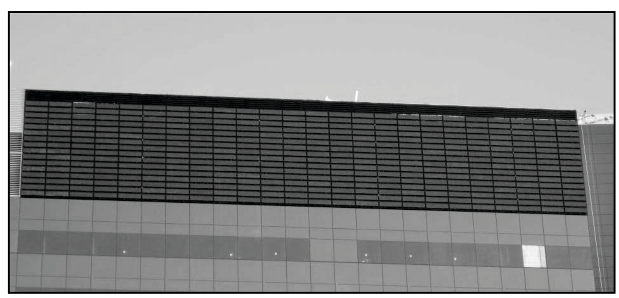

Figure 10. JMSB BIPV/Thermal façade.

The BIPV/T system has been installed at the top section of a façade with a near-south orientation, covering an area of 288 m^2. It consists of 384 polycrystalline PV panels (manufactured by Day Energy) mounted on top of an un-glazed solar air collector (SolarWall® by Conserval Engineering), a perforated metal sheet especially designed for recovery of solar thermal energy. The principle of operation of the façade is illustrated in Figure 11. A fan drives an air stream through a cavity behind the air collector and the PV modules, recovering thermal energy from both. Exterior air is primarily sucked behind the PV modules (removing heat and lowering the module temperature) and then

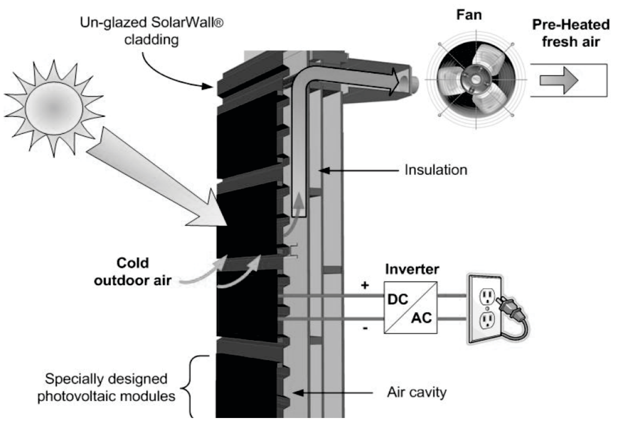

Figure 11. JMSB BIPV/T Façade: Principle of operation.

enters through the air collector perforations and into the air cavity.

A vertical temperature gradient is expected in the BIPV/T façade: in other words, PV modules located at the same level are expected to have similar temperatures. Since the voltage of photovoltaic panels is highly dependent on their temperature, it is recommended that modules with the same temperature should be connected in parallel. To account for this effect and thus improve their electrical output, the PV panels were installed in

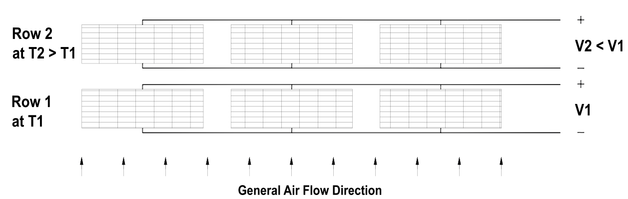

Figure 12. Schematic representation of the connection of the PV arrays. The PV modules temperature increases with height, while their voltage (and power output) decreases.

narrow horizontal rows (expected to be nearly isothermal) and then connected in parallel (Figure 12).

The PV modules, covering about 60% of the entire BIPV/T façade, were custom designed and manufactured to be integrated onto the air collector and to optimize thermal performance. They are not mounted flush against the air collector perforations. Instead, there is a small gap behind the PV panels and the air collector. Most importantly, the lower edge of their frame slightly overlaps one of every three grooves in the air collector (see Figure 11 above). This allows cold outdoor air to pass under the frame, then behind the PV panels and finally through the air collector perforations and into the air cavity. The top edge of the PV module is tight against the air collector, limiting heat loss due to natural convection.

The BIPV/T systems of the two *EQuilibrium* houses have been designed with a single inlet. In contrast, the multiple inlets of the JMSB BIPV/T system allows distributed intake of cold outdoor air. Although this design reduces the final air temperature, it allows a more efficient heat recovery from the PV panels with higher final flow rates for the same fan power. When high temperatures are not required and pre-heating air is a more important factor, multiple-inlet systems are the preferable and most efficient option. In this case, the system will draw approximately 15,000 CFM (7,075 L/s) which will be used, as mentioned above, as preheated fresh air.

The BIPV/T façade will not block daylight for any of the offices in the JMSB building, as it is located in front of the building's mechanical room, which will make it easily accessible. The required electrical and monitoring equipment such as charge controllers, inverters and data acquisition units, are installed on the backside of the façade.

Due to its location in downtown Montréal, the BIPV/T façade is a high-visibility project in Québec and is expected to contribute to public awareness about new solar technologies for buildings.

The performance of this façade will be monitored and studied in order to fully quantify the energy contribution of this unique installation to the JMSB building. An energy display will be installed in the lobby of the JMSB building, allowing students and general public to monitor in real time the electricity generated and the thermal energy collected by the system.

CONCLUSIONS

Three demonstration projects sponsored by the SBRN have been presented in this paper: two of them correspond to detached single-family houses, and the third to a high-rise institutional building.

Demonstration projects are of significant value for the diffusion of new technologies and their eventual adoption as mainstream practices. The EcoTerra^{TM} House and the Alstonvale Net Zero House show the attainability of an annual net-zero (or near net-zero) energy consumption by using solar radiation as the main energy source. Although high insulation values and air-tightness are undoubtedly needed, cost and other considerations (such as indoor air quality) show that they are often not sufficient for achieving the net-zero energy objective in the Canadian climate.

Passive solar design is the cornerstone of the conception of both houses. It is the most effective measure –as well as the most affordable and the easiest to implement– to achieve the net-zero energy objective. The exact values of building envelope insulation, window SHGC and thermal mass will depend on the particular conditions of each case. An optimization design process is therefore necessary. Work is carried out at the SBRN towards the development of a conceptual design software tool for this purpose [13], which may be of considerable assistance to professionals in the building sector.

New window technologies, together with controllable blinds and shades, have allowed increasing window/wall ratios and therefore higher solar heat gains. However, a common mistake is to assume that it is acceptable to keep increasing window insulation values (for example, by adding more layers of glazing) at the expense of the SHGC. Windows should practically be considered part of the mechanical system, as they provide thermal energy of the order of several kilowatts. Sacrificing the SHGC to get a small improvement in thermal resistance would often be counterproductive.

Active technologies, such as the BIPV/T and solar thermal collector systems, also play an essential role. Variability of solar energy also implies that energy storage and control are also necessary, as shown in both the EcoTerra™ and ANZH projects.

The BIPV/T façade of the John Molson Building, a pioneering accomplishment, is a sample of the state-of-the-art technical know-how and creativity available in Canada. It also shows that these technologies can be applied to institutional and commercial buildings.

Despite their differences in approach and scale, a common denominator in these projects has been the integration of electric power generation and heat recovery technologies as building envelope components. Integration and the use of multiple-function components are vital for the success of these projects and contribute to their affordability.

Finally, it is expected that the abundant data collected at these demonstration projects will permit the SBRN to improve design details and issue guidelines for future work.

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