# Energy Performance, Comfort and Lessons Learned From a Near Net-Zero Energy Solar House

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**ABSTRACT**

*This paper examines the performance of a Canadian near net-zero energy solar house known as ÉcoTerra located near Montreal. The total energy consumption and energy end-use breakdown are presented and several findings from the energy analysis are discussed such as the importance of occupant behavior, occupant comfort and the improvements that could lead to achieving full net-zero energy performance . It was demonstrated that large reductions in energy consumption can be achieved with little effect on comfort. Occupants affect the loads significantly and need to be educated and given specific feedback about their energy use patterns in order to help them adjust their behavior for energy efficiency. Although already far below the typical home in energy consumption (about 90%), this paper shows how ÉcoTerra could consume even less energy and how similar houses could be designed or upgraded to achieve net zero energy.*

**INTRODUCTION**

Net-zero energy buildings (NZEBs) represent a new concept for high performance buildings with the ambitious goal of producing as much energy as they consume over the course of a year (Torcellini et al. 2006). NZEBs typically involve a highly-efficient envelope and low operating energy combined with one or more renewable energy systems such as building-integrated photovoltaics and solar thermal systems. NZEBs are attracting considerable interest in research and practice, with major activities such as the International Energy Agency – Solar Heating and Cooling (IEA SHC) Task 40/ECBCS Annex 52 ("Towards net-zero energy solar buildings") (the "Task") (IEA SHC Task 40 - ECBCS Annex 52 2010). This Task is undertaking major research issues, including a review of NZEB definitions, a thorough assessment of design processes and tools, and the creation of a database of NZEBs. In particular, the database will disseminate information to builders and designers by providing real examples of NZEBs for similar buildings in their climate (IEA-SHC 2010). This paper describes and analyzes one of the major case studies in the database – the ÉcoTerra House.

ÉcoTerra was constructed as part of Canada Mortgage and Housing Corporation's EQuilibrium™ competition. From the CMHC website (CMHC 2010):

> "EQuilibrium™ is a national Sustainable Housing Demonstration initiative, led by CMHC, that brings the private and public sectors together to develop homes that combine resource- and energy-efficient technologies with renewable energy technologies in order to reduce their environmental impact. Project teams have been selected to build EQuilibrium™ demonstration projects across Canada."

The EQuilibrium™ competition was announced in May of 2006 when CMHC invited groups to submit applications. 80 teams responded and 15 were selected to build demonstration houses (CMHC 2009).

## ÉCOTERRA HOUSE

ÉcoTerra (see Figure 1) is a two-story, two-bedroom, single family, detached home located in Eastman, Québec, Canada (45.3° N, -72.3° W) with a basement and single car garage. It has a heated floor area of 211.1 $m^2$ (2,272 $ft^2$) and a heated volume of 609.1 $m^3$ (21,510 $ft^3$). The garage accounts for an additional 26.6 $m^2$ (286 $ft^2$) and 76.9 $m^3$ (2,715 $ft^3$). ÉcoTerra was constructed by a prefabricated home manufacturer Alouette Homes, with research support from the Canadian Solar Buildings Research Network and funding from Natural Resources Canada, Canada Mortgage and Housing Corporation, and HydroQuébec.

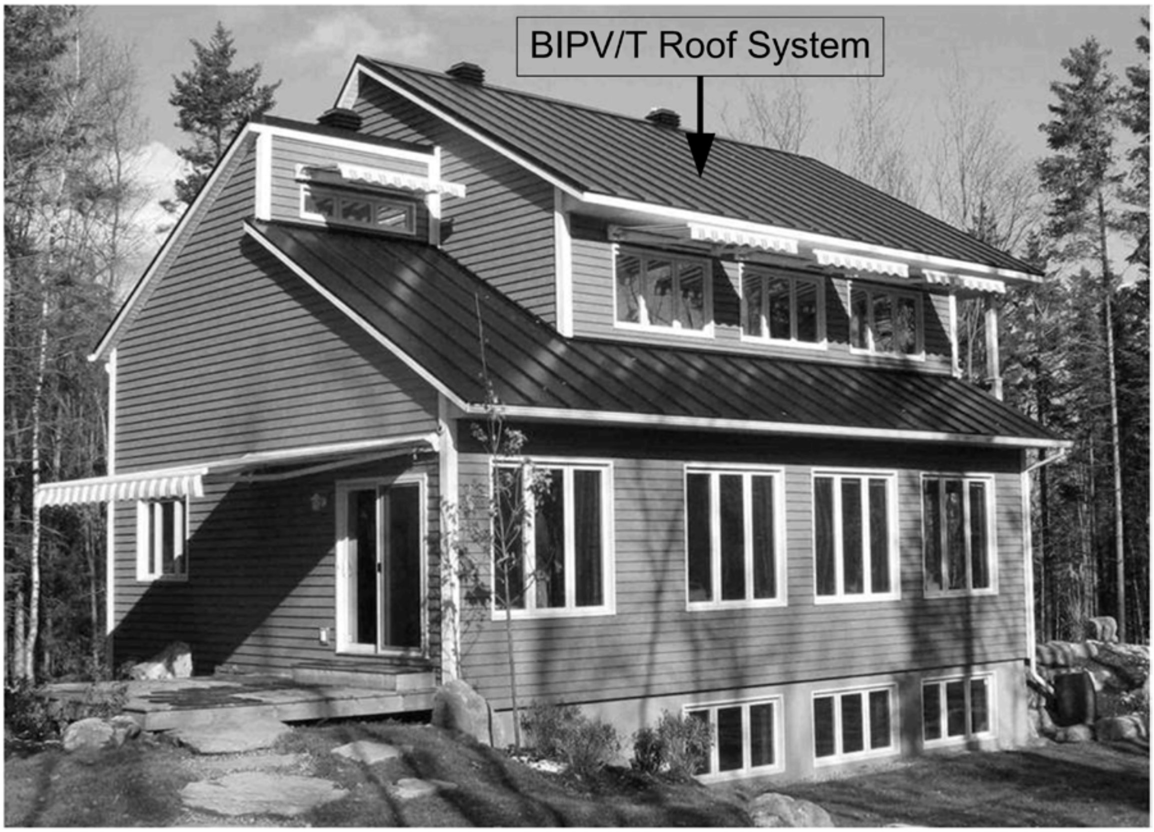


*Figure 1: A photograph of ÉcoTerra house as seen from the south-west, Eastman, Québec, Canada*

ÉcoTerra's building envelope was designed according to passive solar design principles. It has a south facing width-to-depth ratio of 1.38, an overall window-to-wall-area ratio of 15.2% (42% for the south façade) which is equivalent to a solar aperture (south-facing window area-to-total floor area ratio excluding the garage) of 9.1%. The windows are triple-glazed, low-e coated, and argon-filled.

There is significant thermal mass integrated into the basement and main level of the house. The floor is divided into the northern and southern halves. The northern part has a plain concrete slab with a thickness of 75 mm (3 in.), while the southern part has 100 mm (4 in.) of concrete cast over steel decking to form the ventilated slab.. There is a 250 mm (10 in.) thick concrete dividing wall, which splits the basement in two (in the east-west direction) and extends 900 mm (36 in.) high into the first floor of the living space. The main level has a 150 mm (6 in.) thick concrete slab in the south zone. These concrete slabs and walls serve as thermal mass, helping to dampen room temperature swings by storing direct solar gains – leading to both improved energy performance and thermal comfort.

The exterior walls are insulated to approximately RSI 6.4 (R 36.3). The roof is insulated to approximately RSI 9.2 (R 52.2) for the vaulted ceiling portions and RSI 10.9 (R 61.8) for the flat portion. The insulation under the basement slab is approximately RSI 1.3 (R 7.8). The basement walls are insulated to approximately RSI 2.5 (R 14.2) for the above-grade portions and RSI 5.7 (R 32.3) below-grade. After construction, the air-tightness of the house was measured using a blower-door test to be 0.85 at 50 Pa (1.0 lb/ft$^2$).

The house was equipped with new appliances, many of which are EnergyStar, including the fridge, dishwasher, and clothes washer. While compact fluorescent bulbs were installed in all light fixtures upon sale of the house, the owners installed about two dozen additional light bulbs – most of which are halogen.

Traditional solar collectors provide only one type of energy: electricity (photovoltaic type) or thermal energy (solar thermal type). These systems are typically stand-alone systems or add-ons to a building. ÉcoTerra's building-integrated photovoltaic / thermal (BIPV/T) system is designed to increase the overall solar energy collected (by collecting both electrical and thermal energy) and is integrated into the building itself, forming the outer layer of the metal roof (on the south top side).

While the heat recovery system of the BIPV/T roof is operating, air is drawn through openings along the under-side of the soffit of the roof and through channels on the underside of the roof surface by a variable speed fan. This air is heated by the sun as it travels under the metal roof layer and is drawn through an insulated manifold and duct into the mechanical room of the house in the basement to be used. The outer surface of the roof is covered by amorphous silicon photovoltaic (PV) panels which convert the incident solar radiation into electricity. Since the PV panels are about 6% efficient at converting the energy into electricity, much of the remainder can be recovered by the air passing below their surface. Figure 2 shows a system schematic of ÉcoTerra (Chen 2009).

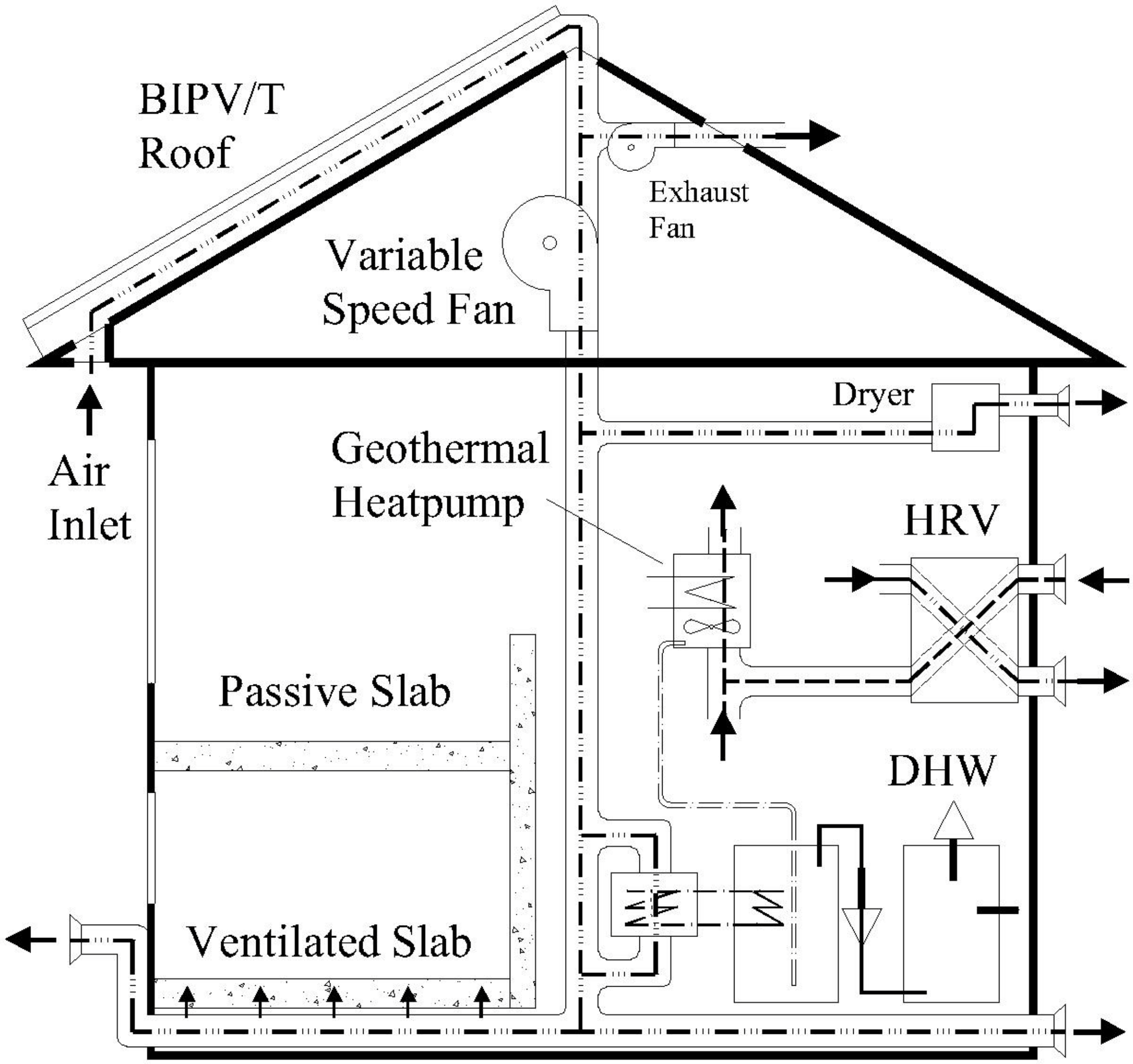


*Figure 2: ÉcoTerra system schematic (Chen et al. 2010)*

The integrated nature of this system means that the surface on which the PV is installed serves the dual purposes of being an energy collector (for electricity and heat) and protecting the house from weather, as standard roofs do. This integration saved on cost and allows the modules to be virtually undetectable by the house's neighbours. The energy balance of the roof is as follows.

$$\alpha IA = E_{PV} + E_{Thermal} + E_0 \tag{1}$$

where $\alpha$ is the mean solar absorptance of the BIPV/T roof, $I$ is the incident solar radiation, $A$ is the roof area, $E_{PV}$ is the rate of electrical energy generation, $E_{Thermal}$ is the rate of thermal energy collection, and $E_O$ is the rate of energy that is lost to the surroundings. For instance, for the current roof under sunny conditions at about solar noon, it's possible to have 1000 $W/m^2$ (317 $Btu/ft^2$) of solar incident solar radiation, of which nearly 6% (3 kW; 10.2 kBtu/hr) can be converted to electrical energy and about 20% (12 kW; 40.8 kBtu/hr) can be converted to thermal energy.

The electrical energy is used on-site and the excess is sold to the electrical utility, while the thermal energy must be used on-site – either immediately or stored for later use. The heated air can be used to preheat the domestic hot water (DHW), assist in drying clothes, heat the ventilated concrete slab (VCS) in the basement or any combination of these.

The slab is a structural element of the house (the basement floor), but also has corrugated metal decking embedded in its bottom, which forms air channels. Heated air from the BIPV/T roof is passed through these channels, thereby actively heating the slab. The energy stored in the significant thermal mass of the floor is then discharged passively into the space in a delayed manner, offsetting the heating load when passive solar gains are unavailable.

The controls for selecting where the heated air from the BIPV/T roof is used were designed to minimize purchased energy use. As a first priority, if the air is warmer than 15°C, has a relative humidity of under 50%, and the owners wish to dry their clothes, it is used for this purpose. Otherwise, it is used to heat the colder of the DHW or VCS (during the heating season only). The controls require that the air leaving the BIPV/T roof be at least 5°C warmer than the DHW tank or 3°C warmer than the VCS for the system to operate; otherwise, the fan energy use may not be justified.

## DESIGN PROCESS

The objectives of the design were to achieve near net-zero energy consumption, while maintaining a healthy and comfortable indoor environment (good thermal comfort, air quality and daylighting) and low water use, as specified by the competition requirements (CMHC 2010). An additional goal was to emphasize building integration of solar technologies and distributed thermal storage. Furthermore, the designers aimed to make the house affordable, with minimal additional cost compared to similarly-sized Canadian houses. Since the house is manufactured, there is also an opportunity for mass-producing the house, thereby facilitating adoption of net-zero energy home design concepts and systems. Also, prefabrication allows construction under high quality control in a factory environment throughout the year. This is in contrast to site-built houses, for which it is often difficult or impossible to work in winter.

The design team was composed an architect-engineer team and about ten other experts. The architect and engineering team provided guidance, but ultimately the builder made the final design decisions. The team began by applying rules of thumb for passive solar design, including form (e.g., aspect ratio of about 1.2 to 1.3 and two storeys), window area, thermal mass location and quantity, and shading. The architect used these to establish a sketch design for presentation at a design charrette.

The design charrette consisted of a two-day intensive meeting that included all of the design team members. A decision was made that the house would combine three main technologies: 1) direct gain passive solar design coupled with a highly-insulated and airtight building envelope, 2) a BIPV/T system as the main active thermal-electric generation system, coupled with a floor integrated active charge/passive release thermal storage, and 3) a geothermal heat pump with vertically-drilled wells, connected to a forced air system as the main HVAC system of the house. The roof design changed significantly after the design charrette. Its slope was reduced from 45 to 30 degrees to allow it to be prefabricated and transported to the site and to ensure that the modules extended the entire length of the roof (eaves to peak) for better building integration. This decision is relatively inconsequential regarding theoretical electrical generation, but proved to result in some snow accumulation and a reduction in useful thermal energy collection, as explained later.

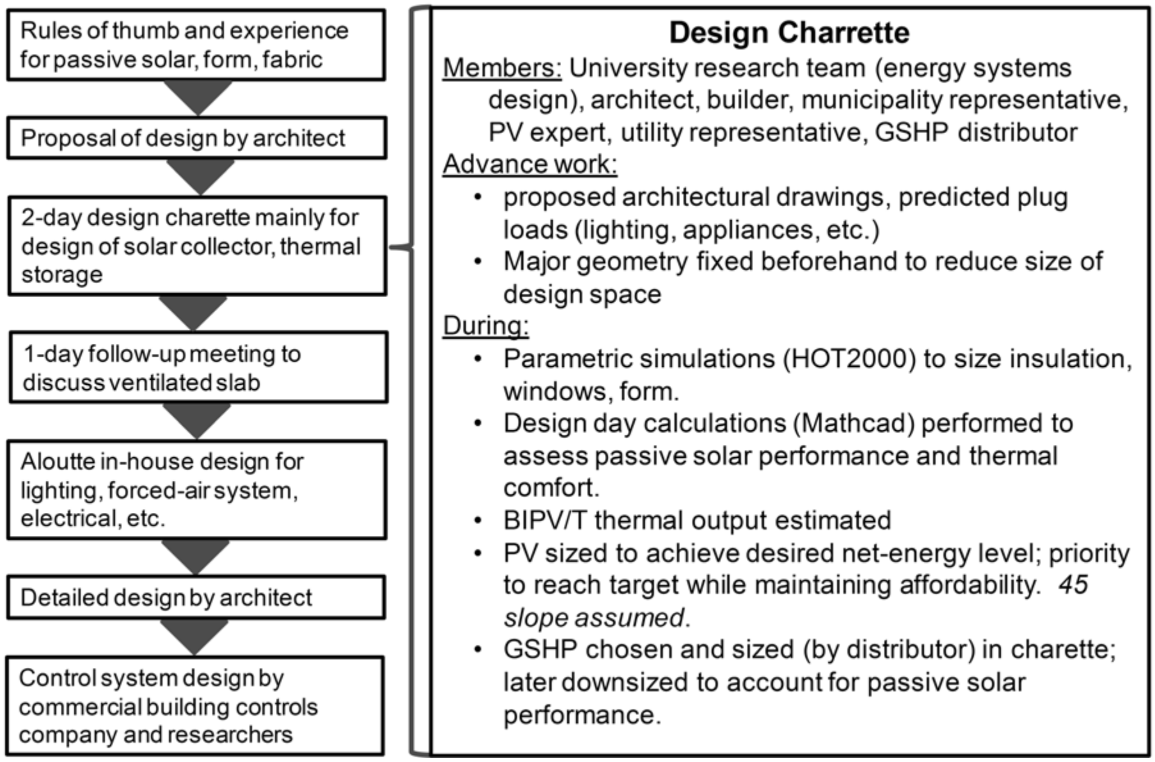


*Figure 3: Design process outline for ÉcoTerra*

## ENERGY CONSUMPTION

ÉcoTerra has been monitored since its construction. There are over 150 sensors installed throughout the house monitoring temperatures, energy consumption, solar radiation, etc. The data is collected automatically and stored in a central database from which it is queried for the various, ongoing analyses that are being performed on the house. The data set includes both occupied and unoccupied periods. For the purposes of this article, the occupied data was examined. Several months after occupancy began, there were significant changes made to the control system in the house so data before this point is not considered. There are twelve months of valid data available for analysis of the occupied house: from December 2009 until December 2010. Figure 4 shows a comparison between ÉcoTerra's annual energy consumption and that of various typical homes in Canada.

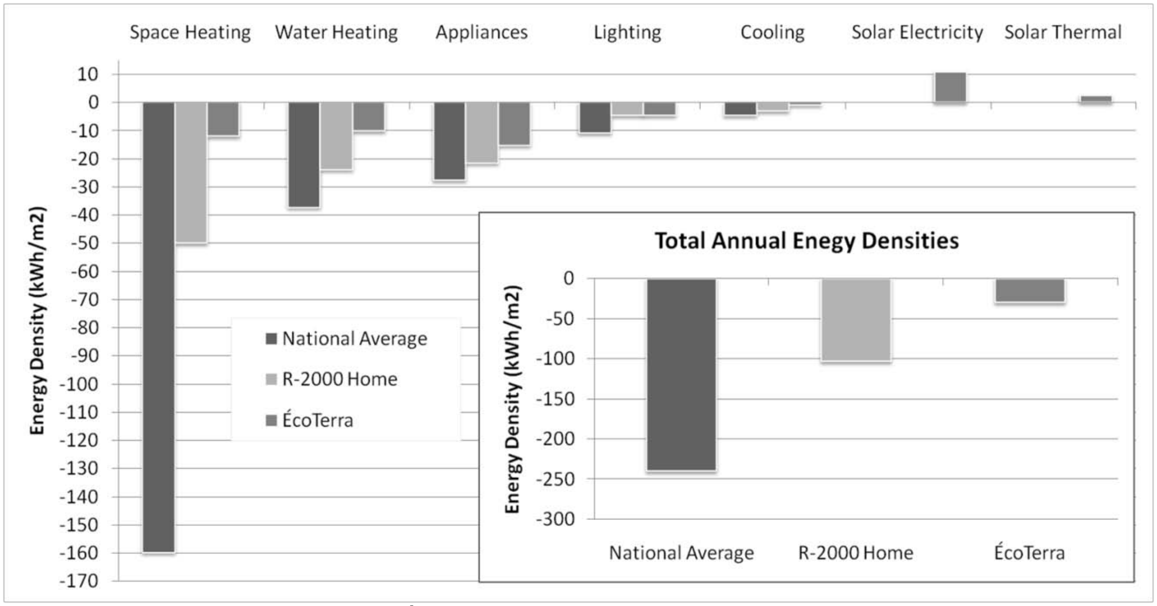


*Figure 4: Comparison of ÉcoTerra with typical homes R-2000 is a successful energy efficiency standard that was established in Canada the 1980s that required significant savings primarily through envelope improvements and air tightness.*

It should be noted that although ÉcoTerra did not reach net-zero energy consumption, it consumes only 12.4% of the energy of a typical Canadian home. In absolute terms, during the occupied year, the house had a gross consumption of 12,888 kWh (12,128 kWh without the garage heater) and 2,570 kWh of PV generation for a net electricity use of 10,318 kWh. The following sections examine a more detailed breakdown of energy use to better understand the house and to help determine potential improvements.

## ENERGY END-USE BREAKDOWN

The energy consumption of various equipment, such as the heat pump, heat recovery ventilator (HRV), domestic hot water tank and BIPV/T fan, are monitored directly. Some loads such as lighting and appliances are not individually monitored, but by subtracting other known, monitored loads, these too can be calculated. Some unexpected loads were discovered, such as the consumption of the owner-installed supplementary electric heater for the garage, and the consumption of the auxiliary electric heater in the heat pump. These loads were identified using a pattern matching search on the collected power data. The few auxiliary heater events were identified visually, but an algorithm was created to automatically find the garage heater events. This algorithm was created by inspecting the distinct energy consumption patterns observed for the garage heater and searching through the power data for this pattern. The breakdown resulting from this filtering offers a complete picture of the home's electricity use. Figure 5 shows the annual energy end-use breakdown that resulted from this analysis.

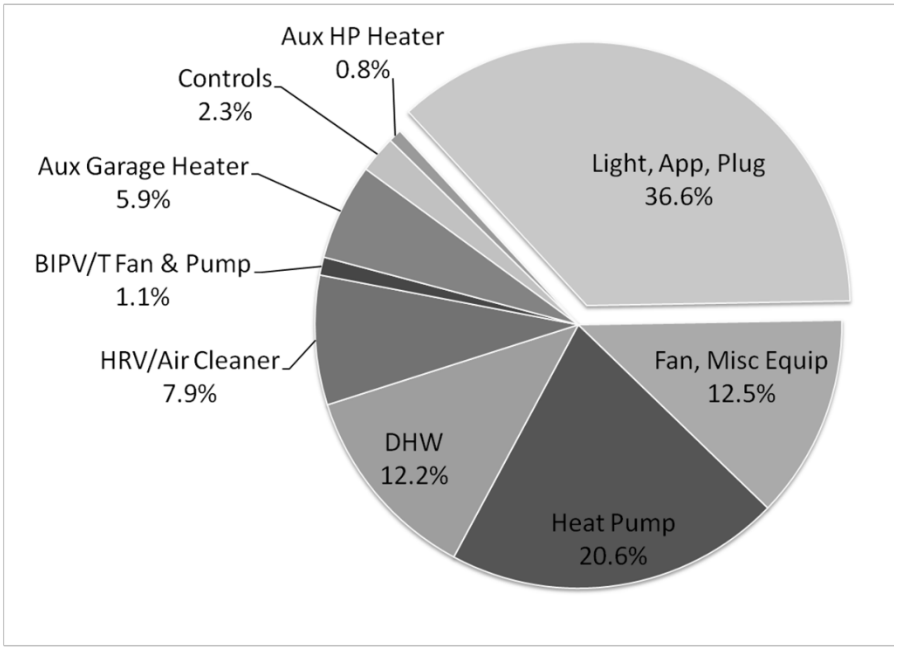


*Figure 5: ÉcoTerra's existing, annual electricity end-use breakdown.*

The auxiliary electric heater of the forced air system, the BIPV/T fan and pump, and the control system itself consume very little energy overall. The owner-installed auxiliary electric heater for the garage uses approximately 29% of the heating-related energy consumption and was deducted from the energy consumption. The heat pump energy includes both heating and cooling and accounts for about a fifth of the energy use in the house. Miscellaneous equipment, such as the well pump, the alarm system, and primarily the heat pump fan while in recirculation mode, account for about 12.5% of the energy consumption. It can also be seen that discretionary loads are the single largest component of the home's energy use. This is an important observation because it indicates that as building energy efficiency and design improve, the occupant-based loads increase in importance. The next section discusses this further.

## OCCUPANT FACTORS

Occupants' understanding of the concepts behind the energy systems of the house is critical to its performance. The occupants need to be trained to use the system differently than they would use a typical thermostat, and the control system interface needs to be designed to provide additional information and options. By having several meetings with the occupants, the house designers were able to both educate them and adapt the controls to optimize thermal comfort and energy performance.

Typical homes (and many commercial buildings a well) often have simple control systems which rely on the assumption that the room air temperature will be maintained at a constant level.. The control systems for a high mass, passive solar building needs to be designed to allow a certain amount of temperature fluctuation following the cyclical solar gains. In ÉcoTerra, there are several setpoint schedules for different times of day and occupancy modes. The principle is to allow the thermal mass of the house to cool in the evenings and overnight so that when the sun rises and begins heating the house, there is sufficient difference in temperature to allow energy to be stored in the slab instead of immediately heating the air in the house. The thermal mass moderates what could otherwise be a large swing in temperature due to passive solar gains by storing the direct solar gains. At night, the setpoint is lowered, again, creating a difference in temperature between the air and thermal mass. This allows the stored energy to be released, thus offsetting space heating requirements.

This benefit of lower setpoints at night matches the observed habits of the ÉcoTerra occupants, and home owners in general (NRCan 2010). The owners of ÉcoTerra appear to prefer cooler temperatures while they sleep and slightly warmer temperatures during the day. The owners had to adapt to the principle that the air temperature as it is displayed on the thermostats is not the only factor in determining if the space will be comfortable. They had to learn to trust that although the temperature may currently be slightly lower than “normal” room air temperature, the sun was rising and would soon boost the home’s air temperature. In a typical house, if the control system had tried to heat the house as soon as the air temperature dropped below the setpoint, the heating system may have heated the house up slightly sooner, but the house might then overheat as the sun rose. Furthermore, this instantaneous increase in the control setpoint can require more heat to be delivered than is capable of being provided by the heat pump; thus requiring heat from the auxiliary heater – a much less efficient heat source.

Another important occupant factor observed at ÉcoTerra was the significant contribution that occupant-based energy consumption has to the overall energy breakdown. As seen in the previous section, occupant-based loads account for 36.6% of the overall energy consumption in the house. Various studies have pointed to the importance of occupant behavior (e.g., Hoes et al. 2009). During the ongoing analysis of ÉcoTerra's energy consumption, a sudden and significant increase in energy use was observed. Upon investigation, it was discovered that the owners had installed a supplementary electric heater in the garage. The owners use the garage as a workshop, but the original design did not provide any heat for that space. Once alerted to the significant energy consumption of the garage heater, the owners quickly reduced its setpoint and so significantly reduced its energy consumption. The garage heater consumed a significant amount of energy – approximately 29% of the heating-related loads of the home.

Most homes do not have ÉcoTerra's level of ongoing energy monitoring and analysis. In a typical home, the garage heater would not have been discovered until the arrival of the significantly larger utility bill. Even then, a typical home-owner may not be able to track down the source of the increased energy use. Furthermore, the additional annual cost of electricity is estimated to be CAD $48 (USD $50) – an amount that may not concern homeowners who are accustomed to conventional houses with large energy bills. This demonstrates the need for energy use feedback. There is an existing touch-screen LCD interface at ÉcoTerra which is already used to provide information about the current state of the home's systems such as heating and cooling status. This interface could easily provide alerts when abnormal energy consumption patterns were detected. Several commercial systems already exist which provide information such as dollars per day or cents per minute energy consumption. These systems are valuable, but should be fully integrated into the house in order to allow more detailed information about the source or reason behind any sudden increases in energy consumption. Such energy-use feedback systems have been shown to lead to savings of up to 10% (Chetty et al. 2008), assuming that the occupants are motivated to make the necessary modifications to their behavior.

The solar-assisted clothes dryer helps demonstrate another occupant factor. The owners report that they have adjusted their habits to try to dry clothes only on sunny days, which allows the BIPV/T system to offset the energy consumed by the electric heating element in the dryer. The house informs the owners when there is appropriate sun for assisted drying, but the dryer can also operate as a conventional clothes dryer. No input is required from the owner to enable the house to use the BIPV/T air, but they may choose the air-only mode on the dryer to further reduce its energy consumption, with drying time being the trade-off. Preliminary testing has been done on the dryer system and it has been shown to function. Additional research is needed to judge its effectiveness and to optimize it.

## LESSONS FROM NON-RESIDENTIAL BUILDINGS

Prefabricated homes have a reputation for high quality due to their controlled manufacturing conditions. This is true of ÉcoTerra as well. Something that is clear from various previous studies is that high performance, low-energy buildings must also be well-constructed buildings (Torcellini et al. 2006). Furthermore, it is becoming clear that the attention to detail is critical to low-energy and net-zero energy houses. As building envelopes improve, the considerations of occupant behavior and the embodied energy of construction materials become more significant. As with other high performance buildings, industry best-practices and building codes for houses are continually advancing. One source of inspiration for potential improvements is the commercial building industry.

The manner in which duct systems are designed and constructed is a good example. An engineer or HVAC expert typically designs the duct system, selects the fans, and oversees its construction in the case of commercial buildings. In the residential sector, an engineer is not usually necessary, but with the HVAC systems in high-performance houses, small deviations from the design can have a significant impact on the performance of the system. This can be seen in the high static pressure loss in the ductwork at ÉcoTerra. There are approximately a dozen 90 degree bends and ten dampers in 27 m (87 ft) of duct. Figure 6 shows a pressure loss diagram for the duct system from the entrance of the roof to the exit after the ventilated slab. The overall static pressure varies depending on the given damper configuration. The estimated worst case static pressure losses in the system were found to be approximately 331.6 Pa (1.33 in. water).

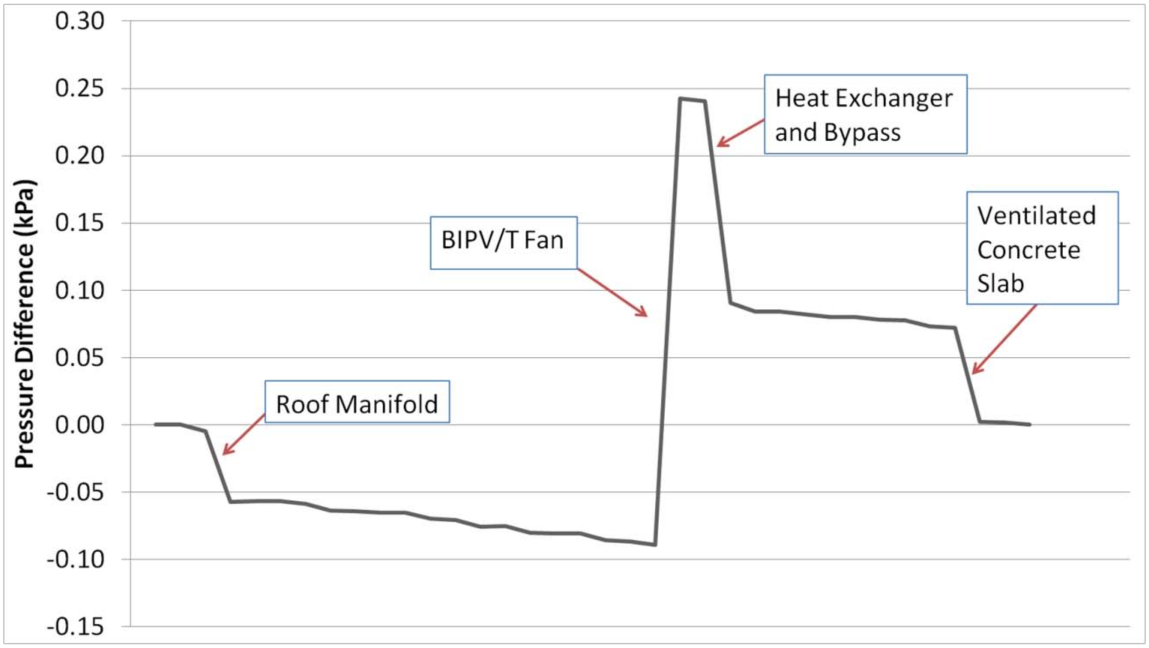


*Figure 6: Pressure losses in the duct system for the1 estimated worst-case*

It is estimated that if features such as standard duct transitions and turning vanes had been included, the pressure losses would have been reduced to approximately 287.8 Pa (1.16 in. Water). If a complete redesign was performed on the duct system and the amount ductwork was reduced in key areas, the pressure losses would be further reduced to approximately 278.7 Pa (1.12 in. Water). Overall, this would be a reduction of 52.9 Pa (0.21 in Water). This would reduce fan energy consumption, fan noise and would possibly have lead to the selection of a different fan during the design process. However, such improvements are best implemented early in design; thus reinforcing the concept of integrated design, in which an engineer or technician was involved from the beginning of design.

Other practices that can further improve the residential sector include full air sealing of all ducts and duct joints and vibration isolation for equipment like fans and pumps. The BIPV/T fan, for example is screwed directly to the floor joist which causes its vibration to be transmitted to the living space under some conditions.

## OCCUPANT COMFORT

It is apparent, from working with the owners of ÉcoTerra, that for occupants, comfort is a priority over energy use. This is understandable and is an important factor to be considered during the design of such a house. Even if this issue is considered carefully by the designers, the occupants ultimately have a significant impact on their own comfort. The placement of floor rugs, the operation of windows and blinds, and the changing of setpoints all affect the comfort of the occupants, yet cannot be predicted easily.

The addition of the garage heater is another issue which may have been predicted if the home was being built for a specific owner. However, ÉcoTerra was not built with anyone in particular in mind. When the new owners began using the garage as a workshop, they found it too cold and installed the heater. Another addition is approximately 24 luminaires. Although daylighting was part of the original design, the owners felt certain areas were too dark and so added some fixtures. The house was designed by minimizing non-south facing windows, as recommended for passive solar design. However, this resulted in a lack of daylight in parts of the north side of the house.

Occupants can act to improve their own comfort, but must be educated and provided with the appropriate information about their home. Occupants should be encouraged to open windows and control blinds at appropriate times, for example.

The owners mentioned that they found the air in the house dry during the previous winter. This may be related to the control of the heat recovery ventilator. By reducing its operating time during unoccupied periods, the air may be less dry and the energy consumption of the HRV will also be reduced. The use of an energy recovery ventilator (ERV), in which latent energy is also recovered would help this problem.

The following figures (7 through 9) show some indoor temperature profiles for different times of the year. Figure 7 shows some overheating due to unseasonably high temperatures. It can be seen that there is a three hour delay between the peak outdoor temperature and the peak indoor temperature – this is due to the significant thermal mass in the house. Figure 8 shows that, in the shoulder seasons, minimal heat is needed for most of a sunny day. Only a small amount of heat was required on March 7th. Even on a cold day, the heating load is significantly reduced by passive solar gains, as shown in Figure 9. For instance, on December 18, no heating was required during daylight hours.

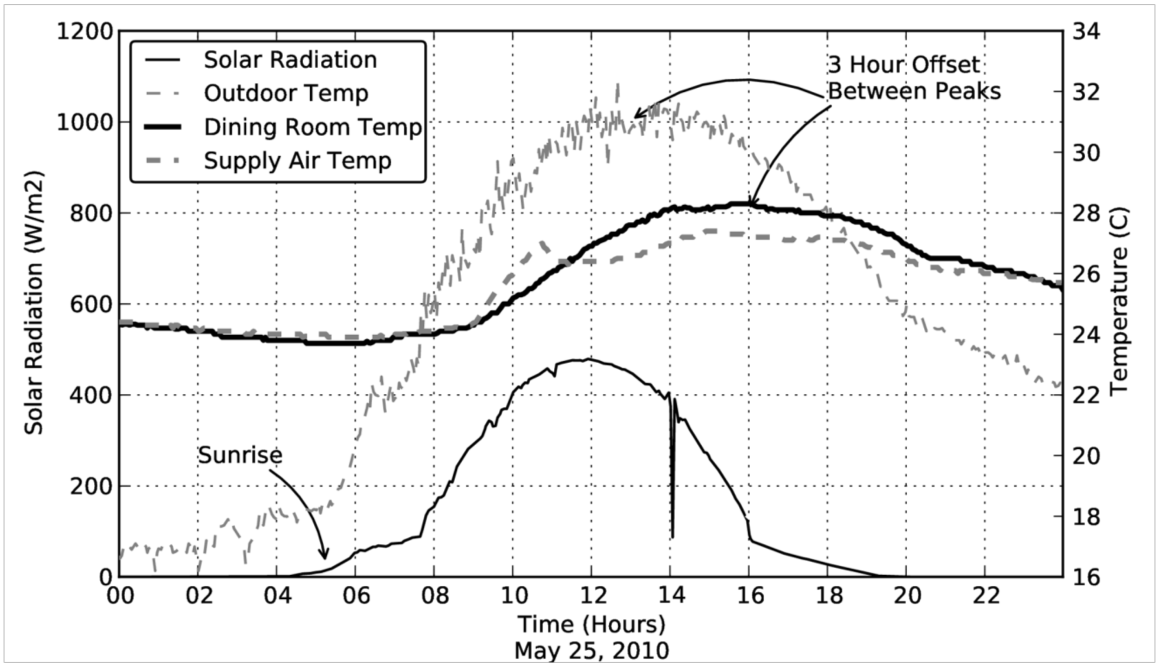


*Figure 7: Solar radiation and indoor temperature – May 25, 2010*

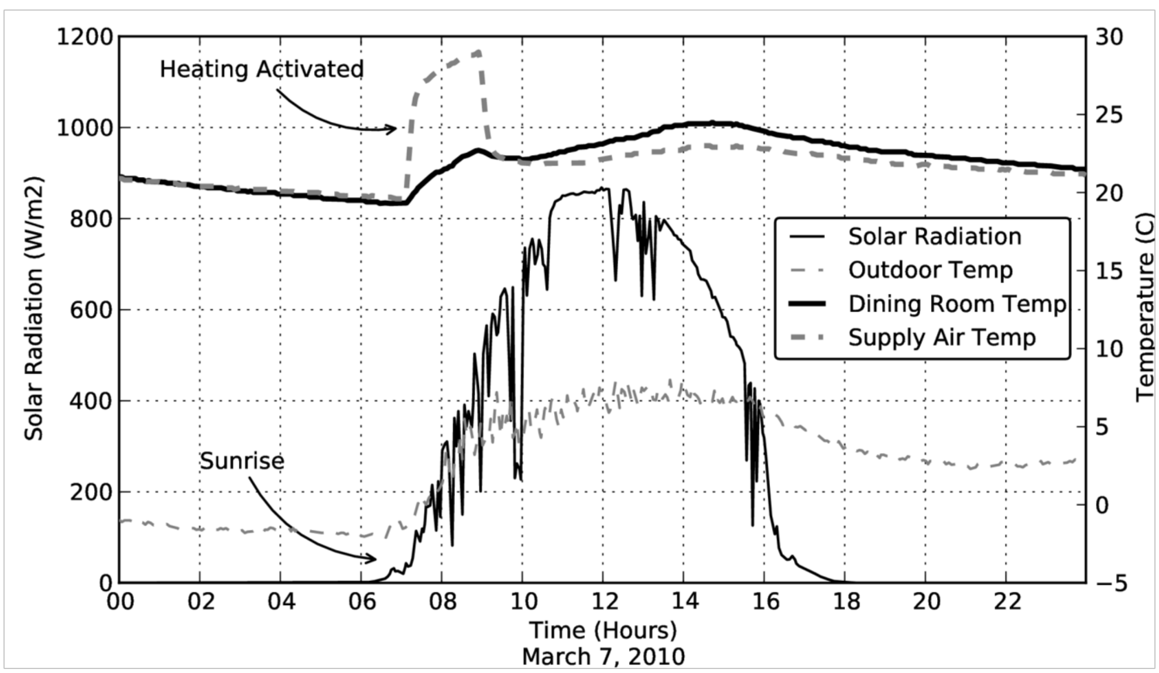


*Figure 8: Solar radiation and indoor temperature – March 7, 2010*

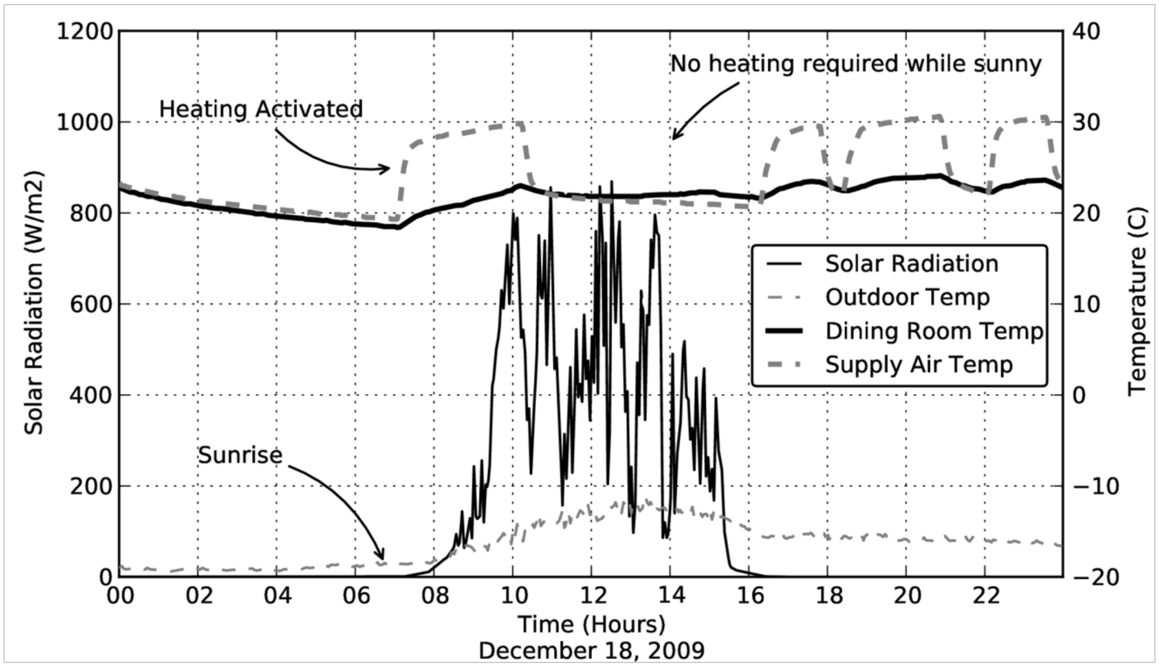


*Figure 9: Solar radiation and indoor temperature - December 18, 2009*

## POTENTIAL IMPROVEMENTS TO ACHIEVE NET-ZERO ENERGY PERFORMANCE

As a re-design exercise, the potential to reduce ÉcoTerra's net energy consumption to zero is considered. Many lessons have been learned throughout the design and construction process and so several improvements could be made to further reduce ÉcoTerra's energy consumption. This process was begun by considering the changes which could be implemented in the easiest and least expensive ways. Operational changes were therefore considered first, followed by changes to the building envelope and finally changes related to generation.

Some of the following improvements were analyzed using a model of ÉcoTerra created in EnergyPlus (US DOE 2009). This tool was chosen for its relative ease of use, extensive features, and interoperability with a variety of other tools. The geometry for the model was derived from the architectural drawings and manually input using SketchUp/OpenStudio (US DOE 2009). The house was modeled as four conditioned zones, in an attempt to properly characterize any discomfort resulting from stratification. In addition, a zone was assigned to each of the roof space and to the garage. A survey of energy-consuming household objects was performed to determine an appropriate internal heat gains schedule. Appliance, lighting, and air distribution loads were assumed to be seasonally-invariant. The infiltration rate was input based on the measured value for the house using a blower door test.

The first operational improvement examined was to change the controls of the heat pump distribution fan. The fan is currently operated in a low-speed, recirculation mode whenever there is no heating or cooling requirement. Simulations were run to determine the potential benefit from reducing the fan run time (when heating and cooling are unneeded) to only operate when the mean air temperature difference between zones exceeds 2°C (3.6 F). This resulted in annual savings of 722 kWh.

Additional savings (442 kWh/year) can be achieved by removing the air cleaner, which can be considered redundant to the air filter built-into the heat recovery ventilator (HRV). The HRV could also be run less during unoccupied periods. A conservative reduction of 10% (53.5 kWh) is assumed for this option.

The addition of intelligent shade control – either manual or automated – was considered. For the cooling season, shades were assumed to be closed during periods when the zone air temperature exceeds 20°C (68°F) during the period from May 1 to September 30. This is predicted to reduce cooling loads by about two-thirds, resulting in 80 kWh of electricity savings. Proper shade control also improves thermal comfort by mitigating overheating and direct beam solar radiation on occupants. However, it must be balanced with the occupants' desire for views to the outside; closed shades are most suitable for unoccupied periods.

The owners have been made aware of the energy consumption of the garage heater, so it is expected that during future winters, its energy consumption will be reduced. The auxiliary heater in the heat pump itself is also expected to operate less due to adjustments in the control sequence which prevents it from being activated unless there is need for emergency heating.

The charging of the domestic hot water preheat tank is also expected to be more effective in upcoming years since a misconfiguration of the system's valves was discovered and corrected.

Air sealing is often a cost-effective method to reduce energy consumption, however, the house is relatively airtight, and so there was little benefit to further sealing the envelope.

As discussed in the "Occupant Factors" section, the discretionary loads are the single largest part of the home's energy consumption. If the occupants are provided with comprehensive/useful feedback on their energy use, it is reasonable that the discretionary loads such as lighting and appliances could be reduced by approximately 10% (Chetty et al. 2008). While energy efficient models for most major appliances (fridge, dishwasher, etc.) were installed in the house, some savings potential could be achieved by replacing the halogen lamps with CFL lamps. Also, lighting energy consumption could be reduced by using occupancy sensors. The appliance loads would also be slightly less due to a change in the control sequence for the solar-assisted dryer which should make it more effective. It would be particularly useful if the electrical loads of the house were further disaggregated (e.g., lighting by room, each major kitchen appliance). This would allow the homeowners to make direct connections between their actions and the associated electricity cost.

If these improvements are implemented, the annual energy consumption of ÉcoTerra is expected to be as low as 7,837 kWh (a 24% reduction). The potential energy end-use breakdown is seen in Figure 10.

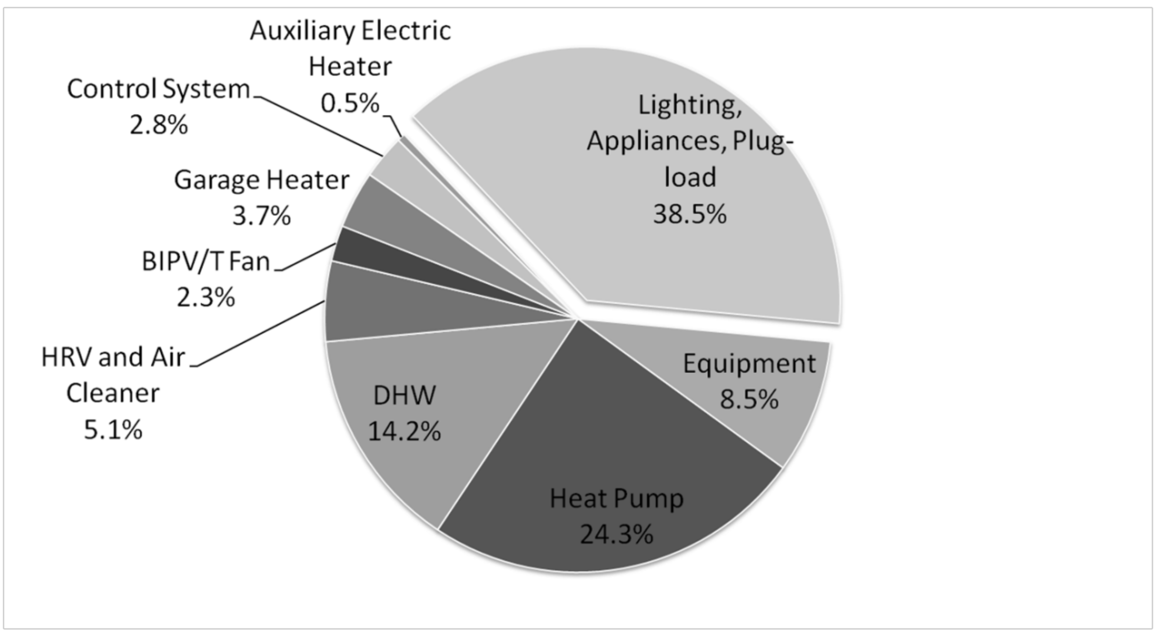


*Figure 10: Potential energy end-use breakdown after potential improvements.*

## LESSONS FOR DESIGN OF FUTURE NET-ZERO HOMES

Other potential improvements for ÉcoTerra would have best been implemented during construction were considered. The purpose of these is primarily to help future designers improve on the already successfully design of ÉcoTerra.

The insulation values on the basement and above-grade walls were judged to be the most cost effective levels at the time of construction. In the future, however, as energy costs rise additional insulation will make sense. The addition of RSI 1 (R5.76) of insulation on the basement and above-grade walls of the house yields an annual reduction in electricity use of about 483 kWh.

The net energy balance for the windows including solar gains is positive - about 1,000 kWh, but they still account for 21% of total losses. The windows include dividers of significant size between each window. The possibility of using windows without dividers was examined. Currently, most of the large south-facing windows are operable and have two dividers in them. This not only increases the conductance of the envelope, it also reduces solar gains. The removal of two-thirds of these (leaving enough operable windows to enable natural ventilation) reduces predicted heating loads by about 20%. The upgrade to better window frames and doors only yields a modest reduction in heating loads and thus they need not be changed.

An issue that should be considered, when dealing with active solar energy collection, is snow accumulation on the roof and its negative impact on wintertime generation. Thus, the effect of increasing the BIPV/T roof slope from the existing 30° to 45° was examined. From experience, slopes of 45° and higher have been found to effectively shed snow, provided that the roof is smooth and that eaves troughs are not used (Athienitis 2007). RETScreen (NRCan 2005) indicates that this increase in slope has a negligible effect on annual incident solar radiation, since both slopes are in the near-optimal range for site's latitude – 45°29' N. Assuming that the base of the south-facing roof remains the same, the additional pitch results in an increase in total roof surface area to 65.6 $m^2$. This new slope and area would result in approximately 22% more PV generation.

The impact on the thermal performance of the BIPV/T roof from increasing the slope is positive. The change causes the roof to be better oriented for the winter when the solar altitude is low and when thermal energy demands are greater. The roof was modeled for both the current 30° slope and the 45° configurations and the thermal output was compared to the space heating and DHW loads on a monthly basis. To simplify the analysis, the thermal energy was only considered useful if the outlet air temperature exceeded 20°C because the air temperature must exceed the basement slab temperature to enable heat transfer. The model used is described by Chen et al. (2010). The results in Figure 11 indicate that the useful thermal output of the BIPV/T roof is nearly doubled for the heating season, while it remains relatively unchanged in the summer. For example, increasing the slope of the roof increases the fraction of loads met by its thermal output for March and November by 60 and 90%, respectively. In addition to increasing the slope, the addition of a solar-assisted heat pump should be considered, as was done for the Alstonvale House (Pogharian 2008), since it would significantly decrease the outlet temperature threshold above which the energy is useful.

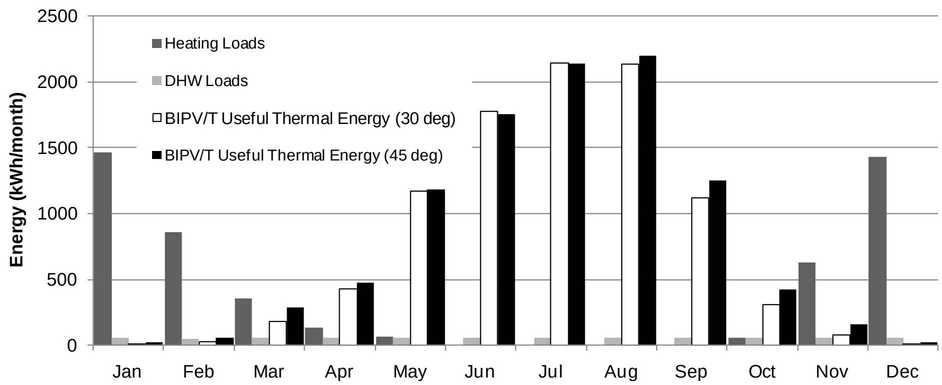


*Figure 11: Comparison of thermal output of BIPV/T roof.*

## REACHING NET-ZERO

Once the previously mentioned upgrades are taken into account, there are few remaining good opportunities to reduce consumption. In order to achieve the desired net-zero energy status, the rest of the gap should be filled on the supply side.

A minimum module efficiency of 10.3% is required to achieve net-zero energy. This takes into account the previously mentioned upgrades and the estimated, potential annual electricity use of 7,837 kWh. This also assumes an inverter efficiency of 95%, shading losses of 8%, and a 90% module coverage area (for spaces and edges). This level of efficiency is above the range of common amorphous silicon modules (5-7%), so poly-silicon or other higher performance modules (such as polycrystalline silicon) are needed. The total capacity of the array must be increased from 2,800 W to at least 6,900 W (a 245% increase).

## DEMAND REDUCTION

Saving energy is important, but reducing the net demand on the grid is also worth examining. Demand, in this case, is defined from the point of view of the electrical utility as the total power consumption (i.e., net power) of the house at any given moment. Due to ÉcoTerra's PV array, the house has the capability of offsetting its drain on the grid by either reducing its draw or actually contributing to the grid's available power generation.

ÉcoTerra's PV array produces power during sunny periods, so its demand is usually less than that of a typical house during these times (by the amount of power being generated at a given moment). This can be seen clearly in Figure 12, where there is an obvious decrease in net power consumption over the sunny part of the day. An important observation to be made from the graph is that although the instantaneous demand is reduced by the photovoltaic generation, the demand peaks occur before sunrise and after sunset when solar radiation and PV generation are negligible. This corresponds to the morning routine before work and the evening preparation of meals. The heat pump also runs more during the times of day when there are reduced solar gains, specifically in the morning after cold nights. Winter and summer cases were also examined and show similar patterns, but with the winter having significantly reduced generation and increased heating energy consumption.

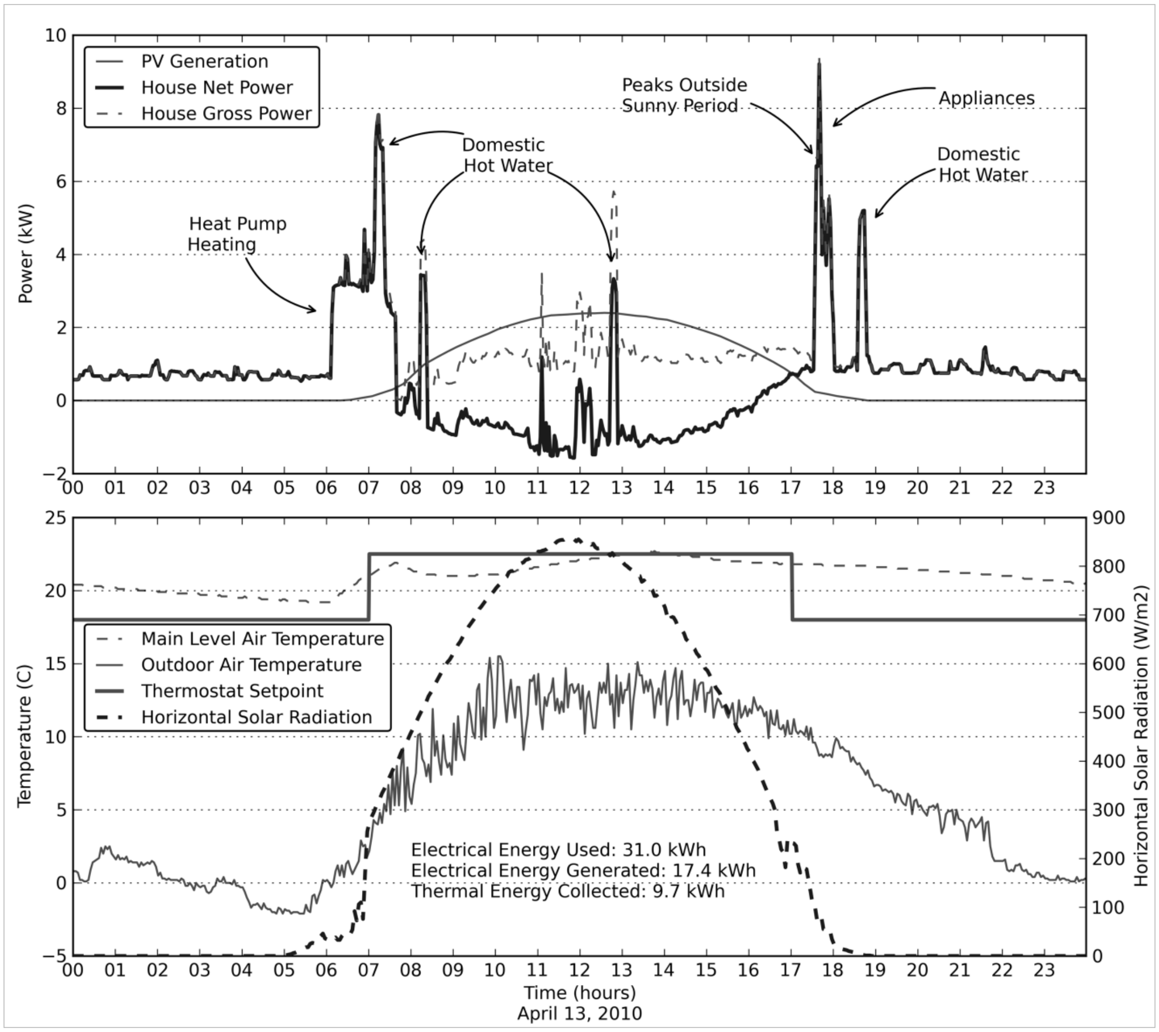


*Figure 12: Sample electricity demand and generation profiles (April 13, 2010) (top) and weather conditions and indoor conditions (bottom).*

## CONCLUSIONS

ÉcoTerra is a demonstration of active and passive solar building-integrated technologies combined with a well-insulated envelope and a geothermal system. The design of the house and its energy performance are presented in this paper. Its energy consumption was shown to be only 12.4% of that of a typical Canadian home. It was shown that occupants affect the loads significantly and need to be educated and given appropriate feedback in order to help them adjust their behavior.

Although already far below the typical home in energy consumption, the paper showed how ÉcoTerra can achieve even lower energy consumption and how similar houses can achieve net-zero energy balance over a year. Improvements examined include changing the controls for the heat pump distribution fan, the HRV, the garage heater and the auxiliary heater. Other improvements include removal of the air-cleaner, the addition of intelligent shade control and correcting of a configuration problem with the domestic hot water valve. Also considered was the improvement of energy use feedback to the occupants. More significant changes were also examined such as adding insulation, redesigning the windows to have fewer dividers and increasing of the roof slope.

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## LIST OF FIGURES