A Study of Design Tools and Processes Through a Near Net-Zero Energy House Redesign

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Abstract

The EcoTerra House is an occupied near net-zero energy house near Montreal, Canada. The house uses a combination of passive solar features, low-energy appliances, and several innovative active solar energy systems to achieve much lower net energy consumption than similarly sized houses in Canada. It is heavily instrumented with over 150 sensors so that its performance can be carefully monitored, as has been done since construction, three years ago. This paper describes the original design process of the house, followed by a re-design exercise that was performed to achieve net-zero energy while evaluating design tools. It contains a description of a calibrated model, an evaluation of the suitability of currently-available design tools for net-zero energy house design, and finally a study of different design pathways for reaching net-zero energy consumption.

1 Introduction

The EcoTerra House was one of 15 demonstration houses selected to be built through a national competition conducted under the Canada Mortgage and Housing Corporation (CMHC) EQuilibrium Healthy Housing Initiative [1]. The house was prefabricated in a factory in seven modules and assembled on site in 2007. Its form and fabric were selected for optimal passive solar performance. To supplement heating and cooling in Quebec's heating-load driven climate, a building-integrated photovoltaic with thermal recovery (BIPV/T) system was built. The upper south-facing roof section consists of 21 laminate amorphous-silicon (A-Si) modules with an airspace underneath, through which air is drawn and warmed from the absorbed solar radiation. The energy content of this air is used to warm (or cool) a ventilated slab in the basement, preheat domestic hot water, or dry clothes, depending on the current demands. A ground-source heat pump with a COP of about 3.7 is used to supplement the passive and active solar heating. A photograph of the house and timeline of major events are shown in Figure 1.

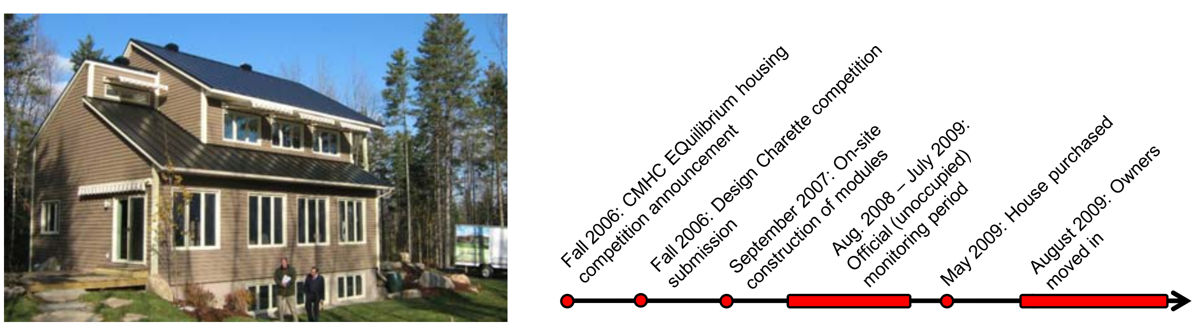

Figure 1: a) EcoTerra House; b) timeline of significant events

2 The Design Process

This section provides a brief summary of the design process that was applied to the EcoTerra house three years ago.

2.1 Design Objectives

The objectives of the house 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 [1]. An additional goal of the design team was to emphasize building integration of solar technologies and thermal storage. Furthermore, the designers aimed to make the house affordable, with a minimal additional cost compared to similarly-sized Canadian houses. Since the house is manufactured, there is an opportunity for mass-producing the house, thereby facilitating adoption of net-zero energy home design concepts and systems. One of the purposes of this paper is to identify potential improvements to the design and disseminate this information to homebuilders.

2.2 Design team and design process

The design team was composed of a team of about ten exports and lead by an architect-engineer team. The complete list of members and a summary of the design process are shown in Figure 2. The design process started with Athienitis proposing some 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 the 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 systems 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. It is interesting to note that 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 extend the entire length of the roof for better building integration - a decision that is relatively inconsequential to theoretical electrical generation, but proved to result in some snow accumulation and reduced useful thermal energy collection. The builder ultimately made the final design decisions.

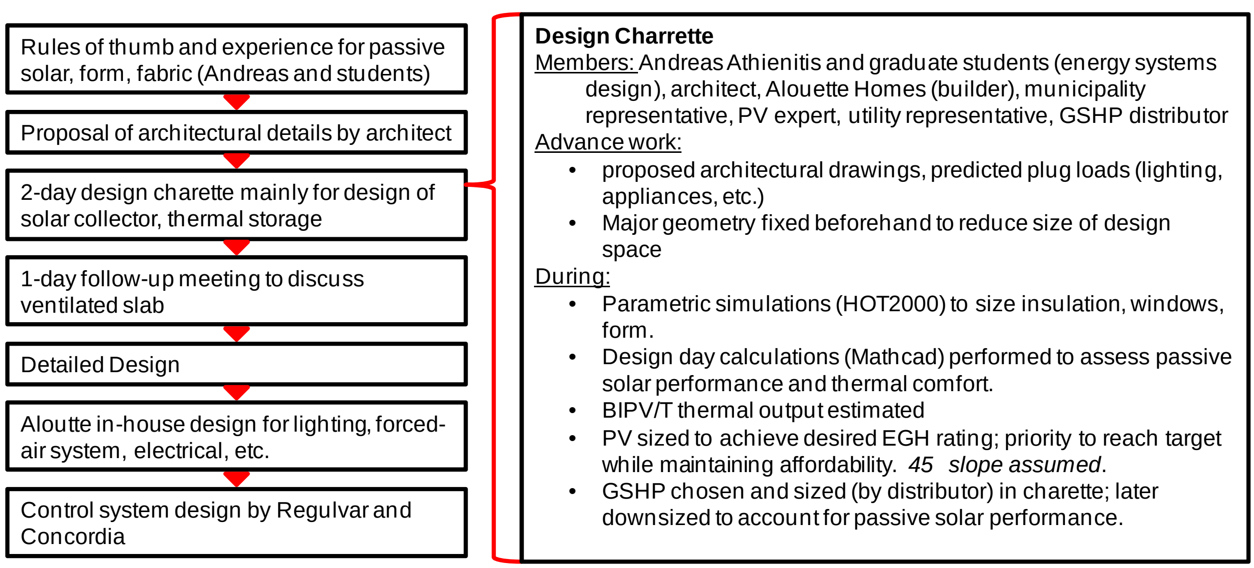

Figure 2: Design process outline

2.3 Use of design and analysis tools

The competition required the use of HOT2000 [2] and RETScreen [3] for predicting performance, as a minimum. The former was used to determine the household energy consumption, while the latter was used to determine the predicted output of renewable energy systems (PV in this case).

HOT2000 uses a bin method and is intended to assess the performance and possible retrofits of detached houses. Its features are aimed at Canadian homes and the associated construction practices (e.g. wood frame) and technologies (e.g., HVAC systems). HOT2000's calculation method makes it less suitable for assessing dynamic behaviour – something that is fundamental for passive solar performance assessment. Also, its lowest reporting frequency for output is monthly, meaning that hourly comfort metrics, which are key to passive solar design, are unavailable. To supplement this, the design team used customized software [4, 5]. The program uses a finite difference method for spatial and temporal discretization, so that short timesteps could be used and the benefit of thermal mass could be properly assessed. Rather than performing whole-year simulations, the emphasis was on characterizing performance for a cold sunny day, which is typical of Montreal's winters. Regardless, HOT2000 was useful in estimating annual performance – an essential element of predicting the net energy consumption (or production) of the house in a standardized way. It should be noted that the next generation of HOT2000 – HOT3000 – uses dynamic simulations by means of a finite difference method, which will improve characterization of passive solar performance [6].

RETScreen [3] is a spreadsheet-based tool for assessing the energy performance and economic feasibility of many building upgrades and renewable energy projects. Its role in the design of EcoTerra was to predict the performance of the PV element of the proposed BIPV/T roof. The tool's simplicity allowed the effect of many design options (such as slope, orientation, and technology) to be explored very quickly. However, the model is steady-state and only intended for stand-alone (non building-integrated) PV installations. This means that the effect of heat transfer to the roof is neglected. Furthermore, thermal coupling with the thermal energy collection aspect of the roof was not possible. Finally, the RETScreen model does not consider snow accumulation in its model, a factor that proved to be significant [7].

To assess the combined performance of the thermal and electrical aspects of the BIPV/T roof, a custom program was built, similar to the one for assessing the house's passive solar performance [4]. The model is described in detail in Chen et al [4]. The results of this analysis were used to make design changes and ultimately to predict the net-energy consumption of the house.

2.4 Assessment of the design process

Upon interviewing several design team members, several notable conclusions were drawn. They stated that the main (two-day) design charrette was very effective, that the collaboration between the large group of experts exceeded expectations, and that the work that was completed in advance was essential to a productive group design session. However, improved communication between the designers and builder teams regarding some of the more innovative aspects of the house, such as the ductwork linking the BIPV/T roof to the sites of demand was desirable. Also, the use of design tools was somewhat fragmented, since at least four separate models were used. It would have been preferable to use a single tool, so that proper thermal couplings between house components could be assessed [8], but such a tool that is available for the early design stage is not currently available. This is difficult when new technologies, such as the BIPV/T roof linked to a ventilated slab, are being modelled.

3 Measured and modelled performance

EnergyPlus [9], selected for its relative ease of use, extensive features, and interoperability with a variety of other tools. To build the model, the geometry was derived from the architectural drawings and manually input using SketchUp/OpenStudio [9]. The house was modelled as four conditioned zones, in an attempt to properly characterize any discomfort resulting from stratification, as shown in Figure 3b. 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 heat gains schedule. Appliance, lighting, and air distribution loads were assumed to be seasonally-invariant. Thus, the five months' measured data was projected to annual values. The infiltration rate was input based on the measured for the house using a blower door test. Details are specified in Figure 3a.

Walls	5.90 m^2K/W
Cathedral Ceiling	7.83 m^2K/W
Other Ceiling	8.35 m^2K/W
Basement Walls	4.01 m^2K/W
Basement Slab	1.72 m^2K/W
Door	0.40 m^2K/W
Frame and Dividers	0.36 m^2K/W
Triple Glazing	0.85 m^2K/W; SHGC = 0.53
Double Glazing	0.44 m^2K/W; SHGC = 0.76
Infiltration Rate	0.043 ach (0.85 @ 50Pa); 8 ach in roof
Ventilation Rate	0.3 ach
HRV Effectiveness	60 %

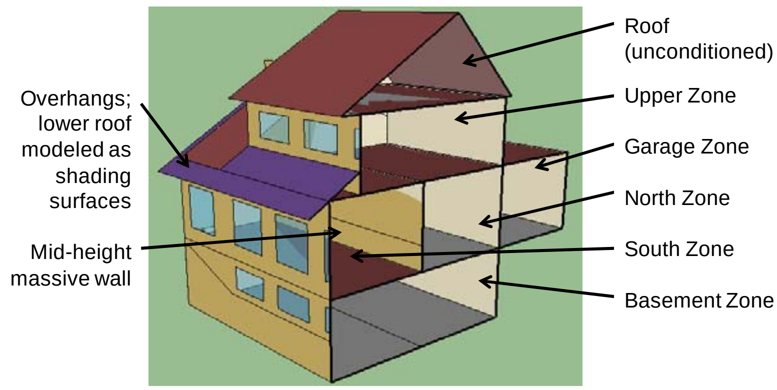

Figure 3: a) Select model inputs; b) section view of thermal model with zoning scheme.

Figure 4a shows the heating energy consumption from the simulation. For it, monthly heating loads were converted to electricity consumption using a COP of 3.7 (as measured to be typical for the heat pump). The first five months of the current year were occupied and monitored. Results indicate that the thermal model is accurate and suitable for assessing the building upgrades that are described in the sections that follow. Figure 4b shows that the PV array underperforms compared to the model. During the winter months, the main cause of this difference is snow accumulation on the roof. Close examination of the data suggests that snow and shading lower annual performance by 14% and 8%, respectively.

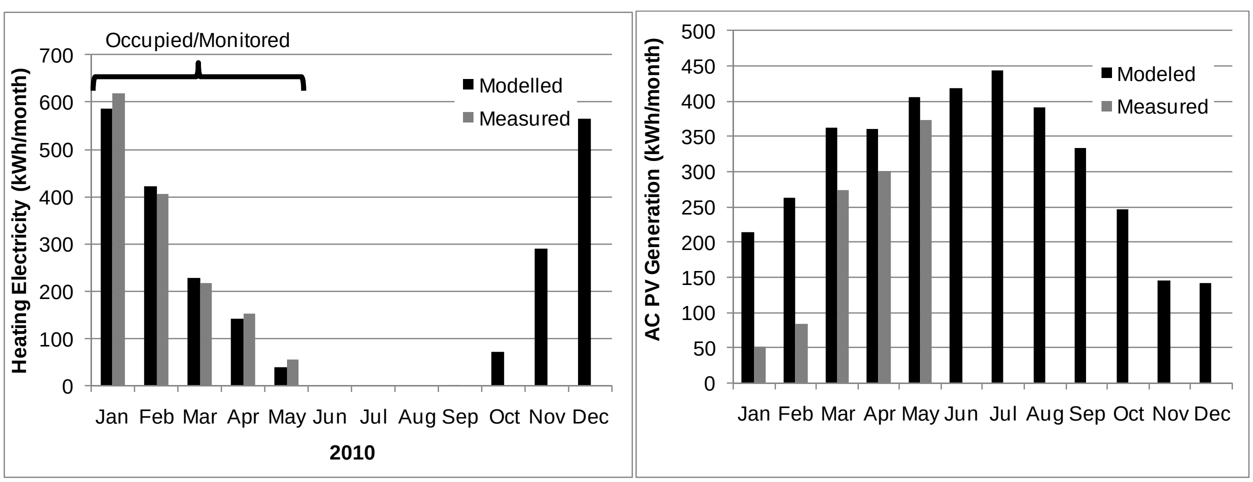

Figure 4: Comparison between the model and measured performance for: a) heating energy consumption and b) PV electricity generation

4 Redesign Study

This section outlines the re-design study that was performed. The fundamental question being asked is: How could the EcoTerra house and other similar low-energy houses have been designed better to achieve net-zero energy status? The calibrated EnergyPlus model was used to assess each upgrade for energy performance and thermal comfort.

4.1 Redesign Strategy Overview

In order to establish the most promising building upgrades, the major energy consumers and producers were examined (Figure 5). Heating and cooling electricity for unmonitored months were obtained from the model. Other electricity uses (which were found to be relatively seasonally-invariant from the measured data) were linearly projected from the monitored period to a whole year. It should be noted that the reason for annualizing all of the performance data is to assess the house's ability to achieve net-zero energy according to the "net-zero site energy" definition [10]. This definition requires that a building's annual energy exports match or exceed imports. In the present case, the house only exports or imports electricity.

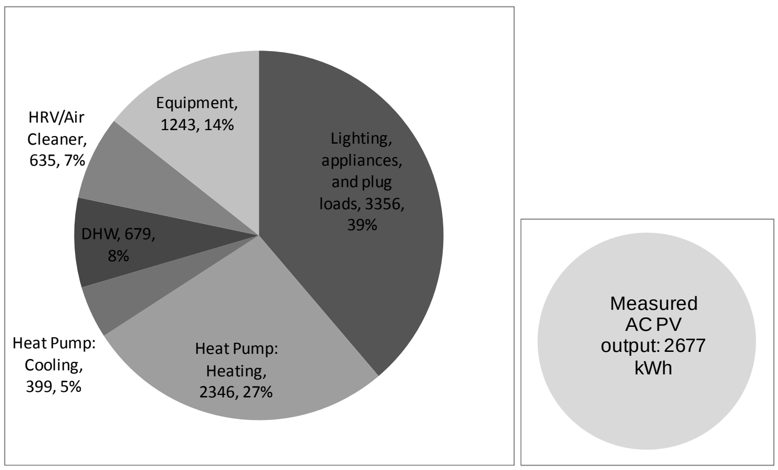

Figure 5: a) projected annual electricity loads by use. b) measured PV electricity generation. Areas are proportional to energy values, which are all in kWh.

There are three major categories of possible upgrades:

1. Operational changes: existing hardware with changes to control strategies such as setpoints and logic for controls related to solar heat collection and usage/storage;
2. Building envelope changes: either passive or active envelope components to change how the house interacts with the environment; and,
3. Generation: active systems to offset energy use.

For re-design, the operational changes will be considered first because they are non-invasive and have no material costs. The second two options – envelope upgrades and generation – will be considered simultaneously. While envelope improvements are often considered the most cost-effective, they provide diminishing returns unlike PV, for which additional costs increase approximately linearly with output, and for which there are some economies of scale (for auxiliary equipment such as inverters in wiring).

A fourth category of upgrades could be considered a modification to occupant behaviour. Nearly 40% of the electrical loads are related to appliances, lighting, and plug loads. Furthermore, some of the heating and cooling can be attributed to the fact that the occupants have the set points at values other than anticipated during design. For instance, the daytime heating setpoint is 22.5°C instead of 21°C, resulting in a predicted 10% increase in heating loads, according to the model. However, these social aspects are considered beyond the scope of the current research. Making assumptions that could lead to sacrifices in comfort and convenience would undermine the occupants' values. While the designer cannot predict discretionary energy use to a high degree of certainty, they can inform the occupants about their habits; either informally or through the installation of an "energy dashboard" that provides useful feedback. For example, the authors visited the occupants at their home after several months of occupancy to show a breakdown of energy use. Upon informing the occupants that the electric resistance heater in the garage was using nearly as much energy as the heat pump, they reduced its use to negligible levels. Chetty et al [11] state that through real-time feedback of household energy consumption, 10% savings with minimal change in behaviour is achievable. Further grid-side benefits can be achieved through shifting non time-sensitive loads, such as clothes and dish washing.

Many of the house's upgrades described in the next section are made possible because EnergyPlus is a detailed tool that has a powerful output facility in which many low-level outputs (e.g. nodal temperatures and heat fluxes) are available on the timestep level. Many earlier stage design/simulation tools, such as HOT2000, use standard configurations. The input of the EnergyPlus model took about five days, which is an order of magnitude longer than for the HOT2000 inputs.

4.2 Upgrades

As mentioned, any major savings that can be achieved through changing the controls of the house were explored first. The "equipment" category, shown in Figure 5, is mainly comprised of the distribution fan built into the heat pump. The fan is currently operated at a constant rate, even when fresh air and conditioning requirements are met. Simulations were run to determine the potential benefit from reducing the fan (when heating and cooling are unneeded) to only operate when the mean air temperature difference between zones exceeds 2°C. Additional savings (286 kWh/year) can be achieved by removing the air cleaner, which can be considered redundant to the air filter in the heat recovery ventilator (HRV).

In order to assess the best opportunities for improvement to the envelope, the sources of heat loss were predicted for the house during the heating season (when all solar gains are assumed to displace mechanical heating) (see Figure 6a). While the window losses account for 21% of total losses, the net energy balance for the windows including solar gains, is positive - about 1000 kWh. Since the house is relatively airtight, there is little benefit to further sealing the envelope. Similarly, the ventilation rate cannot be lowered and the house is already equipped with a HRV. Thus, the opaque envelope and windows represent the only practical potential.

First, the upside of removing the dividers in the windows is 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 were not changed. As for many aspects of the house, the existing vinyl window frames are high performance.

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 22°C. This is predicted to reduce cooling loads by about two-thirds, resulting in 170 kWh of electricity savings. Proper shade control also improves thermal comfort by mitigating overheating and direct beam solar radiation on occupants. The addition of 1 m^2K/W of insulation on the basement and above-grade walls of the house yields an annual reduction in electricity use of about 400 kWh.

The energy implications of each upgrade are quantified in Figure 6b. With these upgrades, there are few good remaining opportunities to reduce consumption without modifying occupant behaviour. The total reduction of predicted energy use was reduced by 21%. If appliance and plug loads are excluded, this figure is 35%. In order to attempt to achieve predicted net-zero energy status, the rest of the gap should be filled with the supply side.

For active solar energy collection, an existing issue that should be considered is snow accumulation on the roof and its negative impact on wintertime generation. Thus, the effect of increasing the BIPV/T roof slope to 45° (from 30°) was examined. From experience, this slope has been found to effectively shed snow [12]. RETScreen [3] indicates that the difference in slope has a negligible effect on annual incident solar radiation of about 1449 kWh/m^2/year, 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 a 22% increase in area for a total surface area of 65.6 m^2.

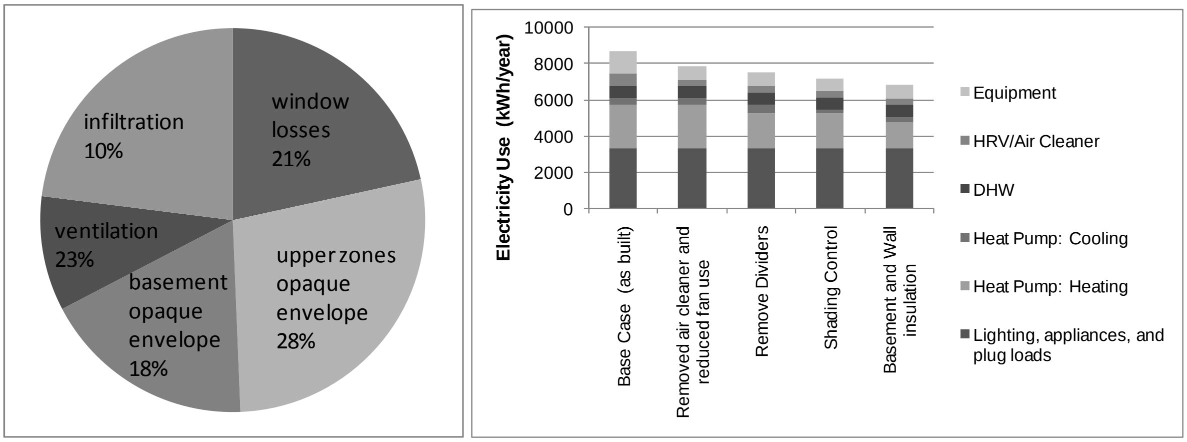

Figure 6: a) distribution of total heat loss during the heating season; b) electricity use for successive upgrades

Assuming annual electricity use of 6800 kWh, an inverter efficiency of 95%, shading losses of 8% (as measured for the site), 90% module coverage area (for spaces and edges), a minimum module efficiency of 9.1% is required to achieve net-zero energy. This level of efficiency is above the range (5-7%) of common amorphous silicon modules, thus poly-silicon or other higher performance modules (such as polycrystalline silicon) are needed. The total capacity of the array must be at least 5400 W (or 90% greater than the existing array).

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 modelled for both the current (30 degree slope) and the 45 degree configurations and the thermal output was compared to the space heating and DHW loads on a monthly basis. 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 in [4]. The results (see Figure 7) 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 heat pump should be considered, as was done for the Alstonvale House design [13], since it would significantly decrease the outlet temperature threshold above which the energy is in a useful form.

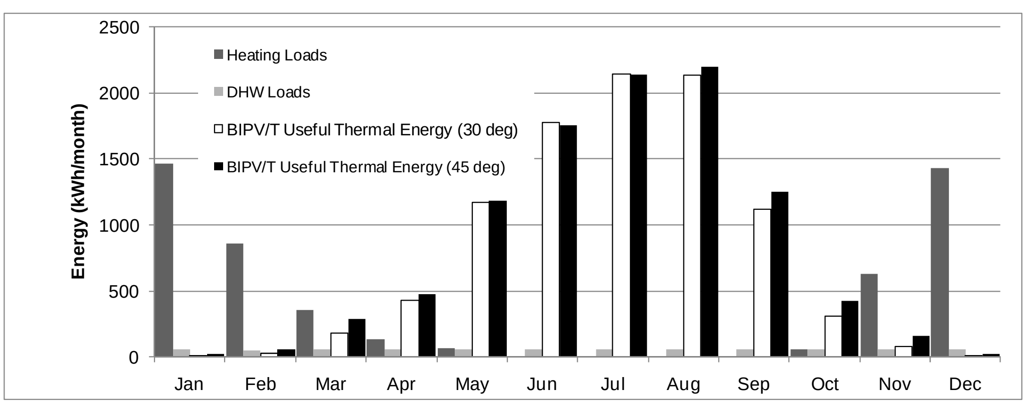

Figure 7: Comparison of thermal loads and BIPV/T useful energy output

5 Conclusions

This paper examined the design process of a near net-zero energy house, presented measured performance results, and suggested how net-zero energy status could be achieved through some design changes. Simulations showed that annual electricity savings of 21% are possible without taking any extreme measures. Beyond that, additional active building-integrated solar energy generation becomes the most practical upgrade to achieve net-zero energy. After the design upgrades, discretionary loads account for over half of electricity use. For houses for which the envelope heat transfer and passive solar performance have been optimized, the greatest remaining opportunity is to influence occupant behaviour by means of advanced controls, display of resource consumption, and education. This represents a significant and necessary area for further research. Two major trends are expected to aid the movement towards widespread implementation of NZESBs: 1) the improvement of efficiency and intelligence of appliances and equipment, and 2) the improvement of active solar energy collectors. This means that even a house that is not net-zero energy today may become so as old equipment is replaced with higher performance equipment over its life cycle.

This work, along with case studies for five diverse net-zero energy buildings, is being expanded into a report for Sourcebook Volume 2 for the IEA SHC Task 40/ECBCS Annex 52 ("Towards net-zero energy solar buildings") Subtask B ("Design Process Tools").

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