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Net Zero Energy Homes of the Future: A Case Study of the ÉcoTerra™ House in Canada

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1 Introduction

EQuilibrium Housing is Canada's official brand of the Net Zero Energy Healthy Housing Initiative, which was led by Canada Mortgage and Housing Corporation (CMHC). It aimed to bring "the public and private sectors together to develop homes that combine resource and energy efficient technologies in order to reduce their environmental impact" [1]. In this paper, a net zero-energy home (NZEH) is defined as a house that consumes as much energy as it produces over a year. In short, the overall goals of Canada's EQuilibrium housing initiative are to:

- develop a clear vision and approach to homebuilding;
- build the capacity of the national housing and renewable energy industry sectors to create high quality product across the country over the long term;
- achieve market acceptance of low-impact healthy houses and sustainable communities; and
- enhance the domestic and global leadership in sustainable residential community design and development.

As a result, a total of 72 teams submitted applications in July 2006, of which 12 winning teams received funding from CMHC.

The ÉcoTerra house is one of the winning projects, developed by the modular housing manufacturer Alouette Homes. The house was planned to demonstrate how low-energy healthy housing techniques and technologies could be implemented and marketed [2]. It was built in November 2007 and represented Canada's first net zero-energy home. The project was completed by holding a 'design charrette' that brought together several housing and energy experts with multidisciplinary background [3]. The house was an attempt to combine energy-efficient construction techniques and renewable energy systems to achieve Canada's energy efficient guide (or 'EnerGuide') for house rating in excess of 98 points [4]. The following sections provide technical information on the design features as to the health, resources, and environmental aspects.

2 Technical Features

The ÉcoTerra house is a two-story detached home built on a 1.1 hectare rural lot of a new residential development located in Eastman in the province of Quebec (Fig 1).

Figure 1: ÉcoTerra house in Eastman, QC

The heated floor area of the house is estimated at 234m^2, including the basement. The house was constructed by making use of Alouette Homes' pre-engineered modular housing system that helped reduce potential on-site construction nuisances, such as bad weather, theft and vandalism. The house has two bedrooms that are both located on the first floor while the semi-private spaces including the kitchen, dining room, living room and sunspace family room are on the ground floor. There is also a basement that serves as a multifunctional space and machine room. A closed garage is located on the north side of the house and is attached to the façade to act as a buffer space and reduce the fabric heat loss. The house walls are fitted with triple-glazed, low-e coated and argon-filled windows that reduce the fabric heat losses.

3 Occupants' Health and Comfort

Day-lighting exposure is of great importance for the occupant's health and comfort. Thus, the glazing areas allocated to the exterior walls of this house are designed to ensure a comfortable level of natural day-lighting and reduce the total amount of electricity required for artificial lighting. The window areas of the south, west, east and north walls are estimated at 20.90m^2, 5.20m^2, 6.67m^2 and 0.65m^2, respectively, and the ratio of south glazing to floor area is approximately 9.1%.

Other key healthy housing design features applied to the ÉcoTerra house are the air-tight construction and the continuous balanced mechanical ventilation. This combination provides good indoor air quality since it isolates the home from outdoor pollutants while ensuring that indoor pollutants are continuously exhausted. In this house, foam insulation material was used to increase the thermal insulation as well as to maintain the building air-tightness at 1 air change per hour (or 1 ACH) at 50 Pa. For the ventilation, the house is equipped with a balanced heat recovery ventilator (HRV). This HRV has the capacity to recover up to 76% of the heat contained in the exhaust air to transfer it to the incoming fresh air. To further contribute to minimise indoor air pollutants, the use of carpets was avoided, particularly for the flooring of the lower levels. Instead of carpeting, the concrete floor mass was covered with dark brown ceramic tiles that can be cleaned easily while allowing for the efficient absorption of the sun's heat (Fig 2).

Figure 2**:** Concrete thermal floor mass covered with ceramic tiles

With due consideration of solar gain potential, sufficient thermal mass was added to the ground and basement floors and walls of the house in order to provide the occupants with thermal comfort without depending solely on the mechanical heat supply. For the cooling season, the overheating caused by strong sunlight was alleviated by the placement of sun-shading overhangs and motorised blinds (Figs 1&2). Furthermore, the house was built to maximise the benefits of the rural setting that encompasses a number of broadleaf trees that comfortably shade a part of the dwelling unit during the summer and protect the house from winds that enhance the fabric heat losses in the winter.

4 Energy Use

Building energy consumption is closely related to the location. In the case of the ÉcoTerra house, the average temperatures at the construction site were estimated at -10.4˚C in January, 4.6˚C in April, 19.4˚C in July and 7.1˚C in October. Thus, space heating was expected to represent an important part of the annual energy consumption. The energy requirements of the ÉcoTerra house was evaluated with HOT2000, a low-rise residential energy analysis and design software developed by Natural Resources Canada [5]. With this tool, the annual gross space heating load of the house was estimated at 21,795kWh without the contributions of passive solar techniques and active renewable energies. With consideration of the house's achievable passive solar gains of 9,592kWh/yr and potential internal gains of 3,491kWh/yr, the estimated annual energy requirement for space heating was reduced to 8,712kWh. As for the domestic hot water (DHW), the heating load was approximated at 3,353kWh/yr for a hot water load of 150L/day at 55°C. The annual electrical load required for interior lighting, appliances and exterior use electrical equipment (e.g. exterior lighting and dryer) was estimated at 3,974kWh. The annual electrical load for mechanical ventilation was evaluated at 617kWh. Accordingly, the annual energy requirement of the house before the application of renewable energy technologies was assessed at approximately 16,656kWh. The following sections aim to reveal the further effect of the renewable technologies on the house energy consumption.

5 BIPV/Thermal System

Building integrated photovoltaic systems have a great advantage compared to stand-alone PV arrays or solar thermal collectors because they generate both thermal and electrical energy simultaneously while being architecturally and functionally integrated into the design of the roof in one complete surface. Therefore, a 3kW BIPV/T based on a system concept developed at Concordia University was introduced to the ÉcoTerra house. The PV array of the BIPV/T system is comprised of 22 Unisolar amorphous silicon 136W laminates placed on the 55m^2 south-facing metal rooftop (Fig 1). The PV potential annual electricity production was evaluated by making use of NRCan's RETScreen clean energy project analysis tool and it was estimated at approximately 3,420kWh for a slope of 30.3° [6]. However, this estimate does not take into account the cooling effect of the air flowing behind the PV laminates. The BIPV/T system is an on-grid application accompanied with an inverter for the AC/DC conversion. The system allows for redirection of the locally generated electricity surpluses to the grid. The net metering programme that made this arrangement possible will be described later.

The heat is being recovered from the PV with a ventilator that forces fresh air to go through the inlets located in the roof soffits and to enter the cavity created behind the PV panels. While flowing in the cavity, the air takes back the heat from the PV. Thus, it is preheated when it is drawn into the lower portion of the house from the roof ridge ducted (Fig 3). The BIPV/T system installed in the ÉcoTerra house has the capacity to produce up to 12kW of heat at 14m^3/min of air flow according to the project team members' experiment [7].

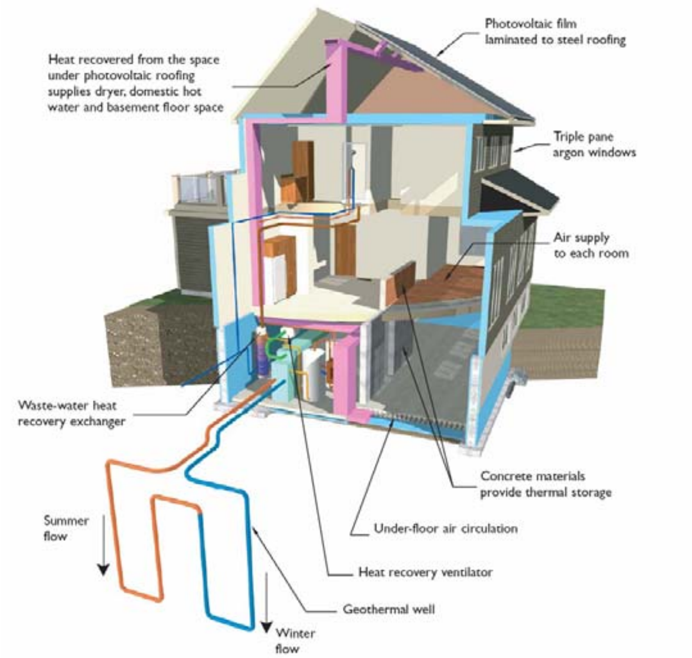

Figure 3: Advanced renewable energy technology scheme [8]

In the ÉcoTerra house, the air recovered from the PV is primarily used for drying clothes whenever the air temperature at the BIPV/T outlet is greater than 15˚C. If the air temperature at the BIPV/T outlet is not high enough for clothes drying, the hot air is used for preheating water through an air-to-water heat exchanger installed in the house. In the case where the outlet air temperature is not sufficiently high to be applied for neither of the two applications mentioned above, the air is sent to the basement under-floor for thermal mass heating where the concrete slab will store the heat at the daytime and release it at night.

The PV heat recovery system introduced to the ÉcoTerra house is estimated to provide 700kWh of the annual 900kWh clothes dryer energy load. From November to March, the hollow core concrete thermal mass in the basement is heated by the warm air from the BIPV/T system (see [3] for more detail). The hollow core floor can also be utilized in the summer for natural cooling with outdoor night air. The BIPV/T system is therefore expected to reduce the space heating load by approximately 3,800kWh in the heating season. For the other 7 months, the BIPV/T is estimated to supply approximately 1,400kWh of the annual DHW heating requirements.

6 Geothermal Heat Pump

The ÉcoTerra house is heated or cooled by a two-stage geothermal heat pump (GHP) with environmentally-friendly refrigerant. In addition to space heating through a ducted forced air system, the heat pump assists water heating with a desuperheater. It is expected to reduce the energy consumption related to water heating by approximately 700kWh/yr. The system lifespan was considered to be over 20 years.

All mechanical equipment including the GHP, BIPV/T fan, electricity distribution panel, heat recovery system and heat exchanger is located in the basement mechanical room that is enclosed by concrete thermal mass. The house is also designed to use the heat released from the machines to supplement space heating by letting the warm air circulate through the open staircase driven by stack effect.

With consideration of the above-mentioned renewable energy technologies combined with the passive solar techniques applied to the ÉcoTerra house, the annual space energy consumption could be as low as 1,130kWh. The electricity used for DHW could be reduced from 3,353kWh to 553kWh as a result of the contributions of the heat pump desuperheater, BIPV/Thermal system and 21% efficient drain-water heat recovery unit (DWHR), but depending on actual water consumption and control strategies the value may become higher. In some cases, the savings from different technologies are not expected to be additive; the heat recovery from BIPV/T can preheat water. If the storage volume is adequate, it can be heated further with the desuperheater. As for the energy consumption of indoor lighting, appliances and exterior use electrical equipment, it was decreased from 3,974kWh to 3,274kWh with the reduced clothes dryer annual energy load. When subtracting the PV electricity generation of 3,420kWh from the sum of these figures, the annual energy consumption of the ÉcoTerra house can be re-estimated at 2,155kWh. However, if the energy systems are not properly controlled in an integrated manner, this consumption could possibly reach 4,000 kWh or more.

To achieve the net zero-energy target, the balance between the house's energy consumption and the generation patterns over the period of a year needs to be taken into account. The following section describes the total annual energy consumption profile of the ÉcoTerra house with due consideration of the net metering arrangement.

7 Net Metering

For the ÉcoTerra house project, the local power company, Hydro-Québec, was already in the position to allow this residential development to demonstrate the 'net metering' arrangement. This agreement enables the home occupants to receive credits for the excess electricity that is generated by the renewable energy sources installed on their house (Fig 4). The project is assumed to benefit from this arrangement so as to demonstrate the house's near-zero-energy consumption.

Generally, the definition of net zero-energy homes being expressed in literature around the globe is still vague. A net zero-energy house can be referred to as a house whose energy 'use' becomes net zero over a fixed period of time whereby a net metering arrangement and renewable energy technologies are brought into effect. On the other hand, a house whose energy 'bill' becomes net zero under the same conditions can be considered net zero-energy-cost housing. The production of net zero-carbon housing, whose value is from time to time considered as equivalent to the net zero-energy counterpart, may perhaps require further steps to be achieved. Farhar suggests that to achieve a zero-carbon housing target, the amount of electricity exported should be 20% greater than the energy used for the operation of a house for at least 25 years [9]. The energy surplus generated by renewable energy technologies installed in a house can be fed into the grid so as to cover the embodied energy used for the production. In this respect, the zero-carbon homes should be designed with the aim to cover the energy required for both building and operating a house.

8 Cost-Benefit Analysis

A cost-benefit analysis of the ÉcoTerra house energy efficiency measures and renewable energy technologies was conducted by making use of the 'Energy Efficiency Measures' module of RETScreen Version 4 [6]. This tool allows a user to model a building by specifying its envelope properties, heating systems and electrical load, and to evaluate the energy and cost savings, the greenhouse gas emissions and the financial viability of various energy efficiency measures.

In order to perform the cost-benefit analysis, a typical house in Quebec was first modelled with the simulation tool. The building envelope properties of the house were assumed to correspond with the minimum requirements specified in the 'Model' National Energy Code of Canada for Houses [10]. For the house's space- and water-heating, 100% efficient electrical heaters were selected. Then, the energy efficiency measures (e.g. compact fluorescent light bulbs, EnergyStar and low-water consumption appliances, DHWR and HRV units, and high thermal performance building envelope) and renewable energy technologies (e.g. BIPV/T and GHP) implemented in the ÉcoTerra house were applied to the standard housing model. The tool was used to assess different combinations to evaluate their cost and benefits.

The electricity rate was set at CAN$0.066 per kWh [11]. Accordingly, the annual energy cost for the operation of the average Quebec house modelled in RETScreen was estimated to be approximately $3,200. When the ÉcoTerra house energy efficiency measures were applied to this base case home, the annual energy cost was reduced to approximately $1,250. This amount represents annual savings of more than 60% for the house operating cost with an additional investment of only around $15,000.

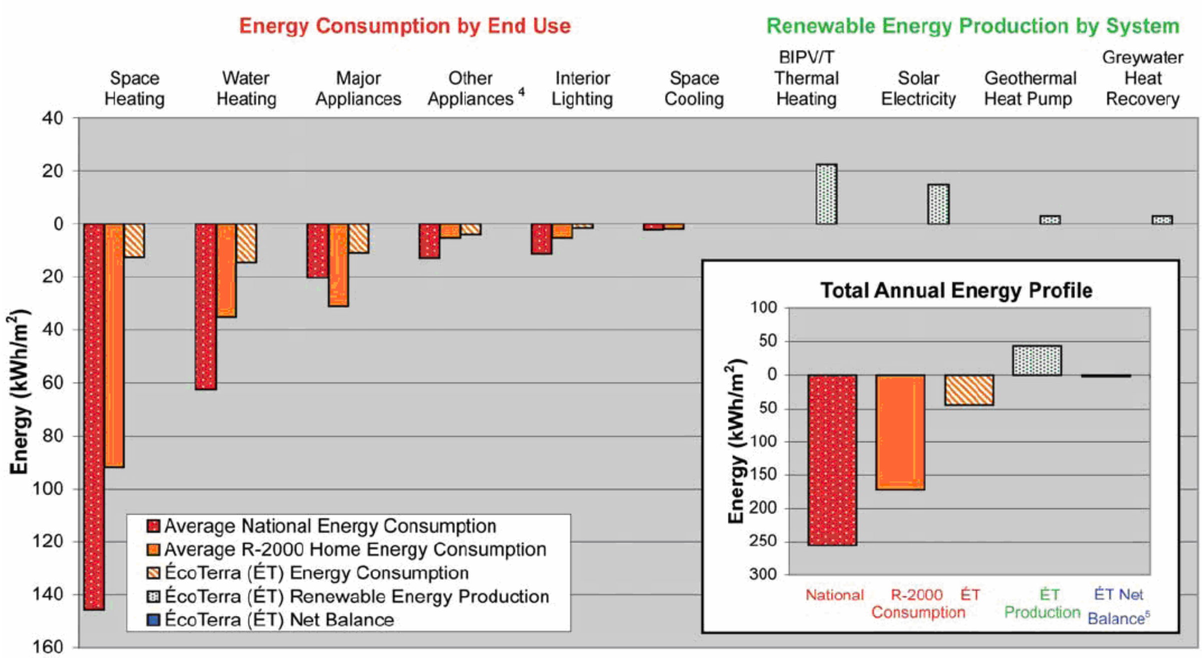

Figure 4: Annual energy consumption and production profiles of the ÉcoTerra house and other typical homes in Canada [8]

The implementation of renewable energy technologies, however, necessitated a more important initial investment. For instance, the additional cost of replacing the standard heating system by a GHP was estimated at $24,000. Combining this technology with energy efficiency measures reduced the annual energy cost of the Quebec standard home to nearly $700. This is almost an 80% reduction from the standard home annual energy expenditure of $3,200. When including the BIPV/T prototype system, the annual savings were in the order of 92%, which corresponds to an estimated annual energy cost of $260. Therefore, if the net metering arrangement provided an additional annual credit the annual energy bill would be zero.

The addition of these renewable energy technologies was essential to achieve the project objective of designing a zero-energy house. The GHP and BIPV/T technologies will need to go down by a factor of 2-4 to become more affordable.

9 Conclusions

The EcoTerra housing prototype presented in this paper was designed to be energy-efficient to minimise negative impact on environment. Moreover, the house provides its occupants with comfortable and healthy indoor living environment and produces as much energy as it consumes on an annual basis. The analysis indicates that the house experiences nearly net-zero energy consumption when it comes into operation.

For the production of low energy housing, the building envelope needs to be equipped with high thermal performance insulation material that reduces the fabric heat loss. Also, air-tight construction approaches should be applied for lowering the ventilation heat loss. Passive solar techniques are essential in maximising the use of free clean sunlight for water- and space-heating as well as day-lighting. The installation of active renewable energy systems is effective in covering the energy use in housing before and after construction.

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